NASA's Ground Test Unit (GTU) Lunar Terrain Vehicle (LTV) Conceptual Hand Controllers Studies

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Abstract— **Over that past year, the National Aeronautics and Space Administration (NASA) has been preparing and developing a set of standardized testing protocols for the commercial LTV vendor selection. Two studies have been conducted on two possible hand controller concepts specifically designed for the operation of NASA's Ground Test Unit (GTU) Lunar Terrain Vehicle (LTV) that can be applied to the heretofore unknown designs developed by future LTV vendors. The objective for the two studies were to determine which hand controller enable acceptable operation of the LTV in a simulated lunar traverse. In the first evaluation a total of nine subjects in shirtsleeves with ungloved hands performed two simulated lunar driving courses in an engineering simulator with each hand controller. Controller concept one was the T-handle fashioned after the Apollo Lunar Roving Vehicle's (LRV) T-Handle controller. The rational for using this design is it's a proven design while in a pressurized suit. However, the LTV does have a driving mode the LRV did not consider. The mode of crabbing or strafing the vehicle at different angles; thus, the idea of a dual T-Handle controllers to accommodate this function without using a switch or display was introduced. The second concept controller is a new innovative controller call the Tri-Rotor [NASA patent review MSC-27385-1]. Inspired by Formula One race steering, the Tri-Rotor was designed to take advantage of the restricted movement and dexterity of a pressurized space suit. During testing, all subjects were able to successfully navigate through two test courses of varying lengths and complexity. Results indicated the dual T-handle had minimal recommendations for improvement while the Tri-Rotor had more extensive ones. It must be noted, the Tri-Rotor is a first-generation prototype and has some known mechanical concerns; thus, recommendations from this study will be incorporated into the second generation.**

The second evaluation used two low fidelity physical GTU mockups with subjects wearing a Z-2 space suit with Portable Air Backpack (PAB) at 4.3 psia, exercised the hand controllers feasibility for pressurized suited operations. The GTU mockups were static in nature. Feedback on usability, clearance, reach, and operability was captured. For the dual T-Handle controllers, results indicated that having to hold a continuous forward motion using the palm of a pressurized gloved hand would be fatiguing. Reach was considered reliable; however, the hand controllers mounted to the mockup did not have the same adjustability range when comparing right and left controllers. With the Tri-Rotor controller, it was observed when using the loop handles for driving operations, the loops induced a simultaneous wrist rotation which caused some flexing in the suit and over time could be fatiguing to the crewmember. This also made have introduced controller cross coupling. This type of cross-coupling was not seen in the earlier shirtsleeve testing. Lowering the hand controller's height approximately 7.62 to 15.24 centimeters (3 to 6 inches) would aid in lessening the issue positioning the arms of the suit parallel to the ground taking full advantage of the suit's wrist bearing reducing the awkward posture and decreasing cross coupling.

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1. INTRODUCTION

The Apollo Lunar Roving Vehicle (LRV) flew on Apollo 15, 16 and 17 lunar missions (Figure ***1*** 1). During each mission, the vehicle was used on three Extravehicular Activities (EVA) totaling nine lunar traverses and allowing the astronauts to explore four times more lunar terrain than in previous Apollo missions. However, the LRV was a single use vehicle weighing in at 209 kilograms (kg) (460 pounds) [1]. NASA's new unpressurized lunar rover concept builds on the LRV, with some added unique aspects (i.e., Lunar South Pole operations, suit interfaces, science, etc.) that requires a different vehicle configuration called the Lunar Terrain Vehicle (LTV) (Figure 2). The additional expended functionality the LTV will provide includes being reusable with a service life of approximately 10 years [2]. The vehicle will have the ability to survive eclipse periods and shadow periods. It can be remotely operated from Earth, Gateway or the Human Landing System (HLS) lander to traverse to points of interest and interface with science instruments and payloads such as a manipulator arm. NASA brought this concept vehicle to life by building the LTV Ground Test Unit (GTU) as an engineering asset for studying flight vehicle design. The GTU will generate and provide reference data for use across the Artemis architecture working groups and studies. This reference data will be backed by engineering analysis and will provide a framework to evaluate proposed design requirements. The vehicle will also provide a reference point when reviewing vendor proposals.

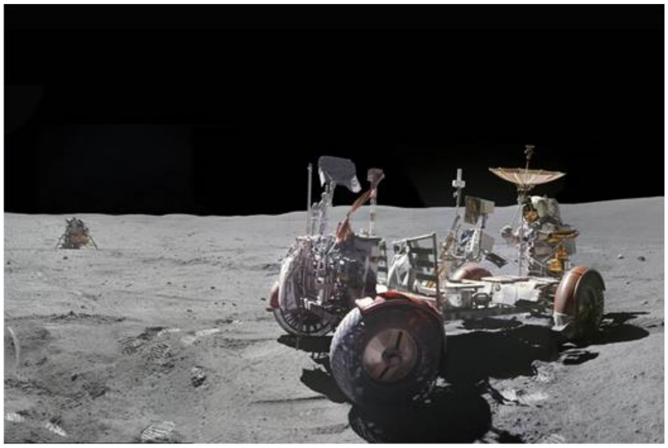


Figure 1. The Apollo Lunar Roving Vehicle (LRV). [Curiosity NASA]

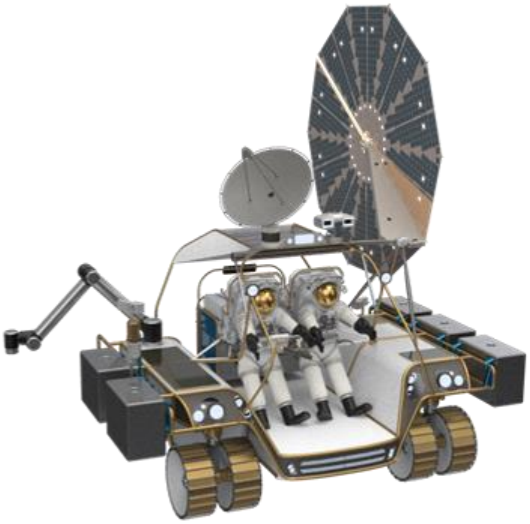


Figure 2. LTV in the Option 4 Configuration rover.

Two hand controller studies were conducted to examined two different LTV hand controller concepts – a legacy T-handle concept and an innovative Tri-Rotor controller. In the first study, subjects were driving shirtsleeve in a virtual simulator stationary environment , while in the second study, subjects interacted with the same hand controls within two different vehicle designs while in a planetary pressurized space suit.

2. TESTING GOALS AND LIMITATIONS

The two objectives these two protocols were to gather both shirtsleeve and pressurized suit data on two hand controller designs for the LTV and NASA's GTU) for the purpose for refining the designs for future field analog testing. The second objective was to refine the hand controller test protocol in preparation for future LTV vendor testing.

The outcome products of the studies consisted of identifying design modifications needed to the Tri-Rotor and T-Handle controllers to enhance future test data collection on NASA's motion platform and to mature the controller design for the field analog vehicle. Additionally, the study identified human factors benefits and liabilities of the control mechanisms inherent in both the controllers tested in both a shirtsleeve and pressurized suit environment. Finally, a draft of LTV performance measures for driving operations (e.g., energetics, obstacle collision avoidance, trafficability, etc.).

3. TEST EQUIPMENT

For the two studies, several pieces of hardware were employed which included a video wall with LTV cockpit, a display for navigation, two concept hand controllers, two rover mockups and a pressurized space suit. Software and modeling were also used.

Systems Engineering Simulator (SES) Video Wall

The video wall is comprised of ten Samsung 140 centimeters (cm) (55-inch) small bezel 1080p monitors, arranged in a 2x5 matrix (Figure 3). A LTV "cockpit" seat, display, hand controller(s) and arm rests to facilitate driving are located one meter (3.3 feet) from the video wall center screens. The eyepoint view was set to align with a notional NASA government reference LTV Option 4 (Figure 4).

Figure 2. The SES video wall facility.

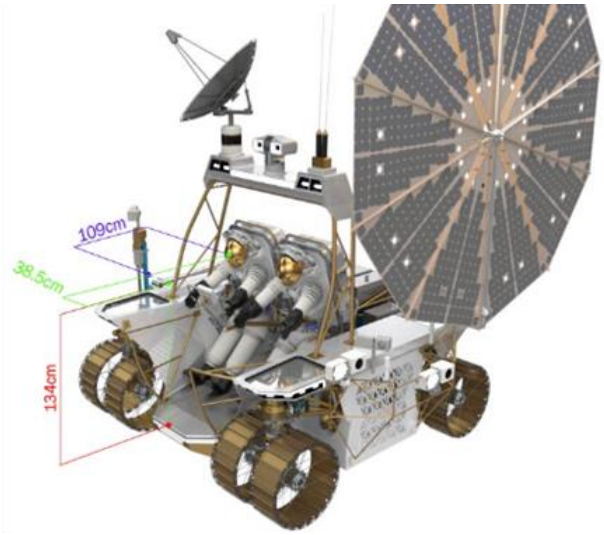


Figure 4. NASA government reference LTV used in the simulation. Distance measurements denote driver eye point for proper alignment between the test subject's chair and visual scene.

LTV Prototype Hand Controllers

Hand controllers are the heart of any vehicle being operated by a human. The first hand controller used in the conceptual LRV was a Boeing pistol grip joystick. Using the Marshall Space Flight Center's (MSFC) LRV simulator (Figure 5) [3], test subjects evaluated the ergonomics of the pistol grip controller and found it was no compatible with a pressurized suited crewmember's gloved hand due to fatigue and being painful to hold [4]. With a newly designed T-Handle controller, Apollo astronauts John Young and Charlie Duke on 11 September 1970 used the LRV simulator for 10 to 15 minutes each to test the T-Handle controller. The new controller eliminated the extreme arm and hand fatigue that had been found in the original controller. [4] Affectionally known today at the "T-Handle" hand controller, the LRV hand controller provided Ackermann functionality such as steering, acceleration, left/right turning, and braking commands (Figure 6) [5]. The legacy Apollo LRV controller was successfully used for rover operations on the Moon during Apollo missions 15, 16, and 17 (Figure). During the "Lunar Grand Prix" where Apollo 15 tested out different performance aspects of the LRV , they conveyed that the T-handle controller was, "…. *Adequate and effective throughout the speed range [of the LRV] and directional control was excellent*. *A minor difficult was experienced with feedback through the suited crewmember to the hand controller during driving but could be improved with a more positive restraint*." [6]

Figure 5. Astronaut John Young in a space suit driving the MSFC LRV Simulator using the T-Handle. [3]

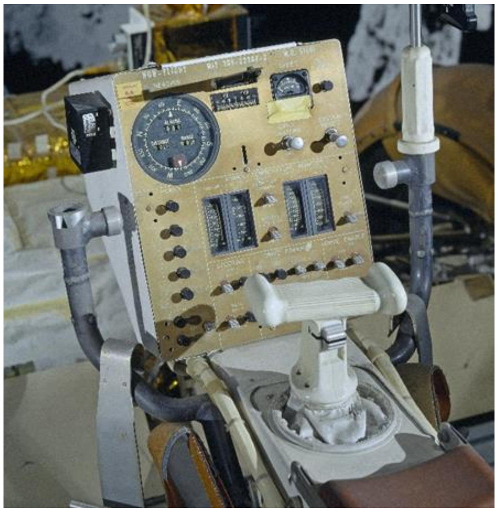


Figure 6. The Apollo LRV T-Handle controller and center display panel. [Curiosity NASA]

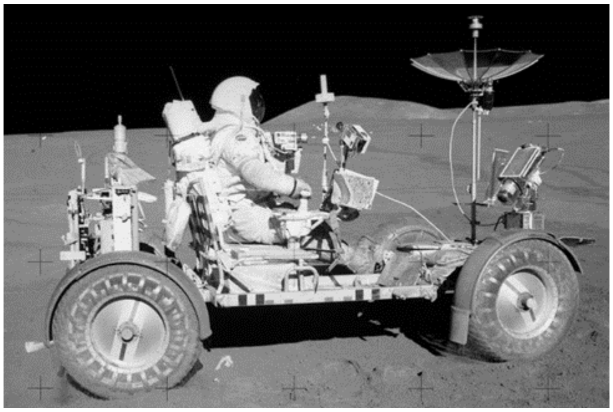


Figure 7. The Apollo LRV on the Moon with an astronaut engaging the T-Handle controller. [Curiosity NASA]

A capability which was not a part of the Ackermann steering functionality of Apollo was crabbing, where a vehicle can strafe across the surface at a chosen angle. Inspired by the Apollo T-Handle controller, the design test at NASA's Center for Design and Space Architecture (CDSA) built a Dual T-Handle system for the LTV which incorporated the crabbing function without relying on display software (Figure 8). The functional mapping of the LTV dual T-Handles is illustrated in Table 1. All units of measures are in centimeters and acceleration units are in kilometers per hour (kph).

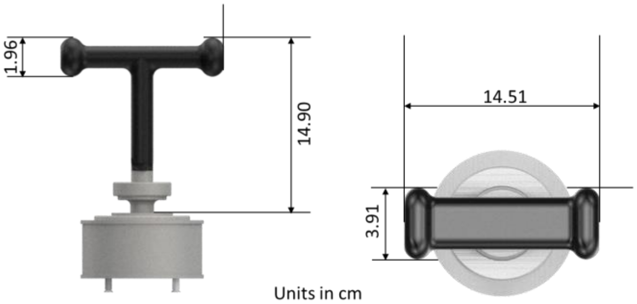


Figure 8. The LTV Dual T-Handle Controller used for testing.

Table 1. *The LTV Dual T-Handle Functional Mapping*

T-Handle Controller	Controller Direction	Element Motion	Function
Rotational Controller (Port)	Forward	Push Controller Forward	Toggle Cruise Control (can set in 0.5 kph (0.3 mph) increments)
	Backward	Push Controller Back	Brake
	Rotate Right	Push/Lean Controller to the Right	Rotate (Turn) Vehicle to the Right
	Rotate Left	Push/Lean Controller to the Left	Rotate (Turn) Vehicle to the Left
Power Controller (Starboard)	Forward	Push Controller Forward	Accelerates vehicle up to max speed of 12 kph (7.46 mph)
	Reverse	Push Controller Back	Backs vehicle up with max speed of 3 kph (1.86 mph)
	Crab Right	Push/Lean Controller to the Right	Vehicle crabs and accelerates to the right
	Crab Left	Push/Lean Controller to the Left	Vehicle crabs and accelerates to the left

A new innovative hand controller concept called the Tri-Rotor [MSC-07385-1] was also tested. Inspired by Formula One racing steering wheels, the Tri-Rotor is a hand controller developed with the intent to take advantage of the restricted range of movement and dexterity of a space suit while operating a vehicle on the surface of a planet or moon (Figure 9). By focusing on the constant volume joints from the glove to the shoulder, the operator can rotate bearings in their wrist and shoulder while their hand rest on the grips without requiring force. These aspects drive towards a finer control of a vehicle while reducing fatigue and operator induced oscillation (Table 2).

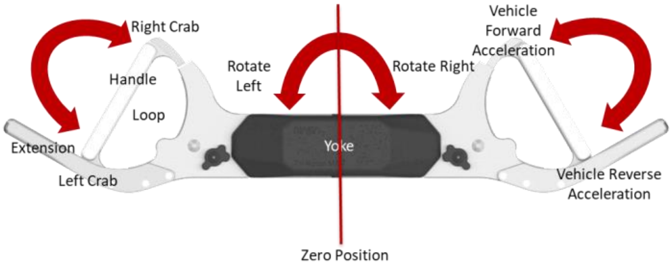


Figure 9. Tri-Rotor functional mapping [MSC-27385-1 under NASA patent review].

Table 2. *Tri-Rotor Functional Mapping*

Tri-Rotor Element	Element Motion	Function
Yoke	Rotate Right or Left	Turning the vehicle Right or Left
Right Loop/Handle	Counterclockwise Rotation	Vehicle Forward Acceleration up to 12 kph (7.46 mph)
Right Loop/Handle	Clockwise Rotation	Vehicle Reverse Acceleration up to 3 kph (1.86 mph)
Left Loop/Handle	Counterclockwise Rotation	Right Crabbing with acceleration

Table 2. *Tri-Rotor Functional Mapping*

Tri-Rotor Element	Element Motion	Function
Left Loop/Handle	Clockwise Rotation	Left Crabbing with acceleration

The Virtual LTV

The LTV simulation is an integrated simulation of a lunar rover based on the NASA reference LTV design. It consists of a multi-body dynamic model developed using MulitBody Dynamics (a NASA custom internal software package) (MBdyn) and the Johnson Space Center's Engineering Orbital Dynamics (JEOD) model, a representative electrical power system model developed using General-Use Nodal Network Solver (GUNNS) software, contact model developed using Pong, and a simple terramechanics model. The multi-body model consists of dynamic model for rover chassis, suspensions, and wheels. It works with the contact model to determine the normal force and tractional force on each wheel. The representative electrical power system model consists of solar array, solar array regulator, batteries, constant power load for rover hotel load, and motor-gearing modules for propulsion and steering. The simulated LTV can traverse forward and backwards, has a turning radius of zero (i.e., can turn in place), crabbing functionality, and can move at speeds up to 12 kilometer per hour (kph) (7.46 miles per hour (mph)) (Figure 10). Velocity requirements for the LTV is a maximum of 15 kph (9.32 mph); however, due to the model motor controllers and the new virtual engine (UnReal 5.1) the max speed of the vehicle implemented in the simulation is 12 kph (7.46 mph) instead of required 15 kph (9.32 mph). The added speed parameter caused some performance issues with the virtual simulation. A solution to this performance issue for future testing is being worked by the SES facility. The virtual rover has full body dynamic modeling and is required to handle slopes of +/- 20º (up-, down-, cross-slope) per the actual LTV performance requirements. In addition, the virtual vehicle has a full lighting and camera array. A simulated terramechanics model was likewise employed to add realism to the virtual environment to resemble the lunar surface more closely (Figure 11).

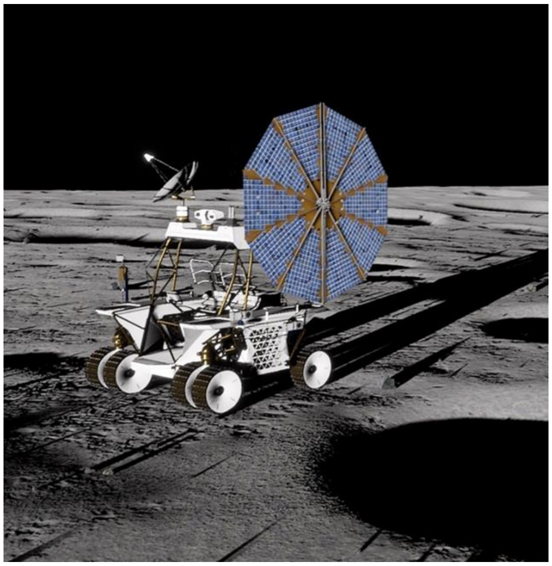


Figure 10. The virtual lunar rover used in testing.

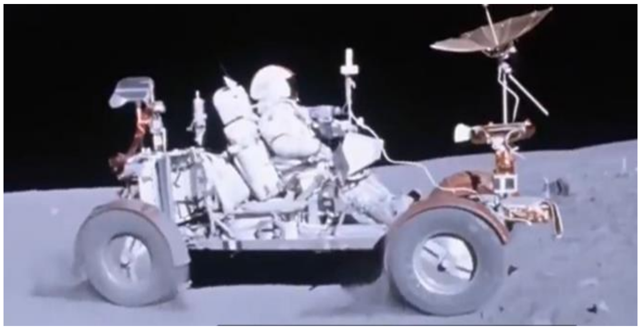


Figure 11. The LRV driving over the lunar surface. Note the wheels digging at the lunar soil. [Photo Curiosity NASA]

Lunar South Pole Terrain Simulation

The lunar terrain incorporated into the simulation was a high-fidelity representation of the South Pole lunar region with a sun elevation angle of 1.2°. Areas where testing took place included the Artemis Base Camp (ABC) habitation area (Figure 12) and the Bear Paw area (Figure 13). Terrain data was based on 5m/pixel Digital Environmental Model (DEM) data and 1m/pixel high-resolution imagery from the Lunar Reconnaissance Orbiter (LRO).

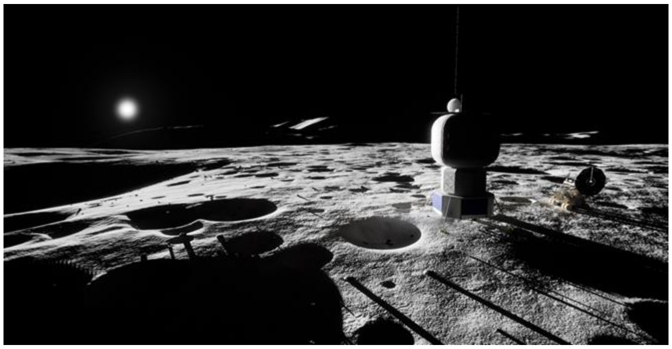


Figure 12. Screen capture of Artemis Base Camp terrain (notional surface habitat on the right).

Figure 13. Screen capture of Bear Paw terrain.

For the second study, two low-fidelity mockups representing a side entry vehicle and front entry vehicle were assembled using ITEM aluminum, aluminum sheet metal flooring, polycarbonate fenders, and 3D printed hand controller assemblies. Each mockup has different seats, footrests, controllers and assemblies, and display location anchor point. Each mockup was load tested as part of the Hazard Analysis (HA) conducted for the Test Readiness Review (TRR) in January 2023. Both mockups were placed in the available Active Response Gravity Offload System (ARGOS) space (Figure 14) to allow for the suited subjects to traverse around the mockups with clearance for the attached ARGOS system.

Figure 14. The side and front entry mockups sitting in ARGOS.

Side Entry Vehicle

The side entry mockup (Figure 15) was designed such that a suited individual would climb a set of steps on the side using a handhold on the left. Once on the platform, the individual would ingress the seat to the immediate right of the entry point. The side entry mockup has a specifically designated translation aid to the left of the entryway stairs, as well as a vertical handhold intended to be gripped by the right hand to aid in providing leverage for seated ingress/egress. This mockup also features the dual T-handle controllers. The outboard T-handle was mounted on a swing arm to allow for clearance for the translation path of the suited individual. Also of note, the side entry mockup had an extended static horizontal footrest, two arm rests, and an angled PLSS cage to rest the suited backpack (Figure 16). The mockup had a display on a bogen arm with an anchor point at a point away from the subject on the midline bar.

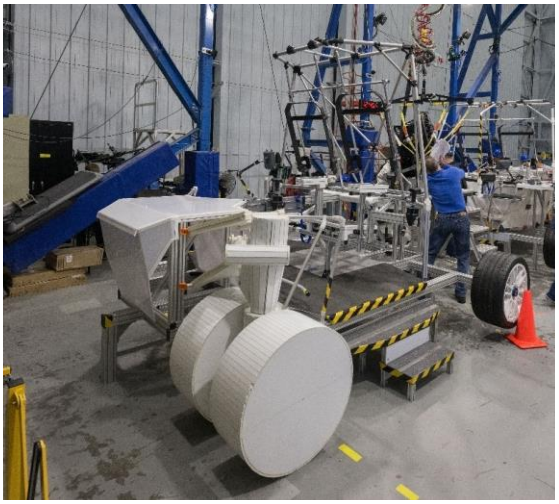


Figure 15. The side entry mockup.

Figure 16. Suited Individual seated in the Side Entry mockup.

Front Entry Vehicle

The front entry vehicle (Figure 17) was designed such that a suited individual would climb a set of steps on the front using handholds on both the left and right. To assist transition onto the platform, subjects could also grasp a vertical mounted center pole. Once on the platform, the individual would ingress the seat to their immediate front, this would require a 180-degree rotation by a suited subject. The front entry mockup has a specifically designated translation aid to the left and right of the entryway stairs, as well as a vertical center pole. There is also a vertical handhold attached intended to be gripped by the left hand to aid in providing leverage for seated ingress/egress. This mockup also features the Tri-Rotor controller that is mounted on a swing arm to allow for clearance for the translation path for the suited individual. Also of note, the front entry mockup had a small T-style footrest that can swing in/out of the space, two arm rests, and an angled PLSS cage to rest the suited backpack

(Figure 18). The mockup had a display on a bogen arm with an anchor point on the tri-rotor slider/mount on the outboard side.

Figure 17. The front entry mockup.

Figure 18. Suited Individual subject seated in the Front Entry mockup.

Z2 Space Suit with Portable Air Backpack (PAB)

The space suit used for the pressurized hand controller testing is the Z2. The Z2 spacesuit is a rear-entry advanced planetary spacesuit demonstrator featuring a composite upper torso and a walking lower torso (Figure 19). The suit features an anthropomorphic pressure enclosure (enclosure includes attachment and opening for breathing gas supply system interface) with quick change sizing capabilities, ventilation flow for CO2 washout, liquid cooling circuit (with attachments an opening for liquid cooling supply circuit interface), potable water (Extravehicular Mobility Unit (EMU) Disposable In-suit Drink Bag (DIDB)), communications system interface, Waste containment (EMU Maximum Absorbency Garment (MAG)). The Z2 was pressurized to 4.3psia for testing. The Portable Air Backpack (PAB) is a self-sustained training unit that interfaces with the Z-2 suit that provides at least 45 minutes of continuous pressurized operation and cooling without replacement/recharge of any components to the Z-2 spacesuit (Figure 20). The PAB system provides fluids such as water and breathing air. The unit also allows for real time swaps of the batteries and cooling tank to allow for continued operations at each 45-minute interval. Prior to testing, subjects completed a fit check of the Z2 in the Building 34 lab.

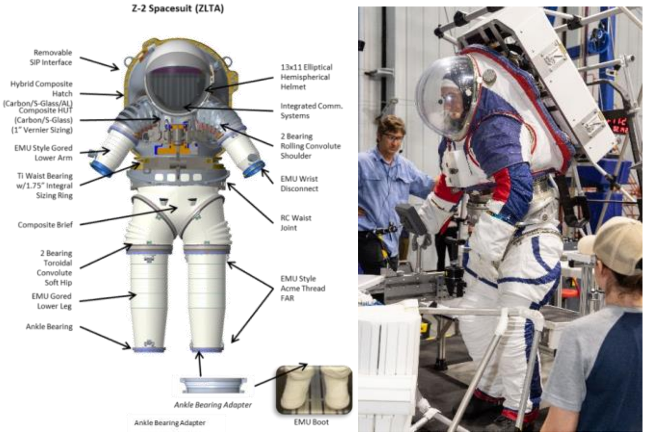


Figure 19. The Z2 spacesuit.

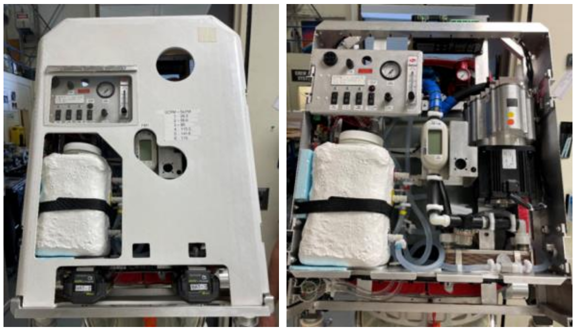


Figure 20. The PAB with (left) and without (right) the cover installed.

4. STUDY DESIGN

Study One

Study one utilized nine engineering subjects of various backgrounds, in a shirtsleeve environment using a standalone LTV cockpit. The single-seat cockpit was placed in the center of the SES video wall facility location at Johnson Space Center's (JSC) Building 16 (Figure 21).

Figure 21. Subject using the existing fixed base video wall simulator in the SES.

Testing consisted of a shirtsleeve subject entering the video wall facility and climbing onto the LTV mockup cockpit and sitting in the seat. The test team assisted the subject in getting arm rests, hand controllers, and display in the preferred, most comfortable position. The subject was given approximately 15 minutes to familiarize themselves with the controllers around the ABC site. With the familiarization session complete, the test conductor placed the subject at the starting point for the first driving task which was a 3.7-kilometer (km) (2.29 miles) distance (Figure 22). This long traverse was designed as a power efficient traverse, meaning the vehicle's solar panel was always in the sun. Subjects experienced a variety of terrain features along this path which would be seen on a nominal lunar traverse (e.g., rocks, craters, sun directions, slopes, etc.). The traverse took approximately 30 to 45 minutes to complete. The long traverse tested the subject's ability (the skill required of the operator to do the action) to drive the vehicle using the controller(s) driving capabilities (e.g., moving the vehicle forward, reverse, turning, crabbing, acceleration, braking, etc.) while avoiding terrain features, which assisted in the evaluation of the controller(s) responsiveness to the subject's inputs. After the completion of the long traverse, subjects were given an acceptability questionnaire on the controller(s) design elements including handling responses.

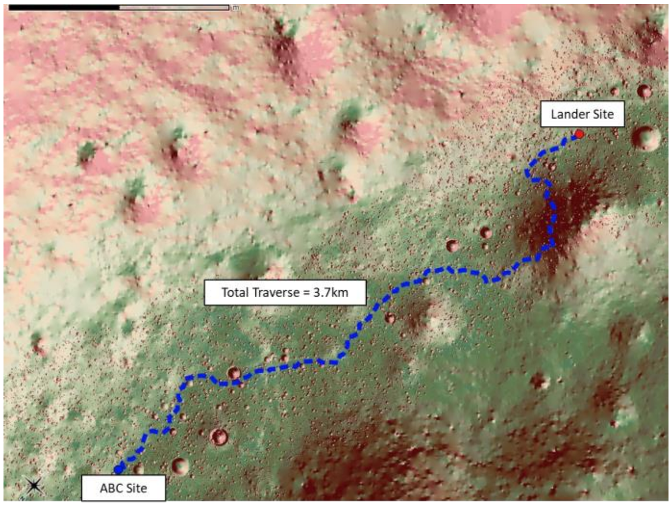


Figure 22. The 3.7 km (2.29 mile) long traverse course.

Next, the subject moved to a scientific site called Bear Paw. Here the subject had to traverse a 394-meter (1,292.6 feet) path to reach a 35-meter (114 foot) diameter crater (Figure 23). Arriving at the crater, the task of crater rim driving using the vehicle's crabbing function was employed. This site was chosen because of its slopes (3º to 23º), terrain features to avoid (e.g., small craters and large boulders) and full sun condition. The task was designed to test the hand controller(s) responsiveness (how the controller reacts to the operator's inputs) and maneuverability (the physical motion of the operator's hand/wrist on the controller). The objective was to get as close to the crater's rim as possible, put the vehicle into crab mode with the front of the vehicle facing the crater, and crab while keeping the distance between the rover's nose and the crater rim at a consistent distance and speed. The subjects were instructed they would have to avoid some objects that were located around the crater rim. After diverting off the rim to avoid said objects, subjects were instructed to intersect the rim again as soon as feasible. With the 360º traverse around the crater rim completed, the subject provided feedback via a subjective questionnaire on the acceptability of the tested hand controller(s). Meanwhile, the test team replaced the first controller with the second controller and the subject repeated the same actions.

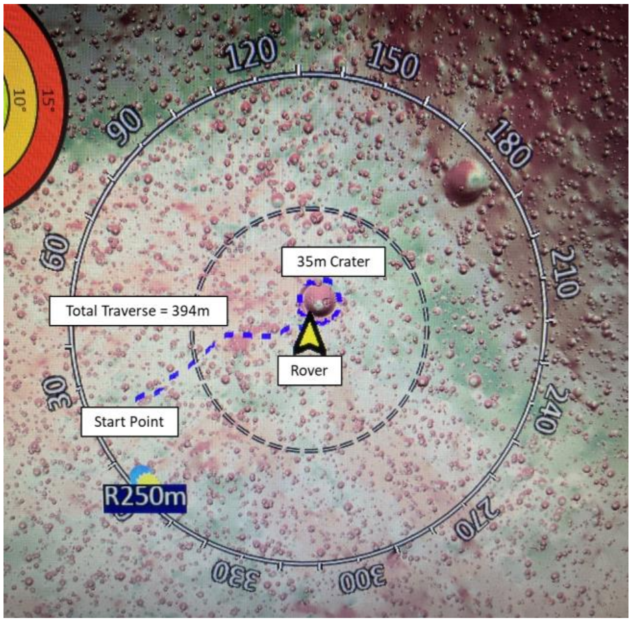
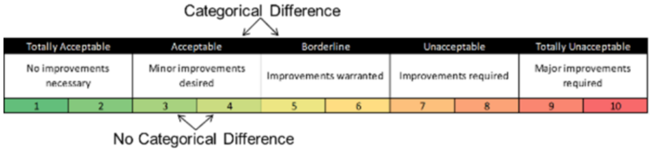


Figure 23. The 394-meter (1,292.6 feet) Bear Paw short traverse course with 35-meter (114 foot) diameter crater.

Both objective and subjective metrics were collected during the evaluation. Objective measurements included distance traveled in kilometers (km), average speed in kilometers per hour (kph), number and location of collisions between specific sized rocks and the LTV structure, task completion time in minutes (mins) and hand controller inputs. These were recorded by the simulation team and given to the test team for analysis.

Subjective data was also collected during the post-test questionnaire portion of the test using the Acceptability Scale. The Acceptability Scale is based on a 10-point Likert scale (1-10) where the scale is divided into five distinct categories with two numerical ratings within each category to discriminate preferences (Figure 24). The scale was designed, in part, from the Cooper-Harper Quality Handling Scale to have a scale that could quantify how the acceptability of the vehicle designs by the subject using a simple scale. Due to the small sample size, the team defined practical significance as a categorical difference on the Likert rating scale. Likert scale data can be considered as either interval or ordinal depending on the presentation of the rating scale to the subject [10]. The Acceptability rating scale is interval because only the rating category, e.g., totally acceptable, acceptable, etc. has a label and descriptor, each individual rating does not have a label. A reasonable interpretation of this scale by a subject is that the distance between the data points along the scale are equal [10]. This is reinforced by the constant width of the scale itself. Interval data can be analyzed with descriptive statistics. The mean and 95% confidence interval will be calculated for the Acceptability rating.

The scale was used to describe how acceptable (or unacceptable) the hand controller(s) operated (e.g., to drive forward/reverse. Turn left/right, crab left/right, accelerate, brake, avoid objects, etc.) under the given South Pole lunar terrain and natural lighting conditions. Specific comments on desired/warranted/required improvement and/or minor/moderate/unacceptable deficiencies were noted for any numerical acceptability rating of 3 or higher.



Totally Acceptable		Acceptable		Borderline		Unacceptable		Totally Unacceptable	
No improvements necessary		Minor improvements desired		Improvements warranted		Improvements required		Major improvements required	
1	2	3	4	5	6	7	8	9	10

Figure 24. The Acceptability Rating Scale describing practically significant (i.e., categorical) differences.

Study Two

Three test subjects participated in suited pressurized tasks on-vehicle. Subjects for this test included four male engineering subjects and one dry run subject. The Anthropometry and Biomechanics Facility (ABF)-provided anthropometry of the subjects for the main test. The population is based on NASA's Human System Integration Requirements parent database (MPCV 70024). The corresponding subject data as percentiles in was provided by the ABF (Table 3). When assessing percentile information, understand that percentiles are presented in a binomial distribution and are referenced to their respective gendered distribution (Male/Female) which may not align with the range of the entire population consisting of both males and females. All the subjects were male. Two points within Subject 3's data worth highlighting are <min or 0 percentile for stature and thumb tip reach, respectively. This is indicative that the subject fell below the expected male population range. The subjects completed the on-vehicle tasks while wearing the Z2 with the PAB. The on-vehicle tasks included LTV ingress/egress, seat design, cockpit design, hand controller(s) usability/reach and reach for both static mockups. The test subject would begin with the Dual T-Handle controller setup in the side entry rover and test out their ability to reach the controller, maneuver the controller, and test the grip of the controller (Figure 25). Once the side entry and T-Handle configuration was complete, the suited crewmember would ingress onto the second front entry rover mockup with Tri-Rotor hand controller configuration. The same tasks as the T-Handle controller were performed for the Tri-Rotor controller (Figure 26). Only the subjective methodology of acceptability was used for this second study.

Table 3. *Subject Percentile Values (%-tile)*

Subject	Stature	Sitting Height	Forearm-Forearm Breadth	Thumb-Tip Reach
S1	58.8	79.4	76.8	27.1
S2	36.5	24.2	41.4	6.5
S3	< min	20.2	19.6	0.0
S4	41.5	36.6	67.1	9.4

Figure 25. Test team working with subject in the side entry mockup vehicle.

Figure 26. Test team working with subject in the front entry mockup vehicle.

5. RESULTS AND DISCUSSION

The most common objective analysis method for hand controller data is using a primary task performance measurement on the level of workload experienced by the operator [6]. A study conducted by Casner and Core (2010) [7] indicates to assess the performance of a primary task either measuring the operator's activity (i.e., control inputs) or measuring the accuracy and speed. When converging these assessment methods, a measure of errors can be identified in the operator's performance—their number, duration, and extent [8]. The assumption is when the control inputs increase, the accuracy drops and the number of errors (their duration, and extent) increases [6]. Individual deviation points are not statistically independent; however, each "error loop" – from start point of deviation until path crosses center line again – could be considered a separate "error event." [6], [9]. Landry, Bulikhov, Zhang, and Minana (2019) [9] indicated each loop on the trajectory has its own duration and extent, while parameters such as delay, gain, and lag can also be calculated [8]. Experiments conducted by researchers [9], [6] show an increase in duration, extent and delay often correlate to a higher vehicle/operator workload.

In this study, the subject was to drive over two different courses (a long and short course) and avoid obstacles or accomplish a precision maneuver using two different hand controller concepts. The lunar simulation used for this study collected measurements of the vehicle every tenth of a second. Using the method described above, the amplitude (extents) and subject reaction time (delay) using the Tri-Rotor were shorter when compared to the dual T-Handle controllers. But the bulk of the Tri-Rotor input durations was slightly higher and more chaotic than the T-Handle. Thus, the Tri-Rotor may require more workload on the operator (as seen by the shorter input duration) and possible drain more energy from the vehicle than using the dual T-Handle controllers. However, the T-Handles may result in more wear and tear on the vehicles wheels and drive motors since the duration amplitude time of control movement with this controller is higher when compared to the Tri-Rotor. More study would be required.

Subjective Data Results

Some definitions are needed to understand what the details of hand controller performance.

- Ability is the skill required of the operator to perform the action with the hand controller.
- Maneuverability is the actual physical motion of the operator's hand/wrist on the controller.
- Responsiveness is how the controller reacts to the operator's inputs.

Dual T-Handles Results

Grip and Other Physical Aspects

Based off the Apollo legacy single T-Handle controller, the addition of another T-Handle was used to initiate the LTV's crabbing function. From a physical perspective of the hand controller, reach for T-Handle was considered comfortable without feeling cramped in the shoulder and arm areas of the body (Figure 27) for unsuited subjects. When gripping the T-Handle with the ungloved hand, subjects considered the grip to be easy to hold onto and adjust one's hand to the grip feel (Figure 28). Additionally, the grip felt comfortable when driving in the rough lunar terrain. This held true during the pressurized suit stud where suited subjects were asked to operate the hand controllers and provide feedback on the grip design with respect to suited glove operability. The T-handles were rated as *acceptable with minor improvements.* Comments varied from citing slightly bigger to making inboard handles a little longer (Figure 29).

Figure 27. Reach to the LTV dual T-Handle controllers was considered comfortable.

Figure 28. Gripping the LTV dual T-Handle controllers was considered easy and comfortable in rough terrain.

Figure 29. A 4.3 psia pressurized gloved hand gripping the LTV T-Handle controller.

Functionality

As for the functionally aspects of the dual T-Handles, the controllers functional mapping was considered very intuitive and easy to understand. Subjects did prefer a button or trigger for cruise control and braking rather than having these functions on the controller. Elimination or close-out of any hand controller twisting was also recommended to aid the operator in avoiding this type of action if not needed, as twisting would result in damage to the hand controllers. The original tested mapping had the Ackermann steering functions split between the two controllers (Figure 30). After driving the simulation, there were suggestions for remapping the steering functions between the controllers. For example, all the Ackermann steering functions could be mapped on the right T-Handle while having discrete crab angle control on the left T-Handle (Figure 31). This would provide for single handed steering of the vehicle. However, this would require a major change to a tri-axial hand controller (three degrees of freedom) from a dual axial hand controller (two degrees of freedom). Thus, unless the T-handles were updated, this change should not be implemented. Regardless of the number of axial positions, it was recommended that the mapping for cruise control not change. Braking could move to a button or trigger and not as a controller input. It is assumed that the force for crabbing left, and right were identical for the controllers, however the action by to hold the controller's inboard was reported as easier than the outboard motion for subjects. So, the recommendation was to reduce the force for crabbing left (controllers are pushed outward) to less than that of crabbing right (controllers are pulled inward). As for future testing, it was recommended to record the torque values of the hand controllers for design improvements.

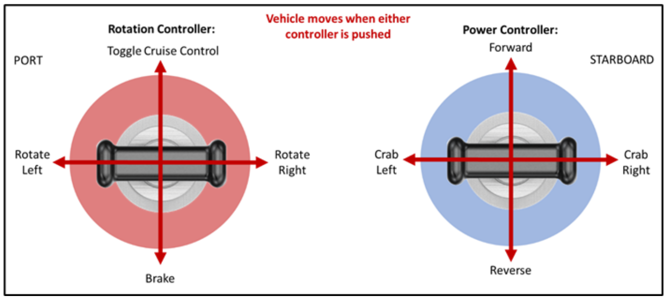


Figure 30. The original tested dual T-Handle controller mapping.

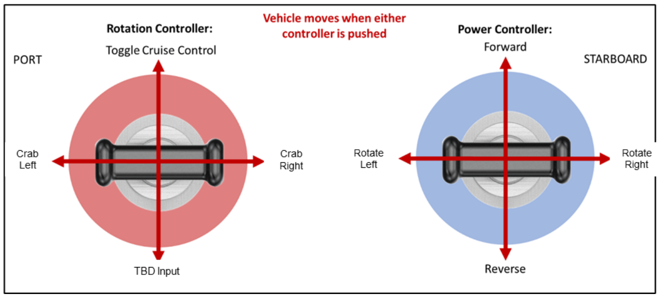


Figure 31. A revised version of the dual T-Handle controller mapping using subject input.

Subjects scored and commented on seven aspects of the hand controllers to operate the vehicle – 1) acceleration, 2) maintaining speed, 3) braking, driving forward, 4) driving reverse, 5) turning left/right, 6) crabbing left/right, 7) and driving with two hands. Having cruise control was a major benefit for maintaining speed over a long traverse as it helped reduce hand fatigue (Figure 32). Accelerating the vehicle by pushing the Power Controller (right T-Handle) forward induced effort and fatigue to accomplish the action. During rough portions of the terrain, the subjects turned off cruise control and manually controlled the vehicle's speed. The T-handle controller worked well for this action. As for braking the vehicle, using the left controller to brake was confusing to subjects. They preferred to move the braking action on the right controller as it was more instinctive and natural. Driving forward was easy, intuitive and straightforward with the right controller. Reverse was also easy and intuitive; however, not for extended period of time due to having no aft situational awareness or visuals. A dedicated rear camera view on the vehicle's display was recommended. In order to turn the vehicle, both hand controllers had to be used. Pushing right controller forward was for acceleration while at the same time rolling the left controller left or right to turn the vehicle. Though not as natural as a steering wheel in a car, these combinations of actions do require some practice in blending; however, they are easy to accomplish in a minimum amount of time. Still some subjects recounted some confusion using the two controllers simultaneously to turn and thought having all the steering functions on the right controller would be more natural and instinctive. Stiffness of the controllers and frequency of use were also cited as possible fatigue factors over time. Lastly, crabbing the vehicle induced a complex operation for the operator by using a combination of turning, crabbing, acceleration and braking inputs. Technically, crabbing was a challenge; however, the controller motion for the crabbing function worked well, but controller sensitivity needs some adjustment. An interesting feature of crabbing with dual T-Handle controllers was when the operator wanted to crab to the left, the operator had to move both hands outboard of the body (Figure 33) which was noted as fatiguing as the operator was exerting outward pressure on the arms and hands. Crabbing right, the operators was pulling both controllers inward towards their body which made accomplishing this action easier (Figure 34).

Figure 32. With cruise control activated, it was easy for a subject to drive single handed reducing fatigue.

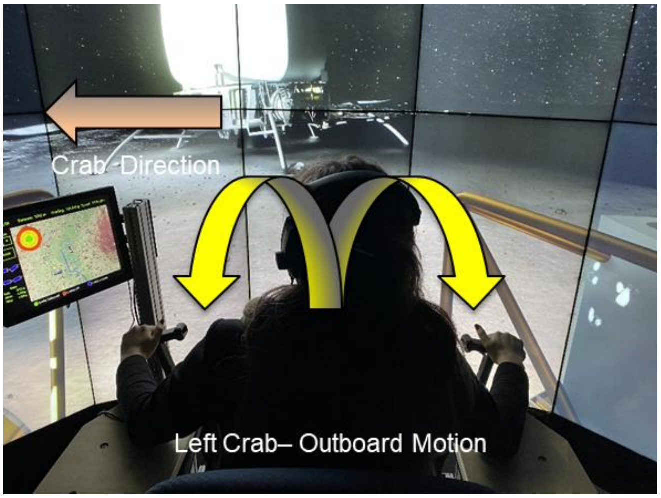


Figure 33. Subject crabbing to the left caused the controllers to be push outward and away from the body.

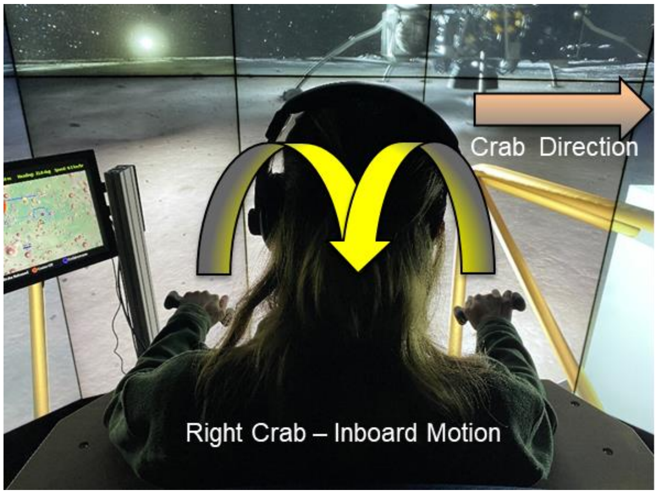


Figure 34. Subject crabbing to the right caused the controllers to be pull inward and to the body.

Maneuverability

Maneuverability (physical action) for the operator using the controllers to avoid terrain features such as rocks or craters seem to behave well with only minor arm movements. Dodging obstacles was easy as the operator needed to pay attention to the terrain and adjust their speed accordingly. For some subjects, combining the right and left dual T-Handle controllers was challenging in avoiding objects. It was also indicated that the mockup's arm rests did not support the wrists well and became fatiguing over time. As for maneuvering around a crater rim with crabbing, mapping of the controllers felt awkward and there was a big learning curve in knowing what motion to initiate to get the correct response from the vehicle. With this case, subjects found it tricky to maintain speed and a consistent distance around the crater rim with crabbing to the left (both controllers pointing outboard); however, the physical actions of the operator and controllers for right crabbing was more manageable (both controllers point inboard) (Figure 35). The suited study noted the adjustability of the hand controller was linked to the ability to operate the controller while suited. For adjustability, two of three subjects rated as *acceptable with minor improvements*, while the third rated as *borderline with improvements warranted*, citing that there was too much travel in the controllers and that the inboard controller struck the seat ingress/egress aid while crabbing (Figure 36). This contact between the controller and the ingress/egress aid also occurred with another subject.

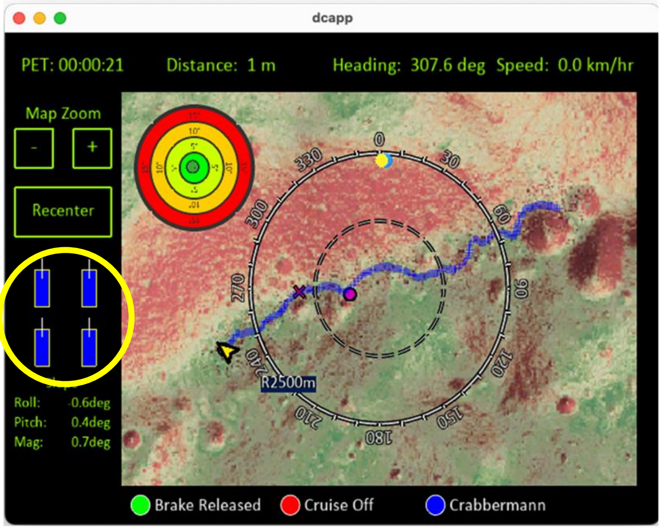
Figure 35. The inboard controller contacting the seat ingress/egress aid with crabbing right.

Figure 36. The subject on the left avoiding obstacles such as rocks, while the subject on the right is driving a crater rim.

Responsiveness

The dual T-Handle controllers were very responsive when avoiding terrain features. Having the controller re-center and stabilize when in neutral/released made it easy for the operator to predict a driving trajectory. Some subjects felt the left/right movement of the controllers were too sensitive with a tendency to overcorrect, but some noted that after approximately 30-minutes the controller felt stiff. It is hypothesized that subjects feeling stiffness in the controller after a certain amount of time could be from fatigue; however, more study would be required. When accomplishing a complex driving maneuver such as crater rim driving, subjects noted due to the responsiveness of the controllers it was easy to make corrections, but they had to stop the vehicle to make them (Figure 37). The wheel diagram on the display (Figure 38) was helpful in seeing how much turn the controller needed to be injected into the system to get the vehicle in the correct course. Nonetheless, operators did experience the steering logic in the wheels fighting with the controller inputs especially on steep slopes and loose regolith.

Figure 37. While crabbing a crater rim, the controllers made corrections easy.



PET: 00:00:21

Distance: 1 m

Heading: 307.6 deg

Speed: 0.0 km/hr

Roll: -0.6deg

Pitch: 0.4deg

Mag: 0.7deg

🟢 Brake Released

🔴 Cruise Off

🔵 Crabbermann

Figure 38. Subjects like the wheel direction icons.

Subjects worked with the dual T-Handle controllers over approximately one hour in a stationary environment. There were reports of fatigue in the hands after approximately 20 minutes, especially in the palm area where pushing the controllers was noticeable. This also held true for suited operation, two of three subjects rated as *acceptable with minor improvements*, while the third rated as *borderline with improvements warranted*, citing that long duration would be tiring due to fatigue. (Figure 39). The fatigue in the shirtsleeve subjects tended to be more noticeable in subjects who opted out of using the cruise control function. Moreover, from all of the actions taken on the controller to operate the vehicle, crabbing tended to be more fatiguing, especially crabbing to the left as the operator had to hold their hand and arm posture for both controllers outboard of the body exerting an outward pressure on those body extremities. Some forearm fatigue was noted due to hovering a hand over the discrete controller. It was observed, for small individuals, the core, pectorals, and back of the arms were almost constantly in use requiring improved arm rest and back support at least for unsuited operation.

Figure 39. Overhead view of a pressurized subject with both hands on the T-Handle controllers.

Tri-Rotor Controller Results

Grip and Other Physical Aspects

Having been inspired by Formula One racing, the Tri-Rotor hand controller is an innovative design that is intended to take advantage of the wrist bearing in a pressurized suit. To get a better understanding of the Tri-Rotor elements, Figure illustrates all the controller's physical layout. Physically, the reach for the Tri-Rotor by unsuited subjects was comfortable, with an easy to adjust assembly, but most operators wanted the controller closer to the body (Figure 41).

Figure 40. The physical elements of the Tri-Rotor controller [MSC-27385-1 under NASA patent review].

Figure 41. Subject using the Tri-Rotor controller.

Moreover, due to the mockup seat arm rests restricting the steering throw, some subjects had to keep the controller further away from the body causing them to extend their arms more than was necessary (Figure 42). Feedback on the size and grip on the handles from pressurized suit subjects provide feedback on the grip design with respect to suited glove operability. The Tri-Rotor was rated as *borderline/unacceptable with improvements warranted or required* for all subjects. Main drivers for the ratings were centering the yoke, the range of rotation and height issues (Figure 43). For the height, pressurized subjects indicated with their hand placement where the ideal placement of the controller should be. Concurrence amongst pressurized subject reported the controller needed to be lowered between 7.6-15.2 cm (3-6 in) from the configuration tested (Figure 44). Due to the variability in responses, the height of the controller may need to be adjustable in future designs.

Figure 42. Note the Tri-Rotor controller hitting the subject's leg caused by a weak spring mechanism.

Figure 43. Pressurized suit subject testing the Tri-Rotor controller.

Figure 44. Preferred placements of the Tri-Rotor controller.

Shirtsleeve subjects indicated the grip size felt comparable to the T-Handle grip. The loop sizing also showed sufficient spacing for the ungloved hand and did not get in the way of any operations. A well-thought-out feature of the Tri-Rotor was the extension bars. These bars were designed to reduce shoulder, arm and hand fatigue by allowing for a resting spot when not actively using the loops. Operators using the bars found them comfortable and useful for resting the outer edge of the hand on during driving (Figure 45).

Figure 45. Subjects like the extension bars to reduce fatigue.

Functionality

Unlike the dual T-Handles, the Tri-Rotor functional mapping was new and not as intuitive as the previous controller. Figure 46 illustrated the tested controller functional mapping. Operators missed not having a braking function and the steering rotation did not seem to be equal in both directions. Feedback indicated that the loops needed to have a center detent indicate to the operator when the controller was in a neutral or zero position. To better aid the subject, the controller needed labels for forward/reverse and left/right crab. As for crabbing, the acceleration of crabbing was integrated into the steering crabbing functions on the left loop, and this became disorienting and disturbing to the subjects as they had issues with distinguishing the crabbing direction coupled with acceleration. With all these issues, remapping the current functions on the controller was desired. For instance, it was suggested to break the crabbing control from the acceleration so that the right handle is where all throttle inputs are located while the left handle does the crabbing angles (Figure 47). This would need to be enabled via a switch or mode change as the right loop is currently mapped to vehicle forward/reverse. Adding cruise control to the controller is a must-have with possible locations indicated by the subjects were a button next to the right-hand position on the yoke or a button on the display.

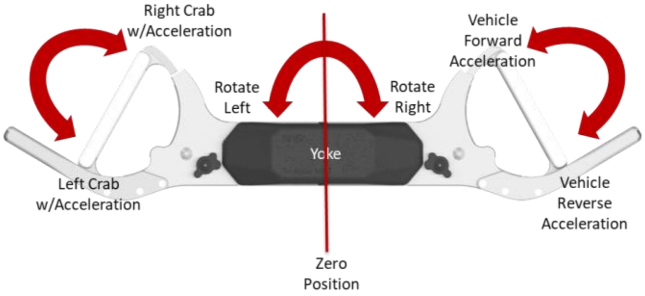


Figure 46. The original functional mapping of the Tri-Rotor as tested [MSC-27385-1 under NASA patent review].

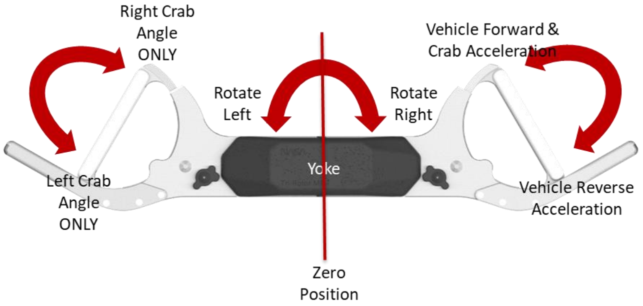


Figure 47. The suggest functional mapping of the Tri-Rotor after testing. [MSC-27385-1 under NASA patent review].

Using the same operational elements as the T-Handles, the ability to accelerate and maintain speed was considered easy. Subjects were able to maintain around 8 kph (4.97 miles per hour (mph)) when the loop was flush with the handle frame (Figure 48); however, the max speed of the vehicle is 12 kph

(7.46 mph) which required the operator to push the loop past the natural hand position hold past the handle frame (Figure 49). This was difficult to achieve as it results in an awkward hand position to maintain the grip. Keeping a flush hand grip with the hand covering that area resulted in a low fatigue maintainable posture at 8kph (4.97 mph) but extending that further yielded complaints on fatigue and grip discomfort. Cruise control with this controller was highly desired. If a cruise control could be implemented, then subjects suggested the max speed should be adjusted clockwise such that max speed is flush with the handle frame. Another suggestion was to add 1 kph (0.62 mph) built-in detents. There was no braking function on this controller and most subjects used the reverse on the right loop to stop the vehicle. The vehicle has regenerative braking; thus, no braking function was required; however, it was found that regenerative braking was not very effective at keeping the vehicle stable when no inputs were given making it mentally fatiguing to constantly "station keep." It was suggested that a centering mechanism of higher fidelity be added to the controller for a complete stop or add a brake button on the controller.

Figure 48. The speed loop flush to the handle frame was the position for maintain speed but not max speed of the vehicle.

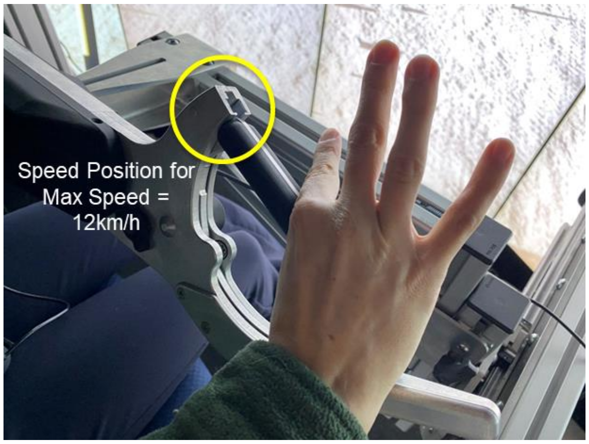


Figure 49. Subject pushed the speed loop all the way passes the handle frame to obtain max speed.

The act of driving forward was easy to accomplish with the Tri-Rotor controller (Figure 50). Regarding forward/reverse: Reverse was very intuitive, much like a car, especially with the controller centered which made this action simple. There was a need for increased speed for reverse when compared to moving forward as well as a need for a rear-view camera in aid with situational awareness. Adding a reverse button to the controller was also suggested.

Figure 50. Driving with the Tri-Rotor was like driving a car.

Turning to either the left or right in Ackermann steering was like driving a car and very intuitive. The controller did need some physical limits to its range of motion to only a few degrees of travel while turning as it rotated further than its actual inputs. Finally, subjects reported that gradual left or right turns were fine; however, with sharp turns the controller was too sensitive resulting in operator induced oscillations. Operators did want to add adjustability to turning sensitivity which was highly desired to allow for individual preferences. Mechanical upgrades are needed to reduce the sensitivity.

Crabbing with the Tri-Rotor was easier when compared with the dual T-Handles (Figure 51). However, to maintain the crab, reaching a sweet spot was difficult, but once a sweet spot was reached it was easy and could be done single handed. In crab mode the wheel speed for crabbing was controlled by the left hand while any forward speed for Ackermann steering was controlled by the right hand; thus, having both loops involved. Participants found it quite undesirable that crabbing thus linked the velocity and the steering angle to the same left loop. It was suggested that due to the nature of crabbing that blending the crab angle (turning) and wheel speed should be accomplished with both loops.

Figure 51. Subject using the Tri-Rotor to crab around the lander.

With left crabbing, there were issues with the outward rotation of the loop having to be continually “fine-tuned” causing the left-hand to be more upright. This continual fine-tuning was due to a weak spring in the controller. Right crabbing was easier to accomplish due to inward rotation causing the left-hand to be more horizontal in a more relaxed wrist posture. For steering, the ease of driving with two hands was reported to be a favorite feature of this controller due to the ability to turn the steering yoke while accelerating without having to use separated left and right controllers.

Maneuverability

Using the Tri-Rotor controller to maneuver around objects such as rocks and craters was like steering a car around object in the road and potholes. The controller’s yoke made this a simple, easy task (Figure 52). However, subjects desired a more consistent resistance on the controller, especially in its range of motion. Due to the amount of travel in the yoke, several operators noted it was challenging. As for driving around the rim of a crater, operators like this controller for crabbing as it was easier than with the dual T-Handle controllers. However, there was a tendency to over rotate the crabbing which made subjects pause to adjust and match the angle of the vehicle with the rim to stay a consistent distance from the rim. But, over time subjects reported this got easier.

Figure 52. Subject using the Tri-Rotor maneuvering around a crater rim.

Responsiveness

Feedback on the controller to avoid terrain features indicated that it felt overly responsive which induced operator oscillations/overcorrections due to the controller being too sensitive. This also held true for crater rim driving. A solution to these sensitivity issues would be to replace the current weak spring with a stiffer spring in the loops and yoke (Figure 53). This would add the desired resistiveness to the controller. To account for the feedback on the range of motion (ROM) issue with the yoke, adding end stops to the controller’s yoke at a range of 20º to 30º would reduce induced oscillations from the operator. Additionally, detents in the handle loops would improve haptic feedback on these controls. For example, for the acceleration loop (right loop) 1 kph (0.62 mph) detents may work. As for the left crabbing loop control, detents increment of 15º, 45º, and 90º crab angles would be a start. Recommendations on detents are conceptual and would need further testing to narrow down what would be appropriate for the controls.

Figure 53. The Tri-Rotor felt overly responsive inducing operator oscillations.

During the pressurized suit study, subject conveyed a concern with a cross-coupling issue that had not come up during the shirtsleeve study. Pressurized suit subjects demonstrated that there was an issue with wrist rotation at the extremes of the Tri-Rotor operation which induced an inadvertent change in acceleration. At the more extreme position the wrist bearing, while rotated, has to rotate even further to apply force to the loop to maintain speed (Figure 54) this is an awkward posture and thus speed cannot be maintained at (and leading up to) that position. It is postulated that the cross-coupling issue is tied to the height issue (below) and may be resolved with an ability to modify the height of the controller. Future testing plans include re-evaluating the Tri-Rotor hand controller with a height modification to determine if the cross-coupling issue is still present.

Figure 54. Cross coupling issue – the wrist bearing (yellow bar) results in an awkward posture at height resulting in a deceleration (orange circle).

Regarding fatigue the controller did provide a freedom of options on where to position the hands which was intended to reduce fatigue, there was hand fatigue using the Tri-Rotor, especially when accelerating. As previously noted, to obtain the max speed of 12 kph (7.46 mph), there was strain put on the right hand due to the overextended loop distance and the amount of pressure to hold the accelerator to full speed along with some pressure on the right thumb to maintain speed and direction. Arm and shoulder fatigue along with wrist, elbow and neck were also experienced from maintaining long exposure times with acceleration. To combat this issue, the right acceleration loop distance for max speed needs to be flush with the handle frame to reduce the hand fatigue experienced as well as changing the throttle spring and improved arm rests (Figure 55). The addition of a cruise control function would also reduce fatigue in general.

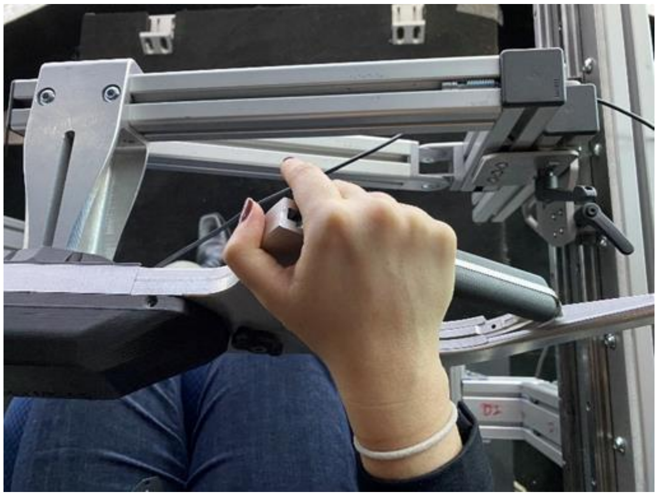


Figure 55. The acceleration right hand loop showing the hand fatigue over time in holding the loop down.

6. CONCLUSIONS

The two studies examined two different hand controller concepts using subjects in shirtsleeves in a simulated virtual South Pole lunar terrain in a stationary cockpit and subjects in pressurized space suits on two static rover mockups. Though these are initial evaluations, the conclusions that can be drawn from this testing is both hand controllers are capable of nominal driving operations of a lunar vehicle on a lunar surface. Each controller has advantages and limitations. For instance, the dual T-Handle controllers included a setup that was very intuitive for driving over terrain and avoiding obstacles, but not for crabbing the vehicle around a crater rim. This was due to the controller mapping feeling awkward and the operator needed to apply constant pressure to the controller to maintain speed and heading, especially when crabbing left. However, in the pressurized suit environment, the T-Handle need more adjustability in the forward/reverse directions and both controllers need to match asymmetrically while seating in the seat. Caution needs to be taken in placing ingress/egress aids in the cockpit as the right T-Handle in the second study show a major interference with its maneuverability as it hit the vertical translation aid. Finally, both studies indicated a need for cruise control to reduce longer duration fatigue.

As for the first-generation Tri-Rotor prototype controller, it is concluded the controller was a solid alternative to the dual T-Handle concept, though the T-handle was preferred overall. The controller advantage was the intuitive nature of the device for a novice non-pilot and operator. Subjects were able to jump in and start driving straight away. However, with pressurized suited subjects, adjustability became a major issue for being able to operate the controller effectively. Researchers discovered the height of the Tri-Rotor is extremely important and pressurized suited subjects cited the controller needs to be lowered between 7.6 to 15.2 cm (3 to 6 inches) from the configuration tested and having the height adjustability could improve the Tri-Rotor status with pressurized crew members. Though not seen specifically in the shirtsleeve study, cross-coupling was a major concern in the pressurized suited study. Conversely, the controller height issue could have been a major factor inducing the cross-coupling exhibited in the study.

There were known limitations to the Tri-Rotor controller. Mainly with mechanical improvements and mapping. These limitations can be refined making this device a more effective hand controller for driving the LTV on the lunar surface. Goals for refining the controller, if funding allows, includes the following second-generation forward work (Figure 56):

- Increase the range of hand controller adjustability in both depth and height, especially for smaller individuals
- Make armrests that support various controller designs more adjustable to allow for flexibility in placement
- Allow for adjustability of the location (position) and orientation (tilt) of the rover display
- Adjust handle to yoke distance to make the center of the operator’s palms closer to the axis of rotation
- Upgrade self-centering mechanism for center yoke
- Upgrade self-centering mechanism for the loops
- Add a reverse switch
- Add a cruise control switch
- Power indicator light
- Integrated palm rests
- Crisper signal out for vehicle driving

Figure 56. The generation 2 Tri-Rotor artist concept [MSC-27385-1 under NASA patent review].

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BIOGRAPHY

Harry L. Litaker, Jr., *is a Senior Human Factors Design Engineer and Project Engineer for the Aerospace Corporation at Johnson Space Center in Houston, Texas. Mr. Litaker works with the Software, Robotics, and Simulation Division and the Human Systems Engineering and Integration Division of the Human Health* *and Performance Directorate at Johnson Space Center. He received his Bachelor of Science degree in Communications from Western Carolina University and a Masters in Aeronautical Science degree from Embry-Riddle Aeronautical University in Human Factors Engineering and Safety Engineering. He has extensive human factors experience in spacecraft design, aviation and airport safety, human-machine interfaces, virtual reality simulation testing and communications. He has worked for the US military conducting human factors evaluation of prototype vehicles and human performance. Currently, Mr. Litaker is the contractor human factor lead for the Lunar Surface Mobility project, the Orion Aft Stowage IVA System (OASIS) and the Orion Speech Intelligibility Testing. His lead responsibilities have also supported the Mars Ascent Vehicle (MAV) design testing, performance research with the Low-Latency Teleoperations (LLT) study, for the Evolvable Mars Campaign (EMC), the Small Pressurized Rover (SPR) and Unpressurized Rover (UPR) project, the Multiple Mission Space Exploration Vehicle (MMSEV) Near Earth Asteroid (NEA) project, the Habitable Airlock (HAL) project, the Broad Agency Announcement (BAA) Cislunar Habitat testing, and the Altair Lunar Lander program. Mr. Litaker has conducted human performance and design research studies in such exploration analog environments as the Desert Research and Technologies Studies (DRATS), the NASA Extreme Environment Mission Operations (NEEMO), NASA's Space Environment Analog for Training, Engineering, Science, and Technology (SEATEST), and in partial gravity simulators.*

***Sarah E. Margerum** is currently a member of the Orion Human Engineering team since August 2015 with a focus on human factors and development and verification of human-to-system interfaces. Since April 2023, Sarah has been the Orion Human Engineering System Manager and was the Deputy System Manager for three years prior to that. Prior to Orion Human Engineering, Sarah worked in Oil and Gas as a human factors consultant for two years. Before that, Sarah worked as a human factors engineer for nine years in the Anthropometry and Biomechanics Facility. Sarah Margerum graduated with a B.S in Biomedical Engineering from Northwestern University and a M.S in BioEngineering from University of Pittsburgh.*

***Dr. Robert L. Howard. Jr.** is the Habitability Domain Lead in the Habitability and Human Factors Branch and co-lead of the Center for Design and Space Architecture at Johnson Space Center in Houston, TX. He leads teams of architects, industrial designers, engineers, and usability experts to develop and evaluate concepts for spacecraft cabin and cockpit configurations. He has served on design teams for several NASA spacecraft study teams including the Orion Multi-Purpose Crew Vehicle, Orion Capsule Parachute Assembly System, Altair Lunar Lander, Lunar Electric Rover / Multi-Mission Space Exploration Vehicle, Deep Space Habitat, Waypoint Spacecraft, Exploration Augmentation Module, Asteroid Retrieval Utilization Mission, Mars Ascent Vehicle, Deep Space Gateway, as well as Mars surface and Phobos mission studies. He received a B.S. in General Science from Morehouse College, a Bachelor of Aerospace Engineering from Georgia Tech, a Master of Science in Industrial Engineering with a focus in Human Factors from North Carolina A&T State University, and a Ph.D. in Aerospace Engineering with a focus in Spacecraft Engineering from the University of Tennessee Space Institute. He also holds a certificate in Human Systems Integration from the Naval Postgraduate School and is a graduate of the NASA Space Systems Engineering Development Program.*

***Athena A. Frangoudis**, is a Human Factors Space Architect for JES Tech working with the Human Systems Engineering and Integration Division of the Human Health and Performance Directorate at Johnson Space Center. She received her Bachelor of Architecture degree from Pratt Institute. She previously worked as an architectural and interior designer enabling her to envision human centric design in space applications. She has experience in habitat design, human machine interface design, and mockup prototyping. Ms. Frangoudis has worked on projects such as the Lunar Terrain Vehicle (LTV), Small Pressurized Rover (SPR), and Gateway.*

***Nadia Scharunovych** is a Technical Mechanical Engineer for KBR working with the Center of Design and Space Architecture of the Human Health and Performance Directorate at Johnson Space Center. She received her Bachelor of Science degree in Mechanical Engineering from Colorado School of Mines. Nadia has experience in human factors in spacecraft design. robotics, and rover design. Nadia is working as a designer for the Lunar Terrain Vehicle (LTV).*