Design Considerations for LTV HITL Testing of Pressurized Suited Crew on a Motion-Based Platform

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The upcoming NASA Lunar Terrain Vehicle (LTV) will succeed the Apollo Lunar Roving Vehicle, performing both surface exploration and logistics transfer in NASA's return to the Moon. Human-in-the-Loop (HITL) testing will play a key role in refining the design of the LTV, ensuring its usability and ability to accommodate the astronaut population. A motion-based platform and a lunar terrain and lighting model can simulate the conditions of the lunar south pole region. It can be used by NASA to conduct HITL testing in concert with HITL testing of the drivable Ground Reference Unit (GTU) concept vehicle. The dynamic motion of the platform combined with the mobility restrictions of pressurized suits could help improve NASA understanding of vehicle-suit-astronaut interfaces. NASA human factors practitioners have proposed multiple HITL test series to use the motion-based platform in conjunction with testing of the GTU in hopes that lessons learned can be applied to help select a commercial partner to develop the Artemis LTV.

I. Introduction

NASA's return to the Moon has been officially placed into US law via the NASA Transition Authorization Act of 2017 [1] and the NASA Authorization Act of 2022 [2]. NASA recently released an update to its Moon to Mars Objectives [3], establishing long term goals for a human lunar presence.

Spacecraft elements supporting the initial human presence on the Moon are expected to include the Human Landing System (HLS) and Commercial Lunar Payload Services (CLPS) landers, logistics carriers, the Lunar Terrain Vehicle (LTV), Pressurized Rover (PR). Additional surface habitation concepts are currently in study and are expected to lead to additional surface elements. [4]

The LTV will be used on the Moon in a similar manner as the Apollo era Lunar Roving Vehicle (LRV) [5] to conduct surface exploration, carrying two astronauts on excursions to investigate the lunar environment. It will also be used to perform logistics transfer, transporting supplies from lander vehicles to elements such as one or more surface habitation elements.

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Human-in-the-Loop (HITL) testing is a key part of the design process for the LTV or any other human spaceflight vehicle. This testing can ensure that the design is able to physically accommodate the crew and it also can assess the usability of the vehicle.

HITL testing was conducted throughout the development of the Orion crew capsule and provided valuable data to drive the development of Orion displays and controls as well as Orion suited seating and restraints, both of which have clear counterparts in LTV. Similarly, HITL testing conducted during and just after the Constellation Program for the NASA Small Pressurized Rover evaluated displays and controls, pilot/driver visibility, and aft deck driving operations. Unpressurized rover HITL evaluations for the NASA Chariot rover also performed usability analyses of the driving station and measured operator fatigue. A suited human-in-the-loop evaluation of the Chariot is shown in Figure 1.

Figure 1. Suited Evaluation of Control Interfaces in the NASA Chariot

NASA plans to acquire LTV services from US industry [5] and HITL testing will be part of the process to assess contractor compliance with NASA requirements. The LTV is the first unpressurized rover to carry crew since the LRV was used on Apollo 15, 16, and 17. The LTV is expected to carry significantly more cargo and operate for substantially greater periods of time than the LRV. It is also intended to improve crew experiences over the LRV, particularly with regard to seat restraints, ride comfort, and driving/navigation.

An internally proposed, but not yet funded, NASA evaluation is to conduct its own internal HITL testing using a motion-based simulator platform. This will enable NASA personnel to determine the importance of position/posture adjustment while driving (e.g., for field of view or reach to buttons or switches), assess operator stability over rough terrain (e.g., stabilization for operator control inputs and prevention of inadvertent control actuation), and evaluate seat restraints with respect to ease of operation, crew perceptions of stability and prevention of ejection from vehicle and prevention of inadvertent contact with other crew, structures, or cargo.

II. Rationale for the use of Pressurized Suited Crew in Motion-Based LTV HITL Testing

A. Consideration for Suit-Crew-Vehicle Interaction

The interface between LTV, suit, and crew must be properly considered. There are no direct interfaces between the LTV and the crew because it is an unpressurized rover. Instead, the LTV interfaces with the spacesuit and the spacesuit interfaces with the individual crew member. Interfaces between the LTV and the suit include photonic interfaces, structural interfaces, thermal interfaces, and electronic interfaces. Interfaces between the suit and the crew include visual interfaces, tactile interfaces, auditory interfaces, and olfactory interfaces. There is also a potential gustatory interface.

The Artemis lunar surface spacesuit is being developed independently [6], and the potential exists for multiple lunar surface spacesuits to be developed over the lifetime of the LTV project. Consequently, the LTV cannot be developed to the unique specifications of only one suit. It is expected that an interface definition will be developed, and all future suits and vehicle augmentations will need to meet that interface.

B. Maturation of LTV Cockpit Design

NASA is developing an LTV Ground Test Unit (GTU) to aid in its development of the Artemis program. The GTU is a concept vehicle that will not go to the Moon itself. It is more of a pathfinder, helping NASA to understand how an LTV fits into the broader lunar infrastructure and how to evaluate Contractor(s) LTV concepts. The GTU features a two-person cockpit, designed for space suited crew members. It features hand controllers and displays for operation of the vehicle. NASA human factors engineers are exploring innovative approaches for the GTU’s display and control interfaces, crew seating and restraints, and driving visibility. HITL testing, inclusive of Virtual Reality, static mockups, a fixed-base simulator, a motion-based simulator, and a drivable prototype are being used to conduct preliminary assessments of cockpit operations.

III. JSC Motion Table and Simulation Specifications and Performance

The JSC Software, Robotics and Simulation Division has acquired a Mikrolar 6-degrree of freedom (DOF) motion platform table in its Systems Engineering Simulator (SES) facility, shown in Figure 2 with specifications as indicated in **Error! Reference source not found.**. This large Stewart platform is a base that can receive various platforms on top of the table that can then be subjected to 3-axis motion. A generic, shirtsleeve, single-person cockpit has been initially developed for the motion platform table. There are long-term plans to utilize a projection system to display the simulated lunar environment, but until funding permits development of the projection system a Virtual Reality headset is worn by the test subject. Additionally, pending funding and schedule, a GTU cockpit will be constructed that can support two suited crew members, emulating their placement on the GTU.

Table 1. Mikrolar 6-DOF Motion Platform Specifications

SPECIFICATION	DATA
Payload	2,500 lbs.
Platform	69.25" Ø
Degrees of Freedom	Six
Loading Height	46.25"
Acceleration (X, Y, Z)	0.5 g
Velocity (X, Y, Z)	24"/sec
Range of Motion (X, Y)	±25"
Range of Motion (Z)	±12"
Range of Motion (Roll, Pitch Yaw)	±28°
Repeatability	1 mm
Accuracy	1 mm
Mechanical Brakes	All Axes
Electric Motors	Six

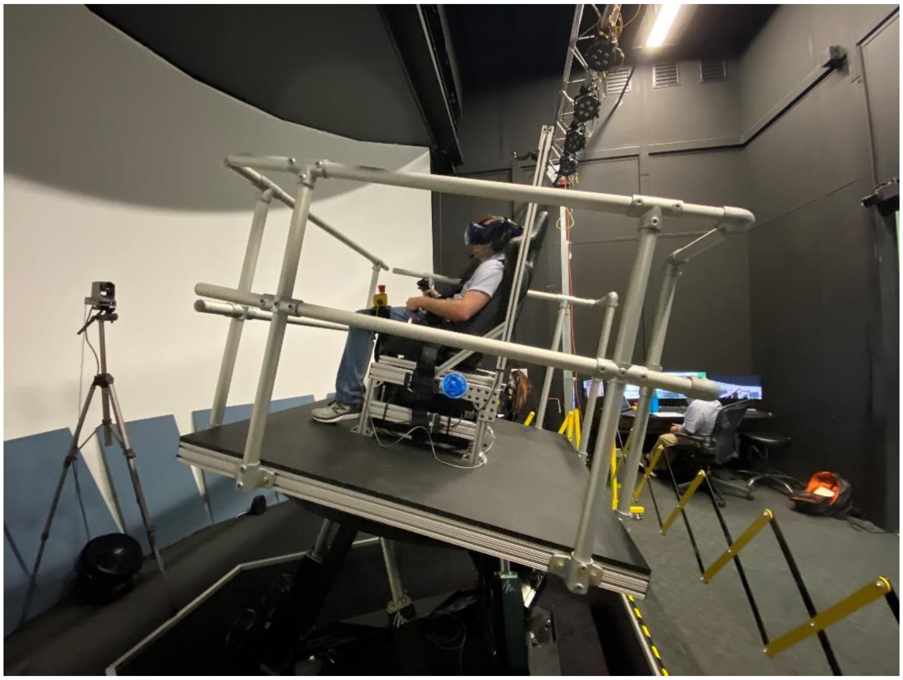

Figure 2. SES Motion Table

A. Lunar Simulation Description

The motion platform can be tied into previously developed lunar terrain and vehicle simulations. The SES has a representation of the lunar south pole that was previously used in a lighting and navigation simulation campaign and in a hand controller evaluation, both of which occurred in its fixed base Video Wall facility, shown in Figure 3. The simulated south pole environment is based on Lunar Reconnaissance Orbiter (LRO) data and includes a variety of terrain conditions (slopes, craters, rocks, etc.). It also includes a lighting model that emulates the low sun angle and the extensive shadowing that results.

Figure 3. SES Video Wall

Two evaluation studies have already been identified for possible use of the motion platform. Under an Internal Research and Development (IRAD) grant, different rating scales for evaluating ground vehicle performance will be tested to determine the appropriate scale(s) for use in future LTV contractor evaluations. Additionally, a test plan is currently in development to conduct hand controller and seating evaluations, both to refine protocols for Contractor simulator evaluations and to identify areas of potential future improvement for the GTU cockpit. This latter test is not currently funded, only proposed at the time of this writing.

IV. Motion-Based Platform Considerations for Pressurized Suited Crew

There is a hard geometric limit to how large the cockpit can be. When the motion table is at its maximum angles in roll, the left and right sides of the cockpit deck must not come into contact with the facility. This is also true for the front and back sides of the cockpit when at maximum extremes of pitch. Additionally, access must be provided for test subjects to enter and exit the cockpit mockup.

Anthropometry will provide some drivers for how large the platform needs to be. Several critical dimensions of test subjects wearing spacesuits will drive the sizing of seats, spacing between them, and access paths on the platform leading between the seats and ingress/egress points. There will also need to be sufficient volume for suit techs to assist with test subject translation. Techs will need to verify that the seat restraints have been properly applied. The difference between maximum and minimum anthropometric dimensions will also drive a need for adjustability in seats, arm rests, displays, and controls. Without this adjustability, some crew members may literally be unable to operate certain controls or may be unable to see display data, while for others awkward body positioning will induce fatigue and discomfort.

NASA operates three prototype or mockup suits that might be used in the motion platform mockup. The ATLAS suit is an unpressurized mockup suit that is often used prior to prototype suits. The Z2 and xEMU are both pressurizeable spacesuit prototypes. The three suits vary slightly in weight and dimension, so the cockpit will need to consider the masses, dimensions, and contours of all three, as well as keep out zones for fragile components or umbilicals. The ATLAS, Z2, and xEMU are shown in Figure 4, Figure 5, and Figure 6 respectively.

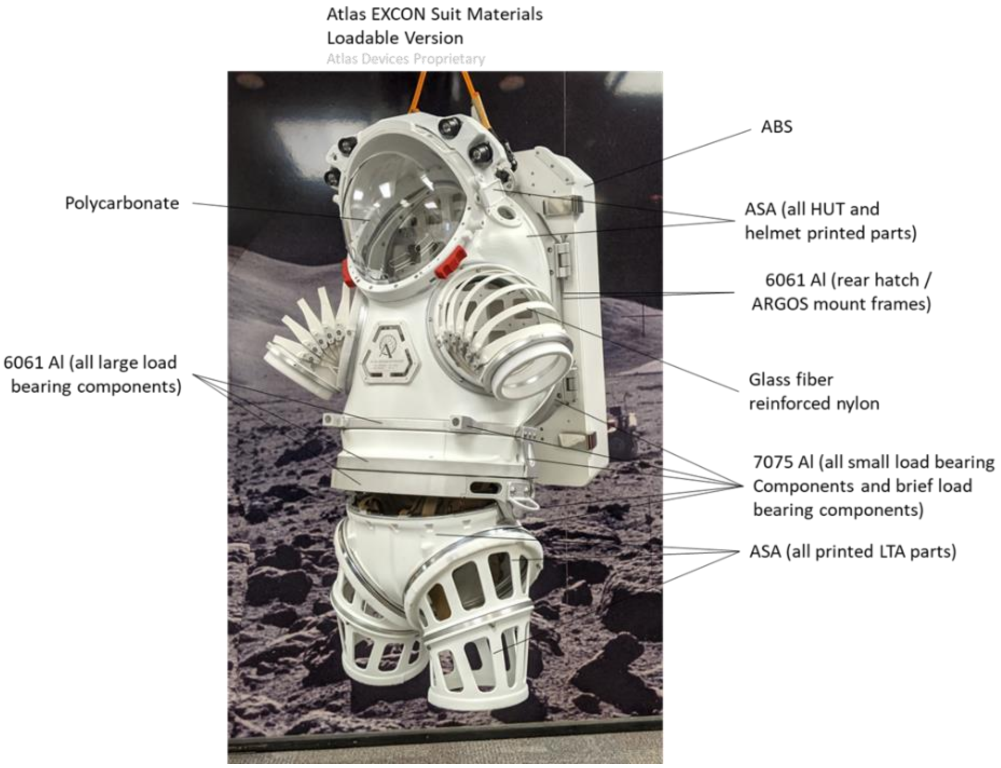

Figure 4. Atlas EXCON Mockup Suit

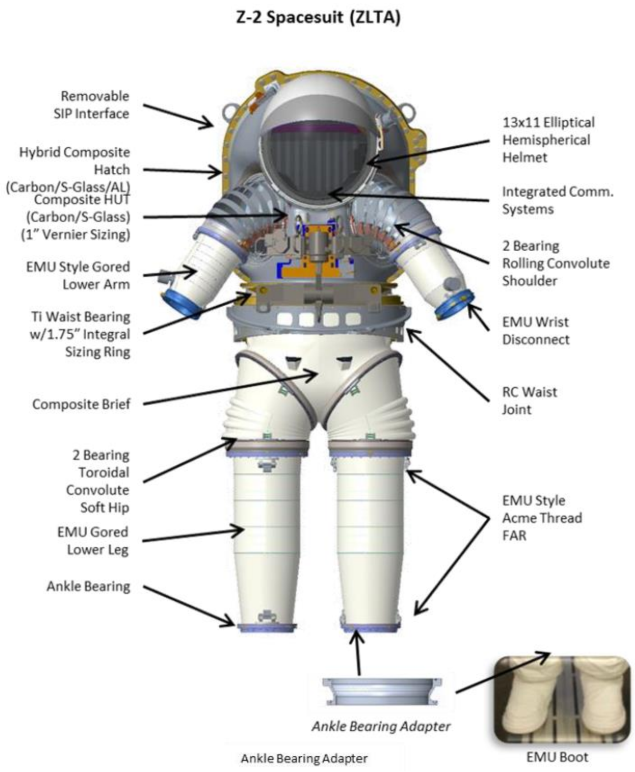

Figure 5. Z-2 Spacesuit Prototype

Figure 6. xEMU Spacesuit Prototype

Suit mobility will also need to be a consideration. The elbow, knee, ankle, neck, wrist (flex), and fingers do not have ring bearings. Any deviation from the neutral position in those joints requires physical effort to initiate and to maintain. The wrist (rotation), hip, and shoulder all have ring bearings. There, the suit motion is a rotation about that bearing. While this is significantly easier to perform, the hip and shoulder bearings in particular have a substantially different motion from the human body, causing the arms and legs to splay out in a manner that a shirtsleeve person would not do. Thus, the cockpit must allow for those body motions in its design.

Each spacesuit will also be equipped with either a prototype or mockup backpack (portable life support system - PLSS) or an umbilical connection in place of a PLSS. The cockpit will need to accommodate both implementations, including umbilical management to prevent the umbilicals from becoming trip hazards or getting snagged in platform motion.

Suit mobility constraints will require design solutions to provide the crew with sufficient situational awareness to (with the assistance of suit techs) ingress and egress their seats and secure/release their restraints. The motion platform is capable of an aggressive range of dynamic motion and its nominal simulation of the GTU operating over lunar terrain is such that body restraints will be needed. Any anomalous, uncommanded motion could be even more extreme. The motion platform's certification requires a 5-point harness for shirtsleeve test subjects. Something that achieves an equivalent level of restraint will be required for suited test subjects. A suited restraint will need to be designed that does not damage the suit or interfere with any suit keep out zones. It must also be accessible by suited crew, taking the reduced reach and range of motion of a pressurized suit into account. A concept suited restraint under development by NASA Center for Design and Space Architecture personnel is shown in Figure 7.

Figure 7. Prototype Suited Seat Restraint

The motion platform must also enable response to any of several potential contingencies. In the event of a test subject medical condition, the platform must quickly be put into a position where the subject can be safely extracted and receive treatment. In the event of a suit failure, the platform must again be quickly put into a safe position. Here, suit techs must have sufficient access to determine if it is an immediately recoverable failure and take the corrective action. If it is not, they must be able to take the appropriate actions to extract the crew member from the platform and suit.

A motion table failure may be more complex. The table could experience an uncontrolled, erratic motion, requiring an immediate emergency stop. If this results in test termination, the platform must be safed to prevent further uncommanded motion while the test subjects are extracted. The table could also stop off-axis and be unable to resume motion. In such a case, there must be a means to extract the crew from the failed platform, which might be at an extreme angle in one or more axes.

V. LTV Motion Table Cockpit Design

The two-person cockpit was initially required to only support shirtsleeve operations, but with sizing that enables it to be upgradable to suited operations. In November of 2022, requirements were established for the shirtsleeve-compatible dual seat cockpit for the motion table:

1. The dual seat cockpit shall consist of a rectangular motion table platform and two seats, each of which shall have identical hand controllers and associated mounting structure.

2. The motion table platform shall be of sufficient length, width, and load carrying capacity to facilitate safe ingress and egress into the seats and on/off the motion table, and to facilitate operation with two crew members in pressurized suits.
3. The seats shall be selected for unsuited use, but the motion table platform shall be sized for pressurized suited use.
4. The dual seat cockpit shall be built exactly like the SES single person cockpit using identical, if not the actual, materials. This may involve the construction of a new cockpit or a modification to the structure of the existing cockpit.
5. The dual seat cockpit shall have the necessary structural integrity to operate on the motion table.
6. The dual seat cockpit shall be capable of operating as a single person cockpit by removing one seat and centering the remaining seat.
7. The dual seat cockpit shall be capable of operating with one test subject in the single seat configuration, two test subjects in the dual seat configuration, and one test subject in the dual seat configuration with ballast to compensate for the absence of the second test subject.
8. Each seat structure on the dual seat cockpit shall be capable of receiving up to 250 lbs [TBR] ballast when not occupied by a test subject.
9. The seats for the dual seat cockpit shall be the Corebeau seat with five-point restraint system.
10. The dual seat cockpit structure shall be built of 80/20 aluminum structure.
11. The dual seat cockpit shall be able to pass the same structural analysis as the SES single seat cockpit.
12. The dual seat cockpit shall have hand controller and display mounts according to SES engineering requirements to meet NASA structural analysis for inadvertent loads.
13. The dual seat cockpit will have hand controller mounts for four different hand controller designs. These being the single SEV joystick hand controller, the single Tri-Rotor hand controller, the single T-Handle hand controller, and the dual T-Handle hand controller.
14. The dual seat cockpit shall be designed and built for the motion table platform to be attached to the existing motion table.
15. The dual seat cockpit motion table platform shall adhere to all NASA and SES safety protocols.

These initial requirements only encompassed a shirtsleeve configuration. However, before design work was completed, evolving test goals shifted to impose an expansion to the initial configuration to include a seating upgrade that will allow suited crew to sit in the cockpit. Given that the platform was always intended to evolve to a suited configuration, this imposed little actual change to the design. Seat spacing and seat-to-platform interfaces had already taken into account the need to accommodate pressurized suited dimensions.

The most significant change is that the shirtsleeve configuration had the option to use Virtual Reality, while the suited configuration cannot as it is impossible to don a Virtual Reality headset while wearing a spacesuit helmet. Consequently, a video wall was added to the forward end of the motion platform. The intention is to now use the video wall for both shirtsleeve and suited operations. This added fidelity to the shirtsleeve operations as the VR implementation in the original single seat motion platform cockpit did not allow for use of the GTU's edge key displays or video data displays. Both displays are usable in the video wall configuration and will enable a more realistic simulation of vehicle operations.

Both configurations are shown in Figure 8. The suited seat restraint shown in Figure 7 is incorporated into this design. Pending completion of a stress analysis, the cockpit is expected to be assembled and installed in the motion platform for HITL testing.

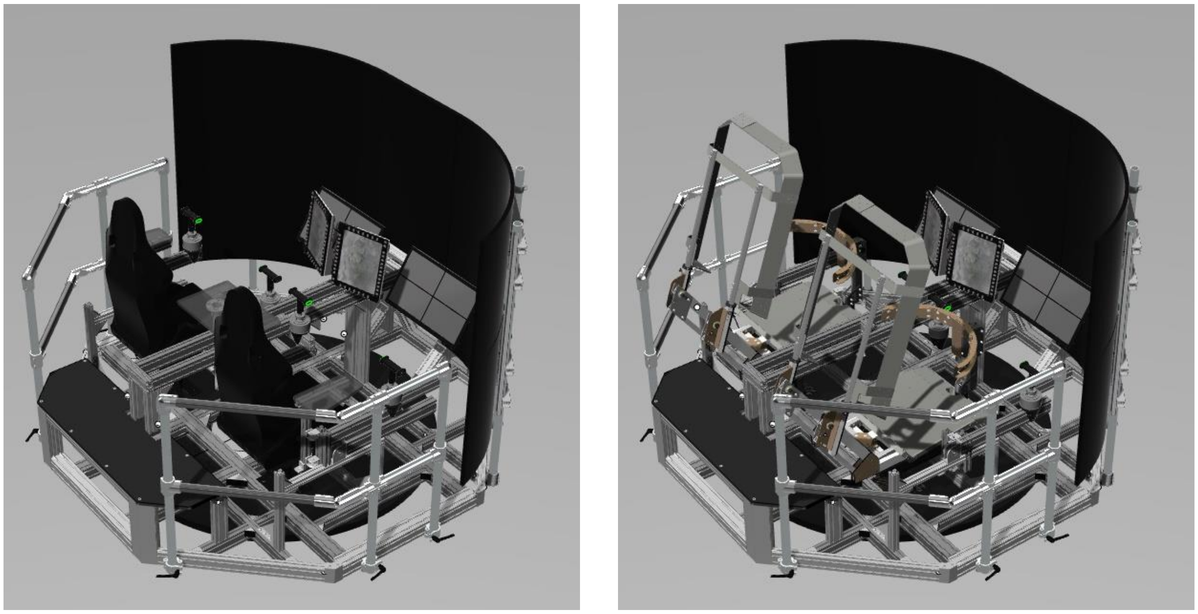

Figure 8. Motion Platform Shirt Sleeve and Suited Configurations

VI. Conclusions and Forward Work

HITL test dates are pending completion of motion platform design and assembly, as well as test-specific funding. A stress analysis is currently in the process of being scheduled with the JSC Structural Engineering Division. Platform assembly can begin once the design has passed stress analysis. The IRAD testing will be performed as soon as the platform is assembled and completes all readiness reviews. EHP testing will be scheduled once the IRAD testing timeline is finalized.

This work is hoped to parallel development work with the GTU, which is currently in the final stages of engineering development activity and has already completed one static mockup evaluation. An additional static test will be performed prior to testing in the JSC rock yard and potential further testing in future years at offsite locations such as analog field testing in remote desert environments. Lessons learned for seats, controls, displays, and mobility aids can be incorporated in either or both the GTU and the motion platform, and each HITL in either testbed can contribute towards both it and the other's design maturity.

GTU static testing will involve assessment of suited test subject reach/access to seat restraints and activation/deactivation/navigation of GTU displays and controls. Use of JSC's Active Response Gravity Offload System (ARGOS) facility for the upcoming static test may involve weight-offloaded crew ingress/egress step up and step-down actions and weight-offloaded crew recovery and securing of incapacitated crew mannequin at different vehicle angles.

JSC rock yard testing may involve assessment of crew training procedures, display and control accessibility at different slope angles and speeds, and seat restraint attach/detach at different slope angles. Analog field tests may involve evaluation of driving/riding experience across extended time and diversity of terrain conditions and evaluation of integration of LTV with other lunar surface elements (e.g., carrying logistics between lander and SH).

Additional future motion platform HITL testing may evaluate simulated vehicle lighting, camera placement, and joint operations with surface EVA and/or pressurized rovers. Use of the SES simulation environment can allow rapid reconfigurations, literally changing lighting configuration and camera placements with the flip of a switch. While this does not replace physical testing, it can enable down-selections of far too many concepts to physically test, offering a substantially more informed decision-making process to determine vehicle configuration(s) to use in field tests. In addition to vehicle design refinement, these test results may be beneficial to LTV Contractor(s) in that they can lead to a greater understanding of potential interfaces and design considerations that need to be taken into account between the LTV and spacesuit.

Vendors working in collaboration with NASA could potentially also install a cockpit on the motion platform to simulate the design of their vehicle concepts in concert with vehicle simulation data that could be included in the SES simulation, thereby enabling the motion platform to be used for studies associated with their contractor specific vehicles, inclusive of rovers, landers, and other mobile, crew-operable assets.

VII. References

[1] United States Congress, "National Aeronautics and Space Administration Transition Authorization Act of 2017," Washington, 2017.

[2] United States Congress, "Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act of 2022," Washington, DC, 2022.

[3] National Aeronautics and Space Administration, "Moon to Mars Objectives," Washington, 2022.

[4] P. Kessler, T. Prater, T. Nickens and D. Harris, "Artemis Deep Space Habitation: Enabling a Sustained Human Presence on the Moon and Beyond," in *2022 IEEE Aerospace Conference*, Big Sky, 2022.

[5] National Aeronautics and Space Administration, "NASA Prompts Companies for Artemis Lunar Terrain Vehicle Solutions," NASA, 31 August 2021. [Online]. Available: https://www.nasa.gov/feature/nasa-prompts-companies-for-artemis-lunar-terrain-vehicle-solutions. [Accessed 11 September 2023].

[6] V. Lloyd and R. Wockes, "NASA Partners with Industry for New Spacewalking, Moonwalking Services," NASA, 1 June 2022. [Online]. Available: https://www.nasa.gov/press-release/nasa-partners-with-industry-for-new-spacewalking-moonwalking-services. [Accessed 11 September 2023].