Initial Testing Results and Forward Design Considerations for the Tri-Rotor Hand Controller

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The Lunar Terrain Vehicle (LTV) is one of the key elements of NASA's Artemis return to the Moon. As an unpressurized rover, the LTV hand controller must take into account the limitations of the spacesuit worn by the crew as well as lessons learned operating the Apollo Lunar Roving Vehicle and preliminary NASA simulations. Because the NASA Ground Test Unit (GTU) design features omnidirectional steering, NASA engineers developed the Tri-Rotor is an innovation to minimize crew fatigue and discomfort. NASA conducted a series of tests, initially with 3D printed mockup controllers, and expanding to a functional prototype used in an LTV video wall simulation. The Tri-Rotor compared favorably with legacy Apollo T-Handles, though numerous test subject comments were collected to improve the controller's usability. Several options to improve the Tri-Rotor's usability are also discussed, along with opportunities to test the Tri-Rotor in Virtual Reality, a motion table, and in field analogs.

I. Introduction

A. NASA Artemis Return to the Moon

NASA's return to the Moon has been officially placed into US law via the NASA Transition Authorization Act of 2017 and the NASA Authorization Act of 2022. NASA recently released an update to its Moon to Mars Objectives, establishing long term goals for a human lunar presence. The initial human presence on the Moon will include the Human Landing System (HLS) and Commercial Lunar Payload Services (CLPS) landers, logistics carriers, the Lunar Terrain Vehicle (LTV), Pressurized Rover (PR), and Surface Habitat (SH). Additional commercial and international elements may add to the surface infrastructure.

The first surface missions will be two-person missions, roughly 6.5 days in duration, with crew living in the HLS. These missions will be augmented with the delivery of the LTV. Following delivery of the PR, the crew will conduct surface missions up to 30 days in duration. Once the SH has been delivered to the lunar surface, the crew size will increase to four, with habitation divided between the SH and PR.

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B. Lunar Terrain Vehicle Overview

The LTV is a multi-mission, unpressurized rover that will be used for both crewed and uncrewed missions. In its crewed role, it will enable crew to conduct surface exploration, extending their range beyond that which would be possible when only walking. It will also support logistics transfer, providing ground transportation to move logistics carriers between landers and other surface elements, including but not limited to the SH and PR.

NASA is developing a Ground Test Unit (GTU). This is not the LTV that will be delivered to the Moon but is instead a pathfinder prototype to help NASA understand the crew and architectural needs of an LTV and to pilot evaluation techniques to be applied to commercial LTV concepts offered in response to the NASA Request for Proposal for LTV as a service (LTVS). After several iterative designs, NASA is constructing a drivable test unit / concept vehicle of a “side entry” LTV ground test unit (GTU), shown in Figure 1. At the time of this image the GTU is in a partially completed configuration, with several components still in development.

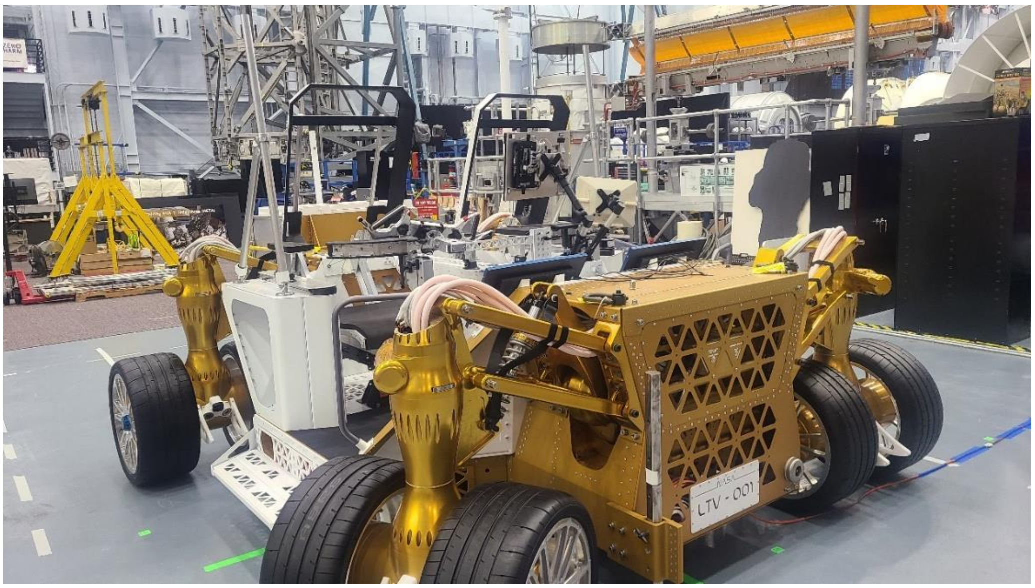

Figure 1. Partially Completed NASA GTU

The GTU includes steering capabilities first piloted in the NASA Small Pressurized Rover (SPR) concept vehicle developed during the Constellation Program and shown in Figure 2.

Figure 2. NASA SPR Concept Vehicle

The GTU features four separate wheel modules, each of which contains two wheels. Each wheel module can rotate (in yaw) in excess of 360 degrees, enabling the vehicle to drive in any direction, rotate about its own axis, or drive sideways (or "crab") around objects such as a crater rim.

C. Challenges for Operation of a Lunar Unpressurized Rover that Affect Hand Controller Design

Because the LTV is an unpressurized rover, crew are in pressurized surface spacesuits whenever using the vehicle, with the inherent limitations in suit mobility and operator fatigue. A key area of concern for vehicle driving is suit mobility in the arm and elbow. Shoulder rotation, elbow bending, wrist rotation, wrist flexing, and finger flexing are all impacted by the mobility of the suit.

The only actual human experience driving an unpressurized rover on the Moon (or anywhere other than the Earth) is the Apollo Lunar Roving Vehicle (LRV), shown in Figure 3, which was used during the Apollo 15, 16, and 17 lunar surface missions. The LRV is a four-wheel, self-propelled, manually operated unpressurized rover capable of transporting two crew and associated equipment. [1] A single hand controller, located between the two crew positions, and a similarly placed control and display console are used to drive the LRV during traverses. Each wheel is equipped with a separate traction drive motor and a mechanical brake. Ackermann-geometry steering is implemented on both the front and rear wheels, with a maximum outer wheel angle of 22 degrees and inner wheel angle of 50 degrees.

LRV Hand Controller Operation:

- T-Handle Pivot Forward - Increased deflection from neutral increases forward speed
- T-Handle Pivot Rearward - Increased deflection from neutral increases reverse speed
- T-Handle Pivot Left - Increased deflection from neutral increases left steering angle
- T-Handle Pivot Right - Increased deflection from neutral increases right steering angle
- T-Handle Displaced Rearward - Rearward movement increases braking force. Full 3-inch rearward applies parking brake. Moving into brake position disables throttle control at 15-degree movement rearward

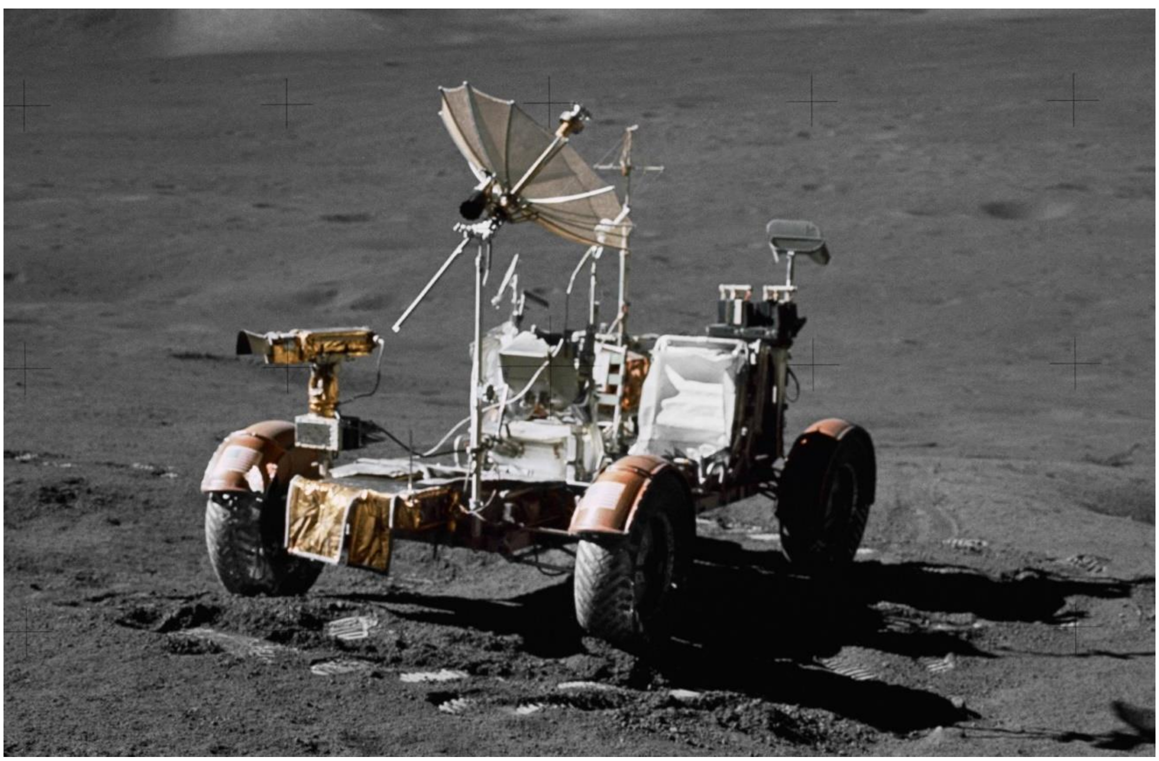

Figure 3. Apollo LRV

II. Origins and Development History of the Tri-Rotor

A. Hand Controller Implications of NASA Rover Omnidirectional Steering Innovations

During the Constellation Program, engineers at the NASA Johnson Space Center developed the Chariot as a robotic lunar truck. Chariot could be used as a cargo transporter, chassis for a pressurized rover, or as an unpressurized rover. The Chariot has six wheel modules, each with two wheels. This enables the Chariot to drive in any direction. The Chariot also featured control pedestals that could rotate in 360 degrees, allowing the operator to also see in any direction. This was inspired by a reluctance on the part of the Apollo astronauts to back up in the LRV because they couldn't see where they were going.

The wheel modules developed by the JSC team have been continued in various fashions – sometimes with the wheel pairs, other times with a single wheel – in virtually all JSC-originated crewed and uncrewed surface mobility concepts since the Constellation program. Centaur 2 [2] was a successor to the original Centaur, a mobility platform designed to carry the humanoid Robonaut on the lunar surface. It also featured omnidirectional steering, but with only one wheel per module. The Modular Robotic Vehicle (MRV) was a testbed vehicle developed in collaboration with the automotive industry to develop technologies for transportation in congested areas. [3] Its wheel modules could rotate 180 degrees about its axis. The wheel modules continued in the Artemis program, with both the NASA concept vehicles for the Pressurized Rover and the Lunar Terrain Vehicle using omnidirectional steering.

B. CDSA Tri-Rotor Design Ideation

The spacesuit wrist does not bend easily and extended grasping with the glove causes fatigue and discomfort. An astronaut in a suit also has very limited tactile feedback in the gloves. Given that this will cause the crew to already experience fatigue and discomfort during their surface EVA science activities (outside of any vehicle driving), it was important to develop a hand controller that limited the extent to which its use causes additional fatigue or discomfort.

The Center for Design and Space Architecture (CDSA) at NASA Johnson Space Center created the initial concept for the Tri-Rotor to be compatible with the restricted range of movement and dexterity of a space suit while operating a vehicle on the surface of a planet or moon. It is more comfortable to rotate the wrist than bend it due to the constant volume wrist bearing in the xEMU suit. Taking advantage of this, the Tri-Rotor proposes to offer finer vehicle control while reducing fatigue and operator induced oscillation, it focuses on the use of constant volume joints from the glove to the shoulder. The operator can rotate bearings in the wrist and shoulder while the hand rests on the grips without requiring force. A display screen with edge key buttons was embedded in the center of the Tri-Rotor. Two early concept 3D printed models are shown in Figure 4.

Figure 4. Early Tri-Rotor Prototype

The CDSA team performed a series of tests in a pressurized glovebox with spacesuit arms/gloves and various prototypes, testing various 3D printed hand controller concepts including the Trigger Yoke, Two-Stick, Twist-Stick, & Tri-Rotor. The Tr-Rotor exhibited superior performance in comfort and was selected for further development.

A higher fidelity, functional prototype was constructed with a mixture of machined and 3D printed parts. The team increased fidelity from a 3D printed concept to a functioning controller. The notional display screen was removed from the Tri-Rotor for better forward visibility. The resulting prototype was integrated into both the Video Wall (described later in this paper) and the GTU. It is shown in Figure 5 on the GTU and will later be integrated into the Motion Platform.

Figure 5. Functional Tri-Rotor Prototype

C. Potential Uses for a Tri-Rotor

Operating the GTU is the primary potential use for the Tri-Rotor. It has been explored on static, low fidelity mockups of two different NASA design concepts – the front entry GTU and the previously mentioned side entry GTU. A CAD image of the front entry GTU is shown in Figure 6.

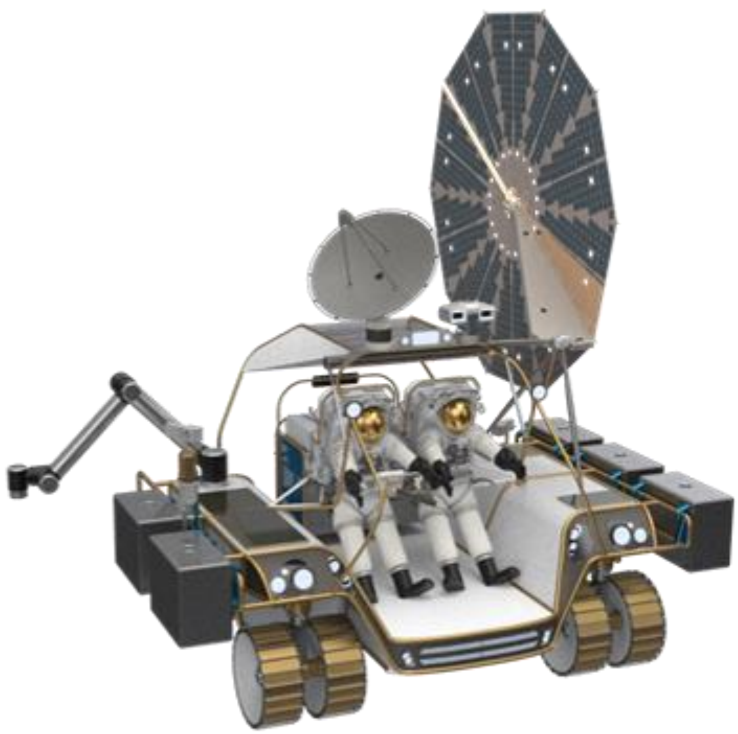

Figure 6. Front Entry GTU

The GTU has been used in preliminary Virtual Reality demonstrations and in a video wall simulation. Plans are to test it on both the NASA GTU concept vehicle and in a motion platform simulation.

Figure 7. Aft Deck Driving on the Constellation-era SPR

The second potential use for the Tri-Rotor is Pressurized Rover (PR) external or "aft deck" driving, as shown in Figure 7. The aft deck is a concept that originated with the NASA SPR concept vehicle during the Constellation Program and is not necessarily limited to the "aft" of a rover. An external driving station could be placed anywhere on the vehicle exterior. The original concept allowed EVA-suited astronauts to drive the rover while docked to the suit ports on the aft deck of the rover.

This enabled short duration driving within the field site, enabling crew to rapidly move between adjacent areas of interest. It also enabled a contingency return to base after a cabin depressurization event or other anomaly that rendered the cabin uninhabitable. And it enabled the crew to perform site preparation or maintenance tasks that required a bulldozer blade or other implement to be attached to the rear of the vehicle. This concept is not limited to the aft of the vehicle or to the use of suit ports. It merely requires an external driving station on a pressurized rover, thereby enabling a PR to be operated as an LTV wherever there is an advantage to doing so. The NASA Artemis Pressurized Rover is early in its development and as of this writing this kind of external driving capability has not been levied as a requirement on the Artemis Pressurized Rover.

A third possible use is as an EVA workstation to enable suited crew on the surface to teleoperate remote assets, such as small rovers, helicopters (on Mars), cranes, or other equipment. Such a Tri-Rotor could notionally be attached to a mounting platform that mates with the xEMU tool belt, transforming it into a body-worn control device. This could be a wireless connection operating over Bluetooth or cellular networks or could be hard wired to the remotely controlled object.

D. Alternatives to the Tri-Rotor

The Tri-Rotor is, of course, not the only hand controller concept. There are perhaps innumerable alternatives and when contemplating LTV hand controllers, it is important to resist the temptation of devising a controller that requires changes to the spacesuit to operate it. NASA has already issued the xEVAS contract for the production of surface spacesuits and will not change the contract to accommodate an LTV hand controller. Additionally, it is possible that additional spacesuits from multiple vendors will find use on the lunar surface during the lifetime of the LTV. Thus, the goal must be that the LTV is controllable with generic spacesuit interfaces and not require one designed specifically for LTV operations.

A traditional joystick has historically been implemented in fighter aircraft as well as most human spaceflight vehicles. It is perhaps most famously associated with the Space Shuttle Orbiter, but is also used in the Orion capsule, Apollo Command Module (CM), and Apollo Lunar Module (LM). In all of these spacecraft it was used as a rotational hand controller – with its inputs controlling vehicle roll, pitch, and yaw. (A translational hand controller of different design controlled translational motion in x, y, and z axes.) The Apollo joystick was initially considered for use in the LRV but was rejected by engineers due to the difficulty using it in a suited glove. (The surface spacesuit glove is not the same as the pressure suit glove used in the Apollo CM and LM, or the same used by shuttle or Orion pilots.)

The Apollo T-handle, shown in Figure 8, was developed in response to concerns identified with the Apollo CM/LM joystick. [1] It is a mature system with known reliability and is the only wheeled vehicle control system with a history of actual use on the Moon. A single T-handle can be used, though it requires mode changes or limited cross-coupling of control inputs. An alternative explored in testing for GTU development is a dual controller architecture where the operator has two T-handles, one used in each hand.

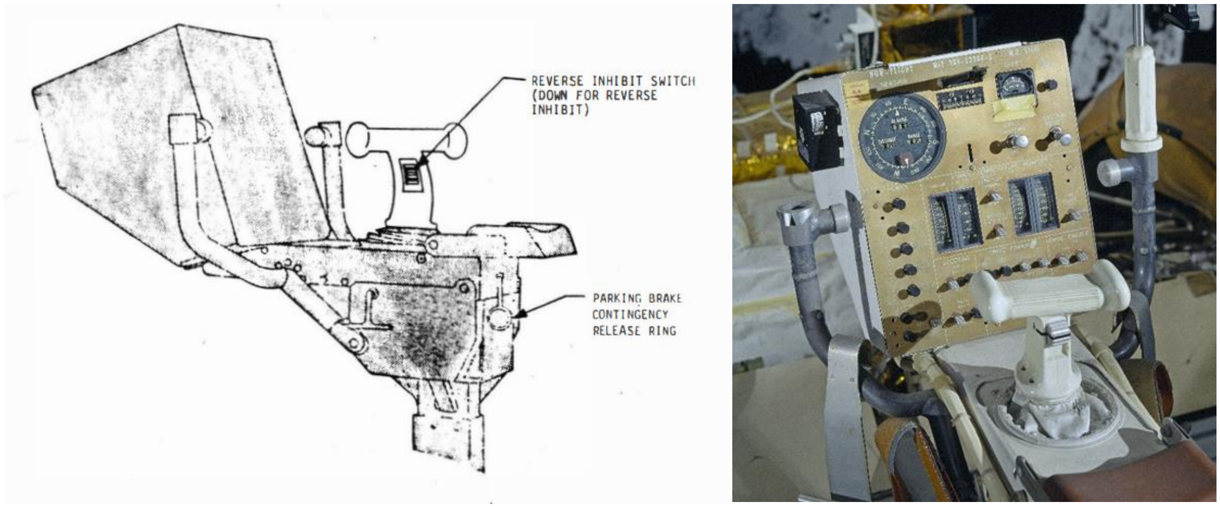

Figure 8. Apollo LRV T-Handle Controller

There is no limit to potential controller solutions that might exist. Both the automotive and gaming industries offer a variety of control systems that could be adapted to an LTV. Further, while many types of hand controllers could be suggested, it would be an inappropriate assumption that the hand must be used to control the LTV, or even body limbs – thus the trade space is not limited to "hand" controllers. Any controller selection should be accompanied by a thorough testing series to evaluate the potential control system's viability in not only expected, but also unexpected usage.

III. LTV Video Wall Testing Series

A. Video Wall Facility Description

The video wall is comprised of ten 55-inch small bezel Samsung LCD 1080p monitors arranged in a 2x5 matrix, shown in Figure 9. It features a "mini-cockpit" complete with seat, display, hand controller and arm rests located approximately 1 meter from the screens. Various types of USB-compatible hand controllers can be utilized in this facility. For this test, two different hand controller configurations were used: a Tri-Rotor and a dual T-Handle. The dual T-Handle is two Apollo-style T-Handles, where one is used by each hand. The functionality of both hand controllers will be described later in this paper. The eyepoint view is aligned with the notional front entry GTU.

Figure 9. Video Wall Facility

High fidelity lunar terrain data was provided by the JSC Astromaterials Research and Exploration Science Division. It is a high-fidelity representation of the South Pole with shadowing based on a 1.2º sun elevation on November 16, 2024. These digital elevation maps are available publicly at https://pgda.gsfc.nasa.gov and more specifically at https://pgda.gsfc.nasa.gov/products/78.

Truth data for the terrain was based on 5m/pixel DEM data and 1m/pixel high-resolution imagery from the Lunar Reconnaissance Orbiter (LRO). The terrain was augmented with sub-resolution features (i.e., rocks and craters) based on statistical models collected from LRO imagery. A small subset of craters was carefully placed manually to align with real crater sizes and positions. Over a half-million rocks were also provided based on crater locations to give the effect of increased rock distribution around some of the larger craters. South pole shadowing was generated using Virtual Shadow Maps in the Unreal 5.0 virtual reality engine and a terramechanics model was used to calculate the overall soil resistance on the rover wheels. These sub-resolution features are not publicly available at the time of this writing, but a public release is anticipated at some point in the future.

The simulation environment includes a notional 500-m radius Surface Habitat area approximately 19 km from the lunar south pole and 9 km from the nearest rim of Shackleton Crater. A second site, colloquially identified by lunar site planning team members as the "Bear Paw" consists of a 500-m radius area that is approximately 8.9 km from the Surface Habitat area. Screen captures of the Surface Habitat terrain and the Bear Paw terrain are shown in Figure 10 and Figure 11 respectively. Joining the two areas is a 500-m wide corridor between the Surface Habitat site and the Bear Paw, shown in Figure 12. These three areas, the two 500-m radius areas and the 500-m wide corridor joining them, are the areas that have been enhanced with sub-resolution features. (The actual environment available in the simulation tool is much larger but was not needed for this evaluation.)

Figure 10. Simulated Surface Habitat Area Terrain

Figure 11. Simulated Bear Paw Terrain

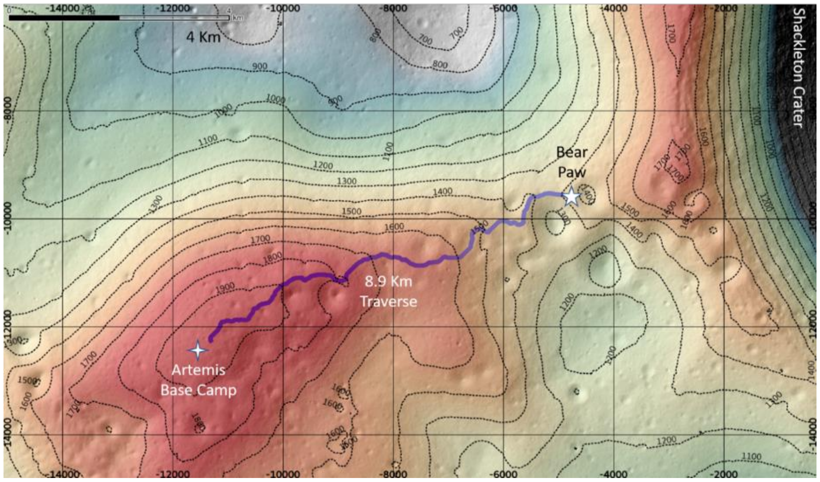

Figure 12. Corridor Linking the Surface Habitat Area to Bear Paw

B. Video Wall Test Description and Objectives

Two driving courses were developed for the video wall test, a Long Course, and a Short Course. The Long Course is a 3.7 km course from the Surface Habitat to Lander site, the latter of which is located along the previously mentioned corridor linking the Surface Habitat to Bear paw. The Long Course is shown in Figure 13.

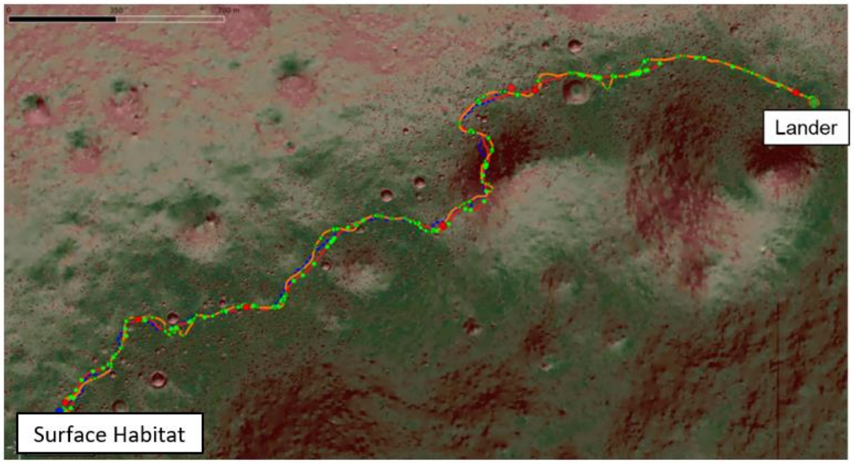

Figure 13. Long Course from Surface Habitat to Lander

The test subject begins at the Surface Habitat and follows a traverse path indicated on an electronic display map. The map was developed with only LRO imagery and thus does not include obstacles that could not be detected by LRO, some of which cannot be traversed safely. Consequently, the operator must deviate when they encounter obstacles to find a safe traverse path. Completion time is estimated to be 30-45 minutes.

The short course is based entirely at Bear Paw, with various terrain features such as pebbles, cobbles, craters and slopes. A special interest feature is a 35-meter crater. The test subject begins at a pre-determined point at Bear Paw and drives roughly 394 meters to the crater. The subject will then drive around the rim of the crater using the crabbing technique to point the nose of the LTV into the crater. This is notionally representative of a hypothetical task to point a forward-facing imaging capability into the crater while conducting a 360-degree drive around to image the target from all sides. While crabbing, the driver will need to avoid various terrain features (e.g., small craters, large boulders, full sun condition). Completion time is estimated to be 5-15 minutes.

Test subjects are asked to consider:

- Controller response to your inputs
- What physical motions are needed
- How your hand/arm/shoulder feels

- Whether the grip feels too big or too small,
- Whether the mapping of the controller(s) functions is easy to understand
- What improvements are needed

Test Objectives are to collect design data on two hand controllers of the LTV GTU for the purpose of refining the design of the hand controller(s) for future field analog testing. Also, where relevant, lessons learned from testing will be used to refine the hand controller test protocol in prep for future LTV vendor testing. Because this test served in part to evaluate the Tri-Rotor in support of design improvements, not all aspects of the test will be applied to LTV vendor testing. The test was performed shirtsleeve – no mockup or actual spacesuits were worn by test participants. It should be noted that the video wall is currently only capable of accommodating shirtsleeve test subjects. Thus, limitations to range of motion, field of view, and comfort imposed by a spacesuit cannot be tested in this facility. A total of five males and four females participated in the evaluation.

IV. Tri-Rotor Performance and Subject Comments

In both the long and short courses there was little to no difference between the Tri-Rotor and Dual T-Handles when comparing them for responsiveness to avoid objects during a simple driving operation. There was also no statistical difference for task completion time, average velocity, or distance traveled – all indicators of responsiveness and maneuverability. Multiple test subjects are shown operating the Tri-Rotor in Figure 14.

Figure 14. Test Subjects Operating the Tri-Rotor

Out of a total of 153 test subject responses to acceptability rating questions evaluating 17 design elements of the Tri-Rotor, 83% of responses were acceptable, 12% borderline, and 5% unacceptable. Test subjects provided additional comments to provide insight into their acceptability ratings:

A. Comments Regarding Physical Access

Reach - Comfortable, easily adjustable and allowed controller close to body. Due to mockup seat arm rests restricting the steering throw, some subjects had to keep the controller further away causing them to extend their arms.

Grip - Fine for EVA glove; however, needs to be sized appropriately for EVA suit compatibility. Grip size is comparable to T-Handle.

Size of the Loops - Sufficient spacing for EVA suit gloves. Loops were large and did not get in the way.

Extension Bars Reduce Fatigue - Comfortable. Useful for resting outer edge of hand during driving; however, could be shorter in length.

B. Comments Regarding Controller Design

Controller Mapping - Remapping current functions is desired. The brake function is missing. There were issues with distinguishing the crab directions. The controller needs labels for forward/reverse and left/right crab. Steering rotation did not seem to be equal in both directions. There is no center detent to tell operator where neutral/zero position was located. Having acceleration for crabbing built into the crabbing function was disorienting and disturbing. It was difficult to accelerate fast due to pressing the right loop further than expected to obtain max speed.

C. Comments Regarding Control of Vehicle

Ability to Accelerate and Maintained Speed - Easy to maintain speed (around 8 kph), but rarely used max speed as the acceleration hand position on the right loop for max speed was difficult to achieve. Cruise control is highly desired. If no cruise control, speed should be adjusted clockwise such that optimal cruise speed position is flush with the frame. 1 kph built in detents would be desired.

Ability to Brake and Stop - There is no brake function on this controller; hand to use reverse on the right loop to stop. Regenerative braking was not very effective at keeping the vehicle stable when no inputs were given making it mentally fatiguing to constantly “station keep.” Add reverse button and put hard break function into controller. Needs a centering mechanism of higher fidelity to completely stop. Add a detent when the throttle is in the middle (no input) position to indicate braking.

Ability to Drive Forward - Easy to accomplish.

Ability to Drive in Reverse - Add a reverse button. Very intuitive, much like a car. With controller centered, driving in reverse was simple. Need a camera when driving in reverse for situational awareness. More throttle distance is needed for reverse when compared to forward.

Ability to Turn Left/Right - Adding adjustability to turning sensitivity is highly desired to allow for individual preference. It was very intuitive and drives like a car. Gradual left/right turns were fine, sharp turns too sensitive resulting in operator induced oscillations; mechanical upgrades are needed to reduce sensitivity. The controller needs a physical limit of only a few degrees of travel while turning.

Ability to Crab - It was easier to crab with this controller compared to the T-handles. Handling crabbing was easy; however, inputs are incorrect, and velocity linked to steering angle is undesirable. Issues with left crabbing due to spring in controller and outward rotation with continual “fine tuning” causing the left-hand position to be more upright. Right crabbing was easier due to inward rotation causing the left-hand position to be facing down in a more relaxed state. Issue with crabbing is wheel speed is controlled by both loops and should be controlled by only one loop due to the nature that crabbing is a blend of turning and wheel speed. Crabbing was easy to maintain once a sweet spot was reached; however, reaching that spot was difficult.

Ease of Driving with Two Hands - Favorite feature was the ability to turn the steering hub while accelerating without having to use separated left and right controls.

D. Comments Regarding Maneuverability

Maneuvering to Avoid Terrain Features (rocks and craters) - Turning the controller hub like a car steering wheel made avoidance easy. More consistent resistance on the controller is desirable. It was challenging due to the amount of travel in the steering control and integration of wheel speed into wheel angle.

Responsiveness of Controller to Avoid Terrain Features (rocks and craters) - Left/right turning felt overly responsive inducing oscillations due to controller being too sensitive.

Maneuvering for Crater Rim Driving - Crabbing was easier with this controller. Would like to try the throttle on the right and the crab angle on the left to possibly have more control of the crab angle and throttle. Tended to over rotate the crabbing to try and match the angle of the vehicle with the rim; however, over time it got easier. Detents are desired in the controller.

Responsiveness of Controller for Crater Rim Driving - Controller way too sensitive with incorrect controls coupled. Spring on left hand loop needs to be fixed

E. Comments Regarding Fatigue

Hand Fatigue - Driving at max speed (12 kph) puts a strain of the right hand over time due to the overextended loop distance and the amount of pressure to hold the accelerator to full speed; however, if loop distance was flush with handle fatigue would be reduced. There was some pressure on right thumb to maintain speed and direction. The controller allowed the freedom of options on where to position hands to reduce fatigue.

Arm and Shoulder Fatigue - Right wrist, elbow, shoulder and neck and elbow experienced fatigue from maintaining pressure on accelerator for a long time. Changing the throttle spring and providing an adjustable arm rest would reduce arm/shoulder fatigue.

V. Forward Options to Improve Usability of the Tri-Rotor

The following eight inputs are needed to fully control the LTV GTU: Forward translation, reverse translation, left rotation, right rotation, left yaw, right yaw, acceleration, and braking. These inputs can be activated in multiple ways, based on mapping of the Tri-Rotor controls. Some of these mappings may be fusions of one or more inputs. The original mapping is as follows and is illustrated in Figure 15:

- Left Handle Twist: Left/Right Crab and Crab Acceleration
- Right Handle Twist: Vehicle Forward/Reverse Acceleration
- Yoke Rotation: Rotate Left/Right

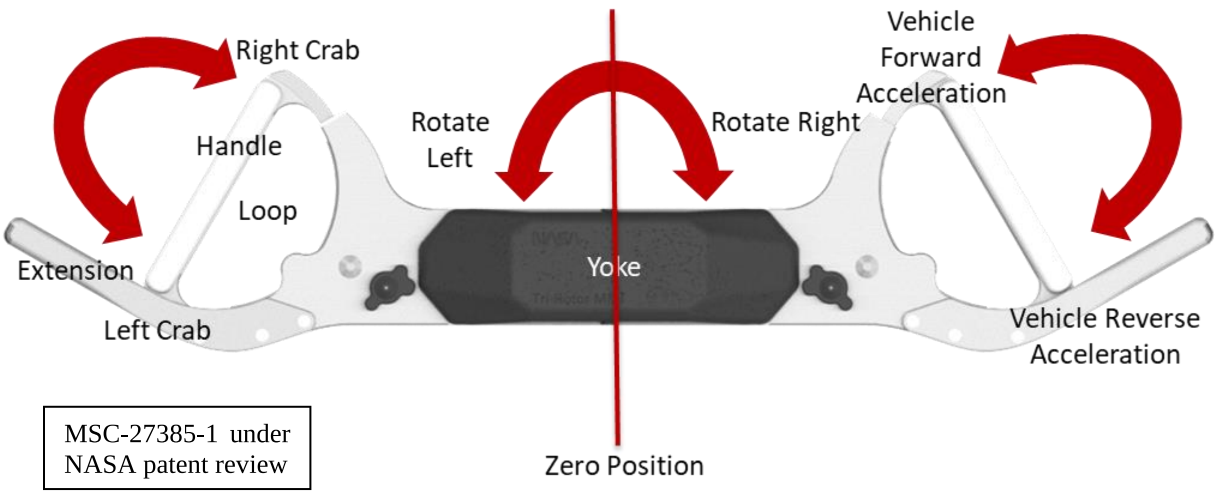

Figure 15. Tri-Rotor Functional Mapping

Braking is not implemented but can be achieved by commanding motion in the opposite direction.

Human factors practitioners also noted that for any control device, body stability will play a key role in the usability of the controller. Because the LTV will operate on unprepared terrain, it is expected that the crew will be subject to unexpected jerking motions. If these motions are transmitted to the controller, unintended control inputs (including, but not limited to, pilot induced oscillations) will result. Thus, it is suspected that in order to retain controllability of the vehicle, the torso will need to be sufficiently restrained.

A. Test Recommendations

Based on test subject comments,

1. Physical repairs or improvements to hardware (items that did not function as intended)
   a. Fix the crabbing spring (would not bounce back to neutral)
   b. Add resistiveness to controller function on the yoke – currently free flowing controller. Needs stiffer rotation springs.
2. Modifications to alter functionality
   a. Break crabbing control and acceleration (during crabbing) into different inputs (No definitive design input on how to implement this based on current mapping, given the current functionality)
   b. Steering (yoke) needs to have a greatly reduced range of motion – add end stops where the controller stops responding to input (a range of 20 or 30 degrees).

c. Make max speed on acceleration loop (right hand) flush with frame to reduce hand fatigue
d. Add cruise control, possibilities indicated by subjects are:
    i. Button next to right hand position on the yoke
    ii. Button on the display
e. Add adjustability to the steering sensitivity to allow for individual preference. Comments on how turns were 'too sharp' at the extremes. (May be a moot point when resistiveness is added to controller function.)
f. Detents in the hand loops to provide haptic feedback for the controls. (No specificity identified for number of detents. Consider 1 kph detents on acceleration (right loop) and 15, 45, 90-degree increments in either crabbing direction (left loop) as a starting place)

B. Alternatives to Ackermann Steering Implementation

However, it is possible that these recommendations might not be sufficient. In particular, no solution was offered to the problem that triggered test subject suggestion 2.a. Some performance deficiencies were associated with the rotation of the yoke in its implementation of Ackermann steering. The current range of motion can allow the Tri-Rotor to strike the crew member's thighs. Also, rotating the Tri-Rotor yoke while also twisting handles is a complex motion, sometimes resulting in unintended inputs. Replacing the yoke rotation with a push/pull could enable alternate mappings of Tri-Rotor functionality, though it also could exacerbate unintended operator-induced inputs due to terrain.

Alternate Mapping 1 maps translation and rotation in a manner to match the hand assignments used by the rotational and translational hand controllers in the space shuttle Orbiter:

- Left Handle Twist: Left/Right Translation
- Right Handle Twist: Left/Right Crab
- Yoke Push/Pull: Vehicle Forward/Reverse Acceleration (similar motion to aircraft yoke push/pull for climb/dive)

Alternate Mapping 2 extends the shuttle controller mapping, but also adds automotive-style foot pedals to supplement the Tri-Rotor:

- Left Handle Twist: Vehicle Left/Right Translation
- Right Handle Twist: Left/Right Crab
- Yoke Push/Pull: Vehicle Forward/Reverse
- Left/Right Foot Pedal: Wheel Braking/Acceleration

Alternate Mapping 3 changes the axis of the Tri-Rotor such that the yoke turns in yaw instead of roll, reminiscent of a bicycle or motorcycle handlebar:

- Left Handle Twist: Left/Right Crab Angle (±90-degree at full deflection)
- Right Handle Twist: Wheel Acceleration (counterclockwise) / Reverse Acceleration (clockwise)
- Yoke Yaw: Forward Wheels Turn (percent different in front wheel crab angles relative to rear wheel angles; traditional Ackerman steering at 0° crab angle)
- Trade: Right Handle Trigger or Single Foot Pedal: Wheel Braking

For the foot pedal input, it is not yet clear if ankle articulation is possible in a lunar surface spacesuit or if this would need to be a full foot motion. It is also not clear if the handle trigger might be prone to inadvertent activation or be fatiguing in a pressurized suit. For all of the Tri-Rotor control options, there is some concern that if the seat restraint (not designed at the time of this evaluation) does not sufficiently restrain the upper torso that any vehicle hard accelerations or decelerations in the forward/reverse direction may cause unintended control inputs.

VI. Tri-Rotor Design Maturation

A. Tri-Rotor Design Maturity

Tri-Rotor is a new hand controller concept. While joysticks and T-handles have decades of established use, the Tri-Rotor has only a few years existence with very limited funding for design refinement or testing. The first-generation prototype is an interesting controller concept. It is intuitive and non-pilot novice test subjects were able to jump in and start driving right away. It does need some mechanical improvement, but once refined it could be an effective hand controller.

Further design maturation will be limited by available funding. Two parallel test campaigns are recommended as a result. The basic test path will continue to use the original Tri-Rotor with not changes. As funding permits, an alternative mapping test path should use second generation Tri-Rotors.

B. Alternative Mapping

Alternative mapping will focus on testing opportunities using the Virtual Reality capabilities in the Center for Design and Space Architecture (CDSA) and/or the Motion Platform in the Systems Engineering Simulator (SES). With sufficient funding, second generation Tri-Rotors can be assembled, and testing can be conducted by running obstacle courses in the CDSA Virtual Reality lab or on the Motion Platform. Test runs can be conducted with the original Tri-Rotor control mapping with recommended modifications, Alternate Mapping 1, Alternate Mapping 2, Alternate Mapping 3, and additional concepts as they emerge.

Promising Tri-Rotors can join or replace the original Tri-Rotor in the basic test path, to be tested as an additional controller in the next planned test. Those test results may drive a post-test disposition to either make additional improvements and continue comparative testing; or discontinue further work on the alternate concept; or replace the original Tri-Rotor with the alternate concept.

C. Basic Test Path

The basic test path picks up with a motion table test using a mockup of the GTU cockpit. The motion table extends the testing conducted in the video wall, but in a motion-based environment. It will confirm or reject conclusions of video wall testing and it will expose any effects of vehicle motion on usability of the Tri-Rotor controller, especially the previously noted concern regarding accidental control inputs. If the motion platform test can be conducted with surface suits, it may highlight impacts of suit mobility on controller usability.

In addition to test subject questionnaires, objective simulation data will be collected including hand controller adjustability, handling qualities of hand controller in a motion-based environment, seat adjustability, armrest adjustability, field of view, total distance, speed, task time, rock contact, hand controller deflections from normal, and hand controller torque values from normal.

The motion table will provide design recommendations applicable to GTU control interfaces and can serve as a testbed for prototyping alternate controls prior to their installation on the GTU. The GTU will be tested in the JSC rock yard, and that test may serve as an acceptance test of a Tri-Rotor before it is deemed acceptable to use in a field analog mission similar to the NASA Desert RATS (Research and Technology Studies) test campaigns. Key performance goals to test in the rock yard include crater rim crabbing, forward/reverse driving, navigating turns, and acceleration and braking. Crater rim crabbing is of special interest because it is a vehicle maneuver not possible with the Apollo LRV but has been mechanically enabled by the omnidirectional steering implemented by NASA on its concept vehicles. However, it is not clear if it can be performed by suited crew due to both limitations in suit mobility and helmet visibility. It is further not clear which vehicle use cases require crabbing, or are enhanced by crabbing, or are only marginally impacted by the ability to crab. A better understanding of the benefits of crabbing is significant for assessing the potential contributions of a control interface such as the Tri-Rotor.

VII. Potential Field-Testing Opportunities

While not part of near-term NASA analog mission plans as of this writing, a set of six field test activities can help explore the capability of the Tri-Rotor to control the vehicle. Each activity represents a different type of traverse for the GTU. These test activities do not represent formal NASA use cases for the LTV but are instead intended to increase NASA understanding of GTU controllability with the Tri-Rotor. While each test activity could support additional objectives that relate to other lunar campaign goals, several objectives specific to the Tri-Rotor will be tested in each test activity.

A. Science Traverse Simulation

The Tri-Rotor test objectives are to establish a baseline of Tri-Rotor unit performance during extended driving, and to assess the usability of the Tri-Rotor as operator fatigue builds during a long EVA. The traverse consists of three 45-minute field site explorations separated by driving segments varying from 15 minutes to 2 hours. It begins with a 30-minute drive, followed by a 45-minute Site 1 science survey. An 80-minute drive leads to Site 2, which also has a 45-minute science survey. The drive to Site 3 is 15 minutes, with a 45-minute science survey. The end of the traverse is a two-hour drive. The terrain includes a mixture of slopes in 10-20-degree range and rock conditions ranging from smooth to rocky.

B. Communications Relay Deployment Simulation

The Tri-Rotor test objectives are to assess the maneuverability of the GTU with the Tri-Rotor to navigate a narrow rock outcropping surface and to assess the controllability of the GTU while carrying an awkward payload – a communications relay. The simulated communications relay is an oddly shaped structure that does not conform to previously established payload dimensions and is secured to the GTU in an awkward fashion that while secure, may allow for some flexing of the payload within the field of view of the driver. The terrain includes a narrow rock outcropping with a sloped path < 20 degrees on top of the outcropping that is at least 50 meters in length, with steep slopes on the other sides. (For purposes of the test, it is not necessary to find terrain with actual steep slopes on the sides – keep out zones can be marked on terrain to indicate where the hazardous slopes would be.)

C. Habitat Logistics Transfer Simulation

The Tri-Rotor test objectives are to assess the controllability of the GTU with the Tri-Rotor while heavily loaded with logistics and to assess the controllability of the GTU with the Tri-Rotor with an unbalanced logistics load. The scenario includes a 5-kilometer drive from a notional lander to a notional habitat field location with the GTU carrying two crew and two full large logistics payloads from the lander. The crew will unload all contents into the habitat and will fill one of the two carriers with other materials (e.g., trash) to be delivered to the lander, which is acting as a disposal site (the other large logistics payload will remain with the habitat). There will then be a 5-kilometer drive from the PR field location to the habitat, with the GTU delivering one full large logistics payload. The terrain includes a mixture of slopes in the 10-20-degree range and rock conditions ranging from smooth to rocky.

D. PR Crew Rescue and Logistics Recovery Simulation

The Tri-Rotor test objectives are to assess the controllability of the GTU with the Tri-Rotor while lightly loaded with logistics; and to assess the controllability of the GTU with the Tri-Rotor while maintaining speed with walking EVA crew. The scenario includes a 10-kilometer drive from the SH (low fidelity mockup) to a disabled PR. The disabled PR is in a small, steep-wall crater with slopes that exceed GTU traverse capability, a depth in excess of 4 meters, and a diameter on the order of 3-10 meters. Outbound, the GTU carries two crew and no large logistics payloads. The scenario includes a 10-kilometer drive to the SH following crew recovery with one partially full large logistics payload recovered from the PR. This carrier represents PR logistics and science payloads recovered from the PR to be transported to the SH. The rescued crew will drive/ride in the GTU and rescuers will walk alongside the GTU during the return leg. The terrain includes mixture of slopes in 10-20-degree range and rock conditions ranging from smooth to rocky.

E. Incapacitated Crew Member Simulation

The Tri-Rotor test objectives are to assess the maneuverability of the GTU with the Tri-Rotor to position the GTU precisely for incapacitated crew recovery from a narrow access; and to assess the controllability of the GTU with the Tri-Rotor while driving with an incapacitated crew member simulated load. In this simulation, a crew member has fallen into a narrow crevice and is unresponsive. Only one crew member is present to conduct the rescue. The scenario includes a 10-kilometer drive at maximum achievable speed to HLS or SH following crew recovery with incapacitated crew member secured to a pre-identified location on the GTU. The incapacitated crew member must be able to be loaded onto the GTU and the rescuer begin driving within 10 minutes or less and the drive must be accomplished within 45 minutes or less. The terrain includes mixture of slopes in 10-20-degree range and rock conditions ranging from smooth to rocky.

VIII. Conclusions

The Tri-Rotor represents an effort to develop an entirely new vehicle control device specifically to maximize operator ability to control the steering features designed into the NASA concept rovers while under the constraint of wearing a pressurized spacesuit. Its use in a shirtsleeve simulation environment indicates potential utility but also recommends further design iteration. Should the Tri-Rotor continue in development and become a viable hand controller system it could potentially see use in pressurized and unpressurized rovers, as well as a variety of remotely operated robotic systems within Artemis and beyond.

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