Development and Testing of Crew Interfaces for an Advanced Unpressurized Exploration Rover

Charles Hanner[1], Nicolas Bolatto [1], Daniil Gribok [1], Spencer Quizon [2], Rowan Quintero [2], Ian Welfeld [2], and David L. Akin[3]

University Of Maryland, College Park, MD, 20742, USA

Although revolutionary in its impact on lunar exploration, the Apollo Lunar Roving Vehicle (LRV) had only rudimentary navigation capabilities, and crew controls were essentially limited to go/stop and turn right/turn left. After more than five decades, rovers supporting the Artemis program will have vastly increased capabilities, and a corresponding need for more detailed and complex crew interfaces. The VERTEX rover has been developed at the University of Maryland as a field test analogue of concepts such as the Lunar Terrain Vehicle, and incorporates advanced capabilities such as active suspension, variable deck height and angle, reconfigurable payload interfaces with multipurpose electronic interfaces, and advanced control modes including teleoperation and autonomous driving. This paper details the development and human factors evaluation of controls, displays, and driver restraint systems for the VERTEX rover, based on both laboratory and field testing. While advanced robotic systems are often controlled from graphical user interfaces including touch screens, the extremes of lighting on the lunar surface and effects of regolith on pressure suit gloves drive designers to greater use of discrete and dedicated control interfaces and single-function displays easy to read in both bright sunshine and darkness. Extensive human factors testing was performed to examine potential layouts for the comparatively large number of discrete displays and controls, without impacting rover ingress/egress in spacesuits. Display and control layouts are also inherently impacted by crew seating and restraints, and a focused effort was made to move beyond the unsatisfactory simple seat belts of the Apollo LRV to restraint systems which are easier to engage and release in a spacesuit. The seat design itself is strongly driven by the portable life support system, and the VERTEX seat system was optimized to accommodate a number of different backpack designs and sizes to support external test objectives.

Nomenclature

BMS	Battery Management System
CG	Center of Gravity
EVA	Extravehicular Activity
HLS	Human Landing System
PLSS	Portable Life Support System
RAVEN	Robotic Assist Vehicle for Extraterrestrial Navigation
ROS	Robot Operating System
SSL	Space Systems Laboratory
TLX	[NASA] Task Load Index
UMd	University of Maryland
VERTEX	Vehicle for Extraterrestrial Research, Transportation, and Exploration
xEMU	Exploration Extravehicular Mobility Unit

[1]Graduate Research Assistant, Space Systems Laboratory
[2]Undergraduate Student, University of Maryland
[3]Director, Space Systems Laboratory. Professor, Department of Aerospace Engineering

I. Introduction

One major lesson from the Apollo program was that the range and extent of scientific exploration was greatly enhanced on the last three missions by the presence of the Apollo Lunar Roving Vehicle (LRV). The lightweight four-wheel vehicle increased the traverse distances by an order of magnitude, reduced fatigue by transporting the astronauts, tools, and samples, and provided a base for continual transmission of images back to Earth [1]. Recognizing this fact, NASA has already begun commercial development of the Lunar Terrain Vehicle (LTV), another unpressurized two-person vehicle for use in the Artemis program.

NASA believes that the Artemis LTV should be a crewed combination of Mars 2020-style exploration rovers and the Apollo LRV in order to enhance the program's scientific capabilities alongside or independently of astronauts [2]. If that is the case, it is important to consider that some of the lessons learned from Apollo were that the LRV was not a perfect vehicle in terms of human interfacing. The A7L pressure garments had to be significantly redesigned into the A7L-B to allow the wearer to sit in the LRV seat; even with those revisions, the seated posture was not completely comfortable. The traditional flexible seat belts were extremely hard to work in pressurized gloves, and did not easily latch around a pressurized suit torso. The control device was a simple two degree-of-freedom control stick, limited to driving the vehicle in Ackermann steering mode while controlling forward speed.

It also needs to be considered that a lunar rover of the 2020's will certainly have extensive improvements in capabilities over one from the 1960's. A current state-of-the-art mobility chassis may well have the ability to change clearance height, deck angle in pitch or roll, or wheel configurations. It may have all-wheel steering, allowing standing turns about a point or driving in a different direction than the central axis of the chassis. Additional degrees of freedom require additional control devices, or at least mode-switching in a primary controller. A modern lunar rover will have much more capable electronics than the Apollo era vehicle, providing additional capabilities, but also requiring much more detailed controls and displays. Critical information such as navigation data needs to be displayed graphically to the driver, reflecting the change from the Apollo-era "this is the direction to the Lunar Module" to autonomous route and path planning with updates from orbital navigation and imaging assets in real time.

Based on all of this discussion, a critical aspect of the design and development of a next-generation lunar roving vehicle for human exploration must be a systematic research program into the three critical areas of rover/human interaction: controls, displays, and safety restraints. An initial start on this research and preliminary integration efforts are the focus of this paper.

To experimentally investigate how a human subject interacts with a highly capable rover system, the first requirement is an available testbed vehicle which includes many of the augmentations under consideration for LTV and future planetary surface vehicles. To that end, the University of Maryland (UMd) Space Systems Laboratory (SSL) is entering the final stages of development of the Vehicle for Extraterrestrial Research, Transportation, and Exploration (VERTEX), an Earth-analogue lunar astronaut-assistance vehicle intended to investigate mission capabilities relevant to NASA's upcoming Artemis program (Figure 1). VERTEX will nominally be capable of transporting an astronaut in an Exploration Extravehicular Mobility Unit (xEMU), in addition to geological sampling tools and other scientific equipment.

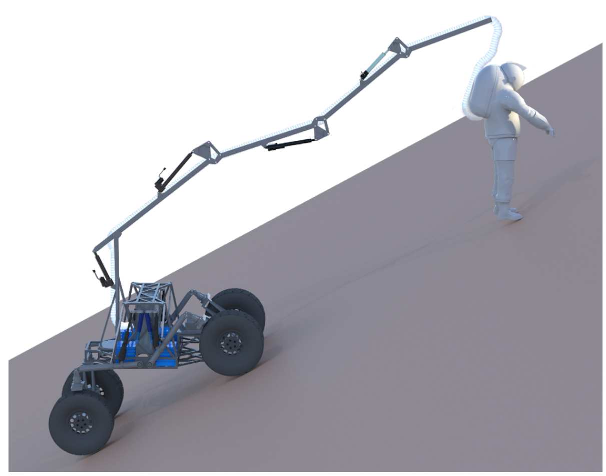

Figure 1. BioBot concept system render with VERTEX rover, umbilical tending arm, and astronaut walking up-slope

The flight version of VERTEX was designed to allow a pair of vehicles to be launched to the moon on a single Commercial Lunar Payload Services (CLPS) lander, to support early Artemis missions without presuming sufficient cargo capacity existing on the human landing system (HLS) vehicle. Such single-person rovers would allow two-astronaut EVAs to double their effective exploration as each conducts their own science stops while remaining within short walking distances of each other in case of a failure. If a failure does occur, a second astronaut can be driven back to base in a jumpseat at the rear of the vehicle. The capability of returning both astronauts to safety can extend the allowable excursion range far beyond NASA's current walkback criteria by introducing an additional fault tolerance.

When the Earth analogue version of VERTEX is used in support of the ongoing BioBot concept testing under NASA Innovative Advanced Concepts (NIAC) support, it will also carry an umbilical-tending robotic manipulator and life support system, providing rover-based life support to offload the astronaut from having to carry a full portable life support system (PLSS). The umbilical tending manipulator will primarily be used alongside VERTEX's autonomous functions, capable of tracking and following an astronaut for exploration of the lunar surface on foot [3]. However, the astronaut may always choose to ride on the vehicle and drive using manual controls between sites.

Figure 2. VERTEX rover presently in development, in a standing pose

Figure 3. Pre-VERTEX development RAVEN rover

Details regarding the design process and functionality of the rover can be found in a previously published paper [4], but in summary VERTEX is a compact rover platform (≈1.5 m wide, ≈2 m long) that uses a custom series-elastic linear actuator configuration to achieve active chassis pitch (25°), roll (40°), and height control (1 meter range) in a fully electrically-driven package. The Earth analogue rover uses 32 inch tires paired with a brushless DC motor and 33:1 planetary gearset capable of climbing 30° slopes with $\pm$ 180° independent steering on each wheel. The rover itself has a total of 12 actuators to continuously control, both in autonomous and manual modes, leading to some unique challenges for any human/rover interfaces.

This complexity is exacerbated by the fact that VERTEX is an unpressurized rover, meaning there are difficulties in keeping all controls both accessible and easy to operate despite a pressurized suit's lack of dexterity and limited range of motion. Considerations for these accessibility issues are discussed later in this paper regarding component selection of the control panel, but this is still an active area of research for the vehicle for items like joysticks. Additional concerns such as dust mitigation are not considered in this investigation, as the rovers for development in question are Earth-analogues more focused on the applicability of the system concepts to EVA and general operations.

The Earth analogue version of VERTEX nearing the end of production as of summer 2023. The main structure and assembly of subsystems is complete with the exception of steering, expected to be integrated by June 2023. However, even if the hardware were complete, the first drive of the rover could not be completed without a semi-comprehensive set of controls and an appropriate astronaut accommodation system. The integration, testing and planning of these control surfaces is occurring concurrently with the VERTEX build, and progress to date in this effort is described later in the paper.

II. Control Panel Functionality

A few basic concepts of operations for the rover have been short-listed as the hardware design evolved, breaking down into low-level operational procedures and higher-level control capabilities.

A. Startup

Low-level operational control items such as items for the startup sequence, battery protection, and computer booting systems are considered to be baseline functions. Protection for not only the user, but also technicians, other students, and people in the area is paramount since this vehicle has a 96V/300A capable power system, has $>$ 1,000 ft-lbs of torque, and weighs $1,750$ lbs. A *Master Enable* switch is activated by key to allow a push button *Master On* to be activated. The emergency stops (E-stops) must be released (more details in section III), and there are several different E-stops including two untethered remote E-stops. VERTEX will also be equipped with lighting systems including forward facing, rearward facing, under-chassis, and hazcam illumination in the near-future. Adjusting the intensity alongside the state of each of the lighting systems individually through a series of toggle switches is expected of the controls system. Each drive wheel on VERTEX is equipped with a normally-on brake that is disengaged when the rover is in a drive-ready state. Additionally, a battery management system (BMS) interface is integrated for monitoring the health (voltage, capacity, etc.) of the battery system alongside debugging and external power storage uses. A driver-focused panel can be alternatively included with only top-level charge information if the standard interface is deemed too complicated. Lastly, two joysticks with a total of 5 degrees-of-freedom (DOFs) will be needed for controlling all 12 of VERTEX's actuators: 4 for driving the wheels, 4 for steering, and 4 for adjusting the rover's pitch, roll, and height (separated in up/down directions). These are yet to be integrated to the final rover as through the integration process the team has been using sets of inexpensive and small joysticks for electronics development, which not suitable for use with EVA gloves. A second iterative step of testing and trade studies will need to be completed before a pair of final joysticks are selected.

B. Control Modes

Manually controlling each of the vehicle's DOFs in driving conditions is challenging without integrating underlying levels of autonomy. One example of this is the rover having a faster-response in chassis roll authority than pitch authority due to the suspension dynamics. Subdividing each of the three actuated rover subsystems into a set number of operator-friendly control modes will greatly simplify both the mental task load and the number of required control interfaces.

1. Chassis Control

Active control of the chassis (also referred to as the *deck*) state is a fundamental capability of the VERTEX vision. The original design feature focused on leveling the chassis on all slopes to increase the stability margins of the rover, even in heavily loaded cases. This quickly extended to potentially influencing the center of gravity beyond maintaining level, in order to maintain stability margins if a large off-hanging payload shifts the overall center of gravity (CG). A series of suspension autonomy modes were defined based on the expected desires of operators in rock- or slope-climbing conditions:

Figure 4. VERTEX suspension with series-elastic linear actuators

- *Auto Zero* maintains a deck angle perpendicular to the gravity vector using inertial measurement units (IMUs) housed onboard.
- *Auto Hold* maintains a specified deck angle relative to the gravity vector in a specified direction. For example, if auto hold is activated with the chassis pitched up 5°, and rolled left 7° on level ground, then as the rover begins to climb an obstacle the linear actuators will servo to maintain these deltas from the gravity vector, and will likely help when the rover CG is significantly displaced from its nominal position at all times.
- *Proportional* control will allow some manual input to adjust pitch and roll proportionally to the joystick inclination, but the rover will revert to *Auto Zero* when there is no manual input. This would allow a driver to roll the vehicle into expected turns, or momentarily pitch the rover towards the ground for a better view of a geological feature. In the future, the autonomous control of the rover's angles based on sensed rover accelerations will be implemented in this mode to maintain greater stability, regardless of driver input. This way, if the rover enters a left turn the chassis would be able to dynamically lean left to increase cornering stability, or lower itself to increase rollover margins while braking.
- *Manual* control will rely purely on operator input across on a 3-DOF joystick. Two axes of the hand-controller will manage chassis pitch and roll angle control, and a third (whether out-of-plane or twist) control axis will adjust the chassis height. Rover height will be possible to adjust manually in all the chassis control schemes since raising the structure for obstacle avoidance should always have a manual override option. However, a

system for sensing and automatically regulating the rover's ground clearance will also be implemented in the future for additional stability.

- The *Lock* function will hold the linear actuators at their present extensions.
- The last autonomous function is *Kneel*, which will prepare the rover to "kneel" by first pitching forwards and then lowering itself to present an easier opportunity for an astronaut to board and deboard (Figure 2).

The driver may also need to be able to independently control the angle of each corner of the rover for precise rock-scaling, which will be accomplished through a series of momentary rocker switches.

2. Steering

Each VERTEX drive wheel has an over-wheel steering system that can rotate each drive assembly $\pm$ 180° as seen in Figure 5. Six independent steering modes will be available for the astronaut to select from. For safety, the steering modes, unlike the suspension modes, will not be able to be adjusted while the rover is moving, at least for the foreseeable future.

Figure 5. VERTEX turning in place

- *Ackermann* steering is expected to be the most commonly selected configuration as it is most similar to a normal car. When selected, the progressive steering system will turn the front left and right wheels as to align to the same turning point that is in-line with the set of steering-locked rear wheels.
- *RWS* (Rear Wheel Steering) switches the roles of the front and back wheels of *Ackermann* to provide maneuverability more similar to that of a forklift.
- *Double Ackermann* will adjust both the front and the rear wheels to align on a common central radii to decrease the turning radius further than the previous settings.
- *Crab* steering mode will align all wheels at the same angle to allow the rover to travel diagonally or sideways without turning the driver, as seen on NASA's Modular Robotic Vehicle (MRV) and Chariot.
- *In Place* will also be able to align the wheels to turn around the geometric center point of the rover so it can turn in place.

3. Drive Control

The rover speed and steering angle (for the dynamically changing steering schemes) are planned to both be controlled with velocity control. Previous laboratory experience with an acceleration-based rover speed controller on a Segway RMP-440LE led to imprecise and jerky control motions from operators, and is not likely to be comfortable or precise as a main control type for the drive and steering motors. A two-axis drive controller with the drive motor velocity axis in-line with the chassis lengthwise, and steering axis aligned either perpendicularly (L/R) or in a yaw axis motion is expected to be included as the final drive controllers.

III. Emergency Stops and Operational Safety

Multiple E-stops will be placed near the operator controls in easily accessible locations for on-board vehicle halting. Initially one will be placed directly next to the driving joystick, since it is likely one of the astronaut's hands will be there in an emergency situation. The other, to be installed after initial evaluations of an integrated panel, will be accessible to both of the astronaut's hands in a central location on the control panel. Additionally, since this is an autonomous vehicle, wireless remote E-stops will be used to halt the vehicle by other operators from a distance. This would ideally be a pair of remote E-stops, one on the test subject's person and another on an outside testing observer keeping a close watch.

The design of the E-stop procedure must be strategic, because VERTEX's E-stops cannot simply cut all power from each subsystem for a few reasons. First, each drive wheel contains a normally-on brake (similar to many commercial hauling vehicles) that is disengages by the control system at times when the motor is spinning. If the E-Stop is pressed and power is immediately cut from the drive system, this brake will engage and may lead to a dangerous situation at any significant speed or when stability margins are decreased. Full system testing of the suspension in different configurations is to happen to evaluate stability under significant and sudden deceleration. Under an E-stop condition the elastic linear actuator system that actively controls wheel position is not expected to see any decrement in performance as the unpowered holding force of the actuator is twice the operating force. However, the steering motors present possibly the largest uncertainty in E-stop conditions.

A stability issue arises as the effective caster angle of the wheels change due to swingarm angle as shown in Figure 6. If the caster angle is negative (e.g., opposite of the front forks of a bicycle), the wheels will not self-align with the direction of motion when unpowered, especially since the brushless DC motor/Harmonic Drive actuators are backdriveable when unpowered. Excessive off-axis torques may be seen in the steering actuators if the wheels turn sideways and collide into rocks at speed, whereas an aligned wheel could tackle the obstacle in combination with the suspension. The current plan to remedy this is to simultaneously cut battery power from the actuators while connecting a large power resistor across the motors. As the motors spin freely, the resistor causes mechanical resistance by loading the circuit, braking the system. Since the entire rover's kinetic energy is being converted into heat by the resistor, high heat-capacity resistors and heatsinks will have to be used to avoid damage. This modified system eliminates the safety issues of not having the E-stop cut all power while also helping keep the rover more stable during a shut-off at speed.

Many controls need input-limiters in software to stop sudden extreme inputs from the astronaut from various sources including rough terrain and accidental motions. These limits will be implemented in software through scaling the maximum input magnitude and shaping of the central dead-zone area. Software also must limit the driver's manual control of deck-angle adjustment to assure that the vehicle is never in danger of rolling. After the initial inertial property testing, the center of gravity placement of the rover should be known within approximately 10%, and a spherical expansion of that point will be made to appropriately encapsulate how any payload for a given mission could change the CG during the testing.

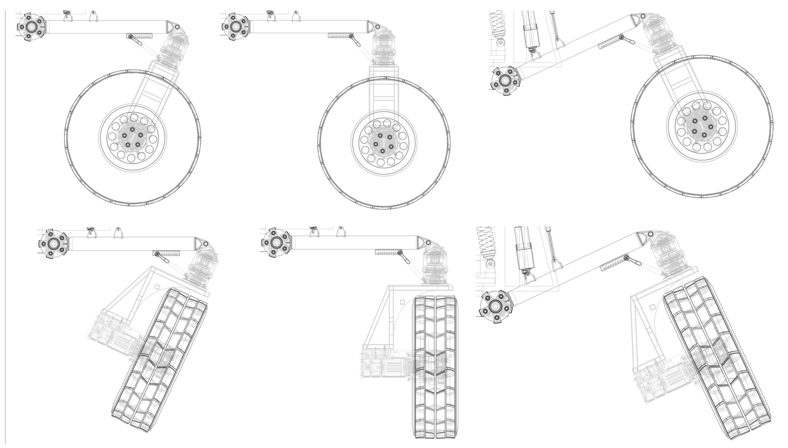

Figure 6. VERTEX Caster and Camber Swing

Finally, for safety of the VERTEX team, a "Development Mode" is intended to be activated via a switch for running basic testing and diagnostics inside the laboratory. This mode will reduce both the maximum input values and the maximum speed of the rover to avoid the rover moving unsafely if the controls are accidentally bumped into.

IV. Control Panel Design Considerations

Some initial design considerations have been outlined to guide a few rounds of experimental iteration detailed in the following sections.

A. Joystick/Drive Controller Design

VERTEX will likely finalize with two multi-degree-of-freedom tactile input devices (joysticks), one for each hand, for controlling the suspension and drive functionality as described in section II. B. Each joystick will likely have an extended hand-rest similar to the Lunar Roving Vehicle (LRV) to reduce required gripping hand pose and reduce exertion. The astronaut will be able to rest their hand on a flat surface, instead of pinning or rigidly attaching the glove in any restrictive way. An initial setup was manufactured in adapting a 3-axis shuttle-style translational hand controller to an LRV configuration as seen in Figure 7. These controllers will not be used in the final VERTEX panel due to their high cost and age. Final selection of a suitable replacement has not yet been sourced.

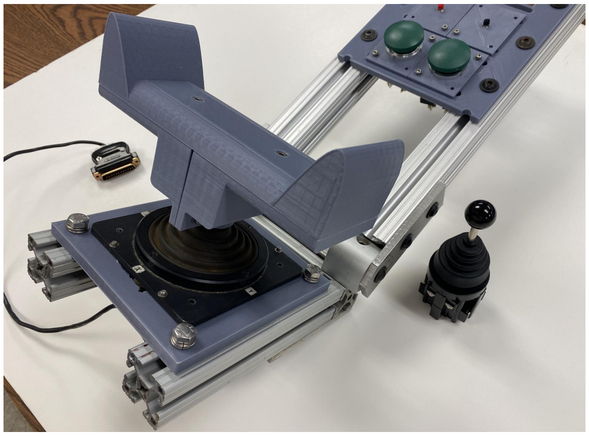

Figure 7. Closeup of conceptual hand controllers for VERTEX

Figure 8. RAVEN rover outfitted with conceptual controllers for initial position and accessibility tests

B. Displays

VERTEX requires a system to display relevant data to the operator. This data varies from self-evident values such as vehicle speed, to exotic parameters such as deck angle and per-cell voltages of the battery. These numbers also vary significantly in update rate requirement - vehicle speed should be updated several times per second, while remaining battery charge can be updated once every few seconds with no adverse effects. A potential solution that accommodates all these needs is a multifunction display. However, due to limited development resources, a fully-featured multifuncition display interface was deemed infeasible for the first generation of VERTEX. Instead, the concept was simplified to use fixed display interfaces, and rely on dedicated buttons to control rover features which may prove better-suited for gloved operators.

Selection of appropriate display devices considered both outdoor readability and adaptability to data update rates. While traditional color panel displays such as LCD, TFT, LED, and plasma suffer from poor sunlight readability their update rates are significantly faster than highly-readable e-ink displays. A combination of both IPS monitors, e-ink displays, and 7-segment LED display modules are included in the first integrated control panel for teams to transfer different metrics between and iterate and develop final screen interfaces and layouts. The details of these panels is described further in section VII.

C. Layout

Logical systems placement is obviously a key to successful operation of VERTEX, and a few assumptions have been made in the course of panel placement. Firstly, a right-hand operation for driving controls and left-hand operation of the chassis suspension controls was selected. Both systems require joysticks to function and the right hand driving controls of RAVEN proved to be natural for operators. The goal of the autonomous vehicle control systems is to allow for infrequent use of the deck-angle controls, which would free the left hand to operate switches and buttons operable while driving such as lights or communications. Throughout testing so far, no operators have complained about these arrangements, though it should be noted that this could change in the future.

Visibility through and around the control panel is a concern, especially considering the large number of controls needed. Firstly, the controls will be placed lower than in most vehicles to reduce forward ground-visibility conflicts. Second, the control panel is made up of a left and right half that do not join in the center. This central gap grants extra visibility for watching the rover's clearance, since it reduces the central blind spot down to the driver's own knees. Another idea to increase visibility under consideration is the use of abrasion-resistant polycarbonate sheeting as a transparent medium to mount the controls and minimize blind-spots in front of the wheels, although this view may become impeded by wiring and electronics boxes.

A few different button styles were tested and selected to be compatible with mockup suit gloves. Large toggles, both momentary and two position, will appear in numerous places along the control panel including lights and independent suspension controls. Buttons were found to be useful as long as some form of a visual confirmation can be made that the button was pressed, since small tactile bumps of most commercial buttons were nearly imperceptible through gloves. Small buttons are also difficult to operate while gloved, especially while the rover is in motion. The rover's integrated panel utlizes mostly large diameter momentary buttons with LED indicators and large multi-position switches as discussed in section VII.

V. Early Control Panel Testing

A. Control Panel Mockup

As a first attempt, low-fidelity mockups were created as an initial test setup, with representative controls and displays layouts affixed to RAVEN to facilitate testing with various undergraduate volunteer groups. Initial test plans focused on subjects rating and operating controls and displays layouts without operating the vehicle. These have consisted of timed reaction tests where a conductor announces actions the operator must perform, after which the subject moves from a neutral driving position to activate the correct button. Such tests are timed and were used to initially informing placement of rarely used but critical interfaces such as the emergency stops and warning lights. These types of tests were used to generate inferences about basic layout structure, but provided little detail on specific operational applicability in the long term. Later tests focused (and continue to focus) on this and are discussed in later sections of this paper.

Figure 9. RAVEN left side controls mockup

Figure 10. RAVEN right side controls mockup

The realization of the sheer number of controls and displays that are needed to operate VERTEX's many DOFs in the varying control schemes led to the development of the first full-size mockups seen in figures 9 and 10. These mockups were mounted to RAVEN in a similar configuration to that of VERTEX, focused around a central seating position as seen in Figure 11. The development team created 2 different control panel layouts to test (referred to as panels A and B) and varied the panel height relative to the seat in *tall* (T) and *short* (S) configurations.

RAVEN's 2-motor skid-steer drive system was disengaged on the rear wheels, and turned into a front wheel drive vehicle with the rear wheels mounted onto casters in order to more closely represent the free-steering style of VERTEX. This improved mobility and ease of control on pavement, at the expense of rear-wheel obstacle

Figure 11. RAVEN with the control panel and seat mockups

climbing and a detriment to off-road performance. As such, initial driving tests with RAVEN took place on closed courses over pavement only. As the VERTEX vehicle's status is brought up to operational, similar tests will take place with the first integrated control system of VERTEX to simulate scenarios in low-risk conditions and gather interable feedback.

B. Testing Procedure

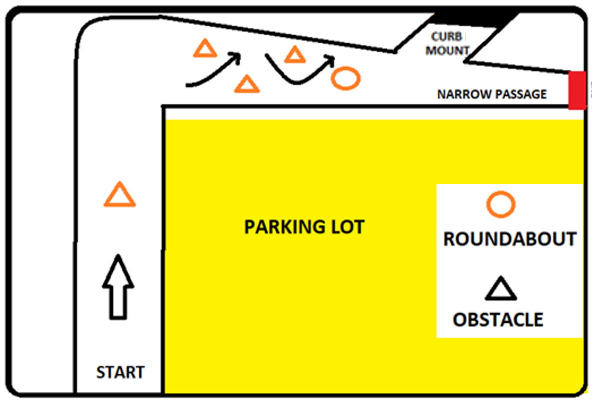

Figure 12. Overhead illustration of the testing path

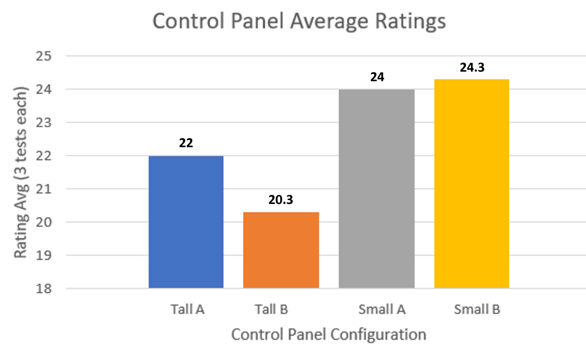

Figure 13. Early preferability results of the four panels

This initial testing was conducted on a course defined by cones as shown in Figure 12. The goal was to drive RAVEN through the course while avoiding obstacles, perform a curb-mount, and finish by driving RAVEN through a narrow passage. The undergraduate team leading these tests believed this would provide an appropriate variety of tasks while not straining available resources during COVID or mobility in RAVEN. During each trial, the test subject was commanded by a test conductor to perform varying startup procedures and then to proceed through a test course consisting of an initial straightaway, several alternating obstacles, and a full rotation around a tight roundabout before driving to a curb mount. Evaluation of an operator's precision in the mobility included counting number of cones displaced, and measuring how far outside the rover was from a goal bounding box in certain areas such as the curb mount.

C. Early Testing Results

At the end of the trial, subjects were prompted with qualitative questions rating 1-5 regarding subjective comfort from the undergraduate team. Questions were of a more qualitative nature than NASA TLX or Cooper-Harper because of the preliminary stage of the control panel design and contents, but subsequent testing more closely aligned with those standards. The average total ratings were 22, 20.3, 24, and 24.3 for the TA, TB, SA, and SB control panels respectively. The high ratings from both SB and SC appear to initially indicate a preference for control panels mounted lower to increase forward visibility. Multiple test subjects noted the course was significantly easier in these lower configurations as it granted a better visual contact with the front wheels. Driver visibility was elevated to a high priority in future iterations as a result of this testing and is the most significant result from these early tests.

VI. Enhanced Control Panel Testing using an RTRS

A. Real-Time Rover Simulation

To build upon the early testing efforts and more-informatively design and optimize the first integrated control panel, a Real-Time Rover Simulation (RTRS) was designed, created, and implemented. The RTRS, shown in use in Figure 14, is a stationary testing apparatus designed to acquire quantitative data from the operator, without the need of an operational vehicle and large navigation course as VERTEX is being assembled in parallel with the control system. RTRS is designed to acquire four categories of data: reaction time, navigation error, visibility, and task load. Each subject wore an SSL-developed space suit analogue (MX-C) and gloves. They were then strapped into the experimental seat restraint to limit mobility similarly to expected on-rover conditions. The RTRS architecture is comprised of the following 5 sections of elements.

1. Modular Testing Panels

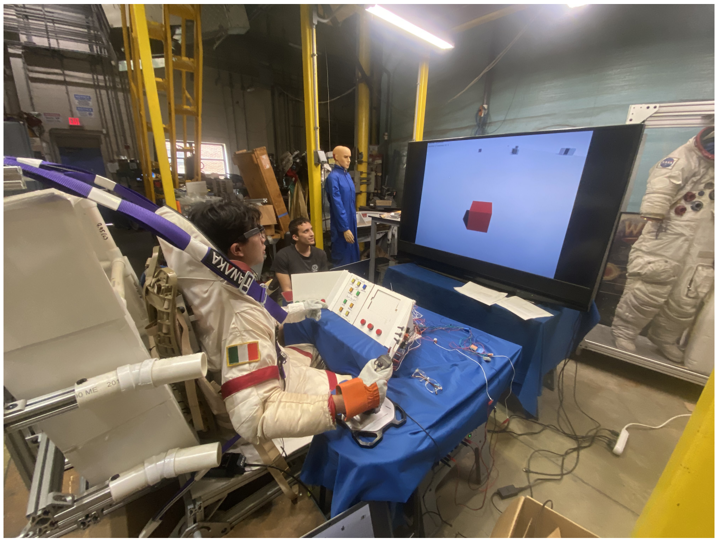

Figure 14. Real-Time Rover Simulation testing

The two main variables that will drive the design of VERTEX's control panel are the type of interfacing component, i.e., buttons or dials and the placement of components and displays. Interfacing with the display will be difficult when operating while strapped in and wearing a space suit, so minimizing the amount of time the astronaut spends with hands off-stick is important. Gaining a better understanding of the benefits and limitations buttons or dials will allow more specific component selection and create a more efficient panel layout that has an easy interface with VERTEX'S wide variety of systems including suspension and drive modes.

To easily iterate between layout and components, a modular control panel architecture was designed with three possible configurations to start with a focus on controlling suspension and steering modes. Configuration 1 (Figure 15) utilizes dials with a display on the far right panel. Configuration 2 (Figure 16) utilizes exclusively buttons. Finally, configuration 3 consists of dials in mirrored position of configuration 1 and a display on the center right panel (Figure 17). Configurations 1 and 2 are designed to provide insights on component selection between systems, and configurations 1 and 3 are designed to provide insights on component and display placement.

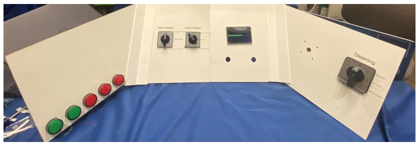

Figure 15. Control panel configuration 1

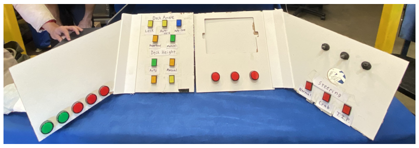

Figure 16. Control panel configuration 2

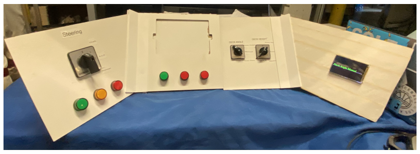

Figure 17. Control panel configuration 3

2. Interactive Component Timing

To understand the performance benefit of various component positions, the time required to carry out each task within a simulation was measured. To accurately measure this time data, the control panel's buttons, lights, dials, and displays were wired to an Arduino Mega tracking each display and command input over the time per trial. The Arduino commands the operator to complete a simple task using the LCD display, recording time between command display and task completion. Time averages will be recorded for two primary operation tasks. The first is steering, which is used to toggle between different drive modes. The second is suspension mode, which is used to manipulate VERTEX'S deck height and angle.

3. Driving Emulator

To emulate the focused effort required in operating a rover, a simulation was developed in Unity simulating simple obstacle avoidance. The obstacle game is displayed on a large screen in front of the rigidly mounted control panel, as seen in Figure 18. The operator can control the red cube via the right joystick of the control panel. The simulation requires test subjects to maneuver the rover away from obstacles (grey) while the rover moves at a continuous speed forward. The simulation records primarily obstacle collision data for post processing alignment with the recorded Arduino data to rank different control panels relative to each other and improve before the next iteration is integrated to the VERTEX rover.

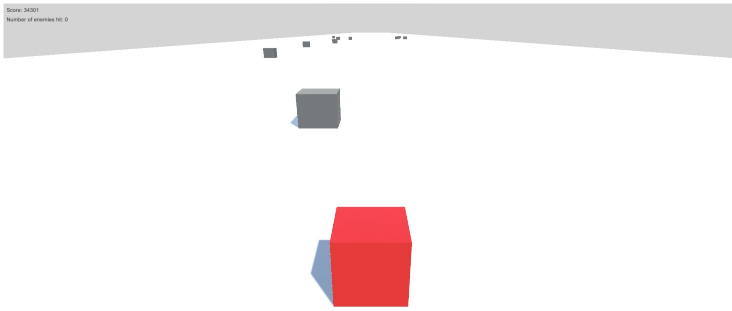

Figure 18. Unity driving simulator with generated obstacles

Figure 19. Operator with Tobii 2 Pro tracking glasses

4. *Eye Tracking Glasses*

A pair of Tobii Pro Glasses 2 eye-tracking glasses were used during each of the tests, alongside the Tobii Pro Lab software suite to help better understand which information media the test subjects refer to the most. Two metrics can be used with this system to justify design. First is the visualization of the precision and accuracy of eye fixations on the panels using generated heat maps looking at the width of the nodal areas in a fixation-count type heat map as shown in Figures 21, 22, and 23. Second is showing the duration of visits where the eyes spend the most time fixating in a specific area with a fixation-duration heat map. By evaluating these items separately, the panels can likely be improved by identifying areas high or low visibility and changing the panel layout accordingly with respect to importance and urgency of each of the panel's components.

B. Results

The RTRS ran 3 times per panel, with a new subject per test. Each test had a duration of three minutes, measuring the operators reaction times, navigation error, visibility, and task load.

1. *Task Reaction Times*

Using the system to measure the operator's time to completion for each task, the average total task time was found for suspension and steering selection tasks. These time averages across all three subjects for each task type and overall averages were plotted for comparison in Figure 20. There is a significant difference in completion times between configuration 2 (button components) and configurations 1 and 3 (dial components). Faster times for configuration 2 reveal the value in the simplicity of button operations. The button press proved to be significantly faster than clicking through each dial to reach the desired setting.

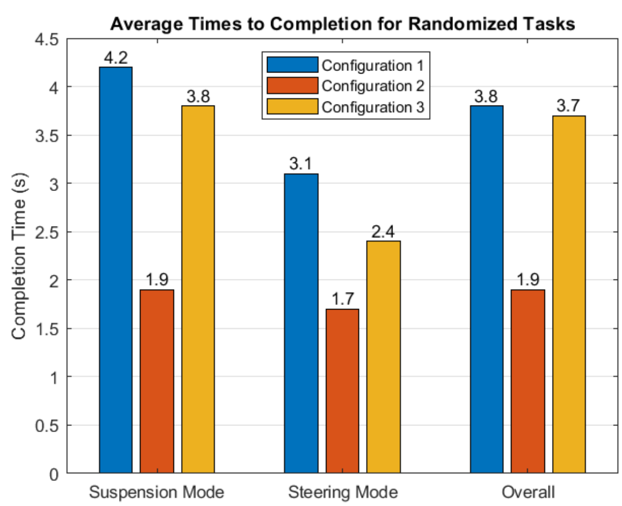

Figure 20. Clustered bar graph of reaction times

Configuration 1 had longer steering and suspension mode task times than in configuration 3. This is likely due to the placement of the rightmost steering dial on configuration 1 requiring a farther reach with the left hand. Since the operator will be driving with their right hand, operators will take longer to reach the rightmost panel with their left hand. However, differentiation placement of components between the center left and center right panels may not be as significant as the steering mode column shows configuration 3 with a faster completion time than configuration 1. This result is more likely due to a compounding effect of the display reading and processing times before switch actuation.

2. Average Navigation Errors

Each time an operator contacted an obstacle in the driving emulator, an error was recorded. Errors are used to partially quantify the level of distraction each configuration induces on the operator. After averaging and rounding across each test, configuration 1 had the most errors at 26, while configuration 2 had the least with 12. Configuration 3 saw an average of 17 collisions, suggesting component or display placement has a significant impact when compared with configuration 1. Configuration 2's low errors point to another advantage in the simplicity of buttons. It should be noted that the individuals who performed this test had extensive experience with the RTRS system before collecting this data, but no learning curve was quantified during these tests and may have been a small factor.

3. Visibility

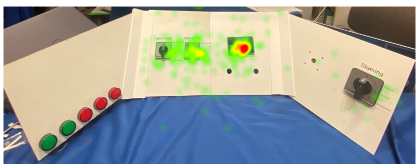

Figure 21. Configuration 1 heat map with fixation count

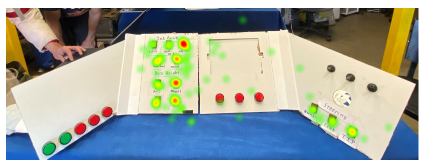

Figure 22. Configuration 2 heat map with fixation count

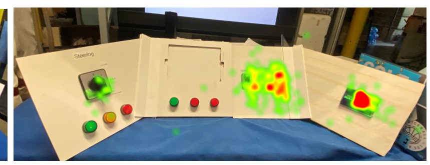

Figure 23. Configuration 3 heat map with fixation count

Using the Tobii 2 Eye Tracking Glasses and Tobii's Pro Lab software, heat maps were generated using assisted mapping. As aforementioned, both duration and fixation count heat maps were generated for each configuration across the test subjects. In each of the figures 21 through 25, red represents areas of high-count, and green represents lower-count in each map style. The fixation count maps (Figures 21, 22, 23) show a stronger concentration of fixation on configuration 3's far left dial when compared to configuration 1's far right dial. These figures also show a high concentration of fixations on the far right display on configuration 3 when compared to the center right display on configuration 1, a result also mirrored in the fixation-duration heatmaps of Figures 24 and 25. This high visual demand of the center right panel of configuration 1 may suggest the far right panel as more desirable as it required less duration for transmission of similar information.

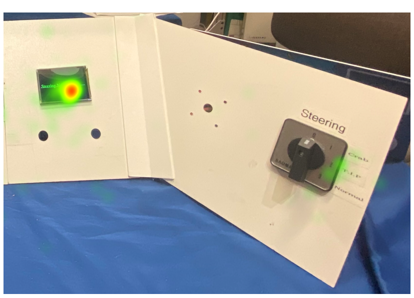

Figure 24. Configuration 1 heat map with fixation duration

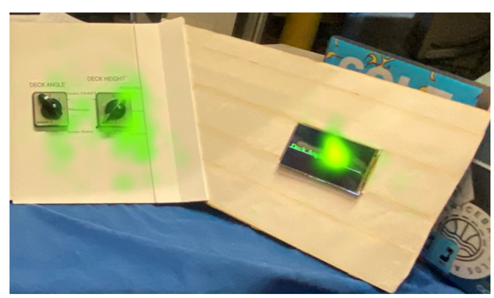

Figure 25. Configuration 3 heat map with fixation duration

Duration of each eye fixation within areas of each interface were also recorded and averaged to understand what dial placement demanded more attention (Figure 26). Configuration 1 demanded the longest fixations for steering, while configuration 3 demanded the least. This may be attributed to the longer time to task completion for a dial on the far right vs. a dial on the far left. Configuration 2 had the longest average duration time for suspension modes. The issue can be attributed to the large number of distributed buttons. A consolidated button layout or a dial could offer faster navigation than a panel with multiple spread-out buttons.

4. *Task Load*

To understand the operator's perspective towards the control panel configurations, the NASA-TLX was assessed immediately following each test. The results show that configuration 1 had the highest rounded task load score of 76 and configuration 2 had the lowest rounded score of 53. Configuration 1 likely had the highest score because of the right most dial causing far reaches. Configurations 1 and 3 displayed higher physical demands likely due to more precise operation required of a dial versus a button.

Operators were also asked to write down aspects of each configuration that worked well and did not work well. A common note was that while strapped into the seat and wearing gloves, using a dial becomes significantly more difficult than pressing a button. Another note said the small button size made it difficult to accurately press in bulky gloves. Lastly, the larger steering dial was easier to operate than the smaller suspension mode dials.

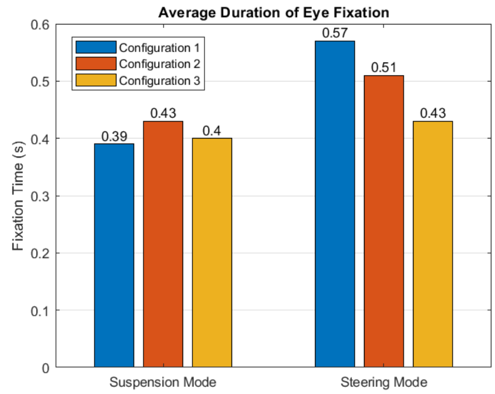

Figure 26. Average eye tracking fixation duration for each configuration

C. Design Conclusions

The RTRS tests provided valuable information regarding component selection and placement for VERTEX'S control panel. With the constraints of a spacesuit, the operation of buttons can be fast and smooth, although possibly requiring additional attention to locate the desired component. Dial operation proved to be more difficult and time costly in comparison and should be left to more time insensitive tasks.

As for button and dial placement, the most costly panel was found to be the far right panel because the operator must reach across the panel with their left hand while operating the rover. The operator will benefit from having most, if not all, interfacing components on the left half of the control panel (barring emergency stop buttons). However, it should be noted displays showed greater visibility and easier fixation when positioned on the far right panel.

It is apparent that there is no clear overall choice for interface components. While buttons work well for smooth operation, dials work better for consolidation and panel simplicity and the integrated panel reflects this.

VII. Control Panel Design and Implementation

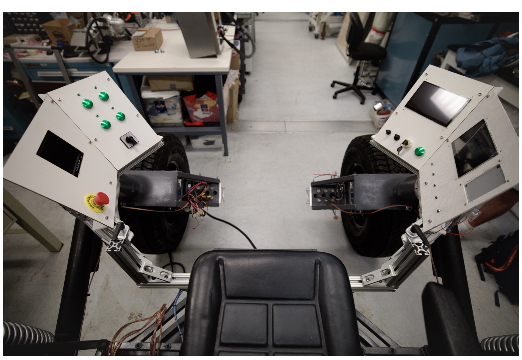

Figure 27. Integrated control panel in open position

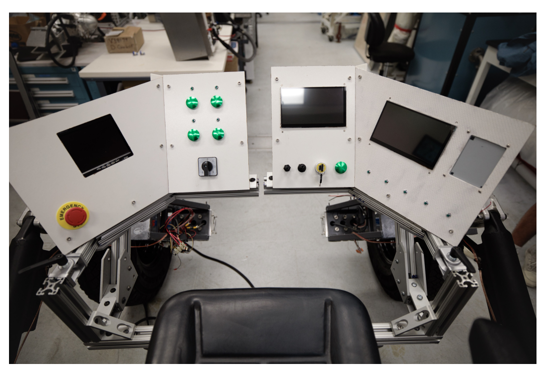

Figure 28. Integrated control panel in closed position

The first integrated design utilizes both buttons for steering modes and dials for suspension modes to maximize each of their benefits. Steering modes are expected to be changed frequently depending on terrain, thus lending advantage to buttons and have been simplified to a 4 button layout. Suspension modes utilize dials which reduces panel clutter and is not expected to be changed from auto-leveling often. The panel has displays featured on the right side of the control panel, with all interfacing components and a battery management screen positioned on the left half. The panels can be found in Figures 27 and 28 integrated to the rover.

Moving from left to right across the panels, the far left segment contains an E-stop next the the more accessible hand of the astronaut and the battery management system screen. The center left panel has the four buttons for steering and one multi-position rotary switch for suspension control. The four buttons will each activate the Ackermann, Rear Wheel Steering, Crab, and In Place steering modes. To activate Double Ackermann, the astronaut will press both Ackermann and Rear Wheel Steering, preventing additional clutter. Each button is accommodated by an LED indicator. The center right panel contains one IPS screen for driving data, two switches for auxiliary accessories like lights, a two-position key start, and a button for vehicle startup. The two-position key start allows for the rover to activate non-driving electronics or all electronics depending on the selection, similar to a typical car ignition switch. The far right panel contains an array of indicator lights for monitoring the status of simple systems, an additional IPS screen for less driving-focused data, and an e-ink display for low-refresh rate but highly-critical data. The right panel only has informational components because it is the least accessible, yet most visible panel.

Final selection of data placement on specific panels has yet to occur, and will likely change continuously throughout the first few months of driving the rover. Items such as a hazcam display could be put on whichever display is most preferable, aiding in any blind-spot compensation.

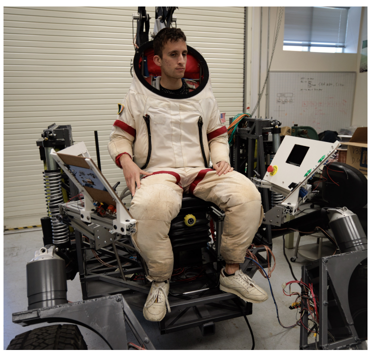

Figure 29. Integrated control panel in open position with test subject

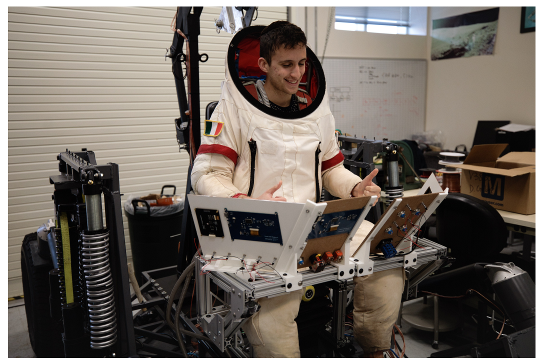

Figure 30. Integrated control panel in closed position with test subject

As the first iteration of VERTEX'S control panel, the design will reinforce previous findings and identify areas of improvement. In the next phase, conducting additional tests on specific features will further tailor the panel to fit VERTEX'S needs. Applying the early testing and the Real-Time Rover Simulation has provided strong, objective insights into the selection and placement of components, which establishes a sturdy foundation for further design and enhancement.

VIII. Seating and Restraints

A new Portable Life Support System (PLSS) series is under development at the SSL for the purpose of evaluating the BioBot concept's astronaut-assistance focused architecture. Each astronaut will carry a minimum functional life-support backpack to house solid-state cooling and ventilation, which will carry mounts for a series of volumetric and mass simulators for untethered EVA activity shown in table 1.

Unit	Duration (min)	Size (cm)	Lunar weight (kg)
Cooling and Ventilation	N/A	30x15x8	TBD
Short	20-40	50x22x22	3
Medium	240	50x50x22	10
Long	480	50x74x22	17

Table 1. Suit simulator portable life support system sizing

Due to VERTEX's unpressurized nature, it must be compatible with the various PLSS sizes in the SSL's upcoming

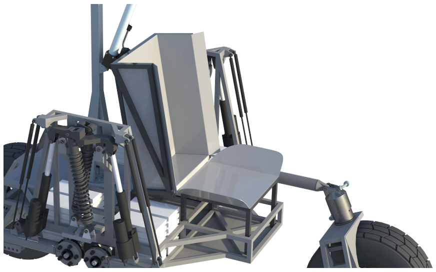

Figure 31. Bent sheet steel and welded seat chassis concept

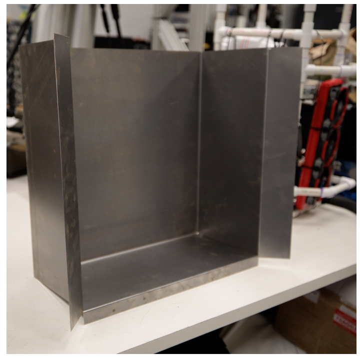

Figure 32. Bent sheet metal seat back - will be installed in a welded structure

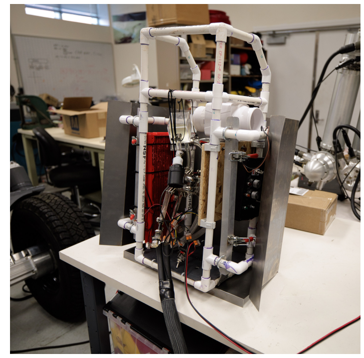

Figure 33. Bent sheet metal seat back with prototype suit backpack installed

lineup. A rectangular, semi-form-fitting cavity has been designed into the EVA seat to provide room for each backpack, as seen in Figures 31, 32, and 33. Unlike the upcoming Artemis suit architecture, the new MX-D suits being developed in-house are not Hard Upper Torso (HUT) style but rather are fabric suits with high-fidelity mobility restrictions. This is one scenario where the use of the upcoming hard upper torsos in the xEVAS suit may provide benefit, potentially allowing for a direct and semi-rigid connection using this hard structure between the astronaut and seat without the astronaut engaging any restraints. The EVA seat fabricated in Figures 32 and 33 is focused on the Medium size to create a smaller seatback to maintain clearance for other systems like the umbilical tending robotic arm, and it is expected that test subjects will not percieve a large difference in a 14cm shorter seat than if it were to conform to the Long size.

To reduce fatigue generated by flexing joints in a pressurized suit, armrests will be adjusted to conform as much as possible to a relaxed body posture used when driving and will be integrated with the final control panel. The armrests will support the astronaut's arm both vertically and laterally to prevent the astronaut's elbows from naturally splaying out further than the joystick operation pose due to suit pressurization. A similar strategy may need to be implemented with the subject's knees, all of which are intended to increase stability and with the astronaut subconsciously perceiving their stability.

Figure 34. Initial testing of a seat concept by volunteer ENAE100 team

The main restraint systems are a source of continual conflict between appropriately securing the astronaut, and restraining them to a point of safety concern. In the event of a rollover or significant anomaly, simple latch mechanisms need to be both easy to release (ideally with one hand) but 2-fault tolerant so as to not unlatch accidentally. Furthermore, restraints need to be accessible within easy working space of the astronaut hands for both reaching and buckling. Restraints must also respect "keep out" zones for any VERTEX peripheral payloads like the umbilical tending manipulator, any wheel zones, or any overhead roll-cage effectively eliminating overhead bound restraints. A first iteration of restraints that may satisfy these conditions is shown in Figure 34. A four-point commercial webbing harness was purchased and integrated with an early-prototype seat and found to be somewhat difficult to secure but was easy to remove while wearing gloves. The next iteration will likely include 3D printed grip-aids to help astronauts affix the belts without full hand dexterity.

Acknowledgments

The authors would like to thank the NASA Innovative Advanced Concepts (NIAC) program as well as the 2021 Moon-to-Mars eXploration Systems and Habitation (M2M X-Hab) program as supporters of VERTEX over the last three years of development. Additionally, the authors would like to thank the following volunteers for their work and contribution in concepts and prototyping as a part of ENAE100: Chris Kingsley (mentor), Joshua Sambrano, Bence Szego, Dira De Andrade, Sathya Gopalakrishnan, Sam Ondrusek, Chethin Gamage, Daniel Mehreteab, Jesus Quintana, Benjamin Kraft, Sravanthi Papolu, and Mathew Scholl.

References

[1] Earl Swift. *Across the Airless Wilds: The Lunar Rover and the Triumph of the Final Moon Landings*. Custom House/Harper Collins, July 2021.

[2] NASA. *LTV Industry Day Aug 2022 Presentation.pptx*. Online. Accessed: 2022-28-10. URL: `https://sam.gov/opp/16c5e42788c4406d8687cb22ec5d3a70/view`.

[3] Nicolas Bolatto, Robert Fink IV, Joshua Martin, Zachary Lachance, Rahul Vishnoi, and David Akin. "Development of an Autonomous Umbilical Tending System for Rover-Supported Surface EVAs". In: *51st International Conference on Environmental Systems*. ICES-2022-361. July 2022.

[4] Charles Hanner, Nicolas Bolatto, Joshua Martin, Daniil Gribok, and David Akin. "Development and Testing of the BioBot EVA Support System". In: *51st International Conference on Environmental Systems*. July 2022.