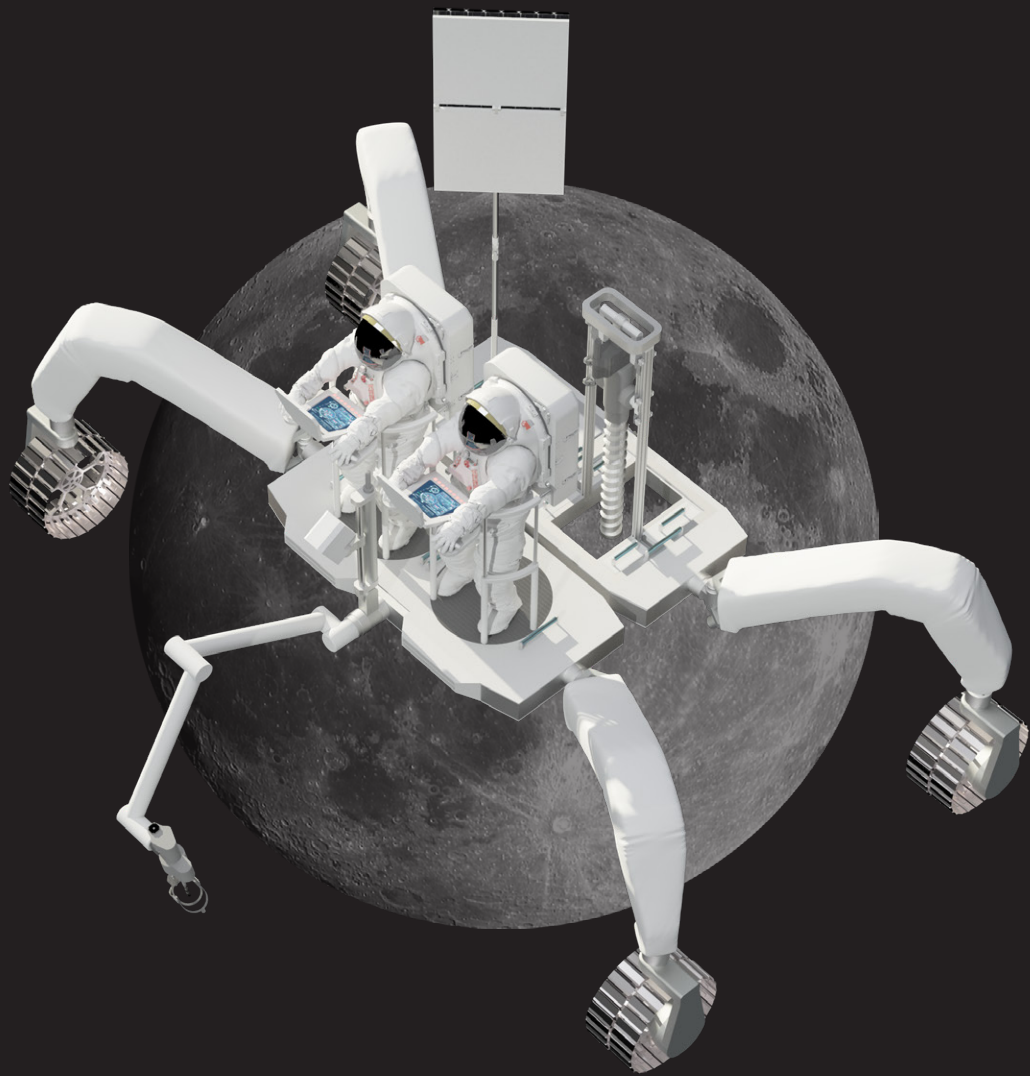
SICSA
Sasakawa International Center for Space Architecture

MUV

UNIVERSITY of HOUSTON

MODULAR UTILITY VEICHLE

RASC - AL COMPETITION REPORT



VITTORIO NETTI - TEAM LEADER
Graduate Student - Sakasawa International Center for Space Architecture / UH

PETE MORGAN-DIMMICK
Graduate Student - Sakasawa International Center for Space Architecture / UH

JAVIER LOPEZ JR.
Graduate Student - Sakasawa International Center for Space Architecture / UH

OLGA BANNOVA - FACULTY ADVISOR
Program Director - Sakasawa International Center for Space Architecture / UH

INDEX

ABSTRACT

MUV - Modular Utility Vehicle for South Lunar Pole

This paper presents a concept for an unpressurized Lunar Rover, called the Modular Utility Vehicle (MUV), as a feasible design for a modular, upgradeable, telerobotically operated and manned rover for navigating the Lunar South Pole. Its capabilities include payload deployment, water-ice sample collection, geologic analysis, and terrain mapping. The defining aspect of this modular approach enables MUV to fulfil future mission requirements and objectives.

The modular aspects of the vehicle allow it to perform multiple tasks at once, either as a singular unified vehicle, or to be broken into smaller components and used singularly or as a swarm. This allows significant flexibility of vehicle management and the eventual deployment of habitation and scientific structures on the Lunar surface. Modularity also increases redundancy, and adds options for mitigating vehicle damage, failed components, or emergency return to the lander.

The basic vehicle design is made up of a single chassis. The chassis has an outfitted mass of approximately 150kg and can support 30x its own weight. Nominally operated in pairs of two, each chassis provides two payload bays, two utility bays, 1.6kWh of batteries, computers, keep alive functions, communications, and four external connections to mate-up with more chassis, drive mechanisms, or robotic manipulators.

Payload bays provide the vehicles' primary interface though the installation of human drive controls, science packages, or capability expansions such as extra batteries to help it to survive the 14-day long Lunar nights. The vehicle follows a 1.4 factor of safety to meet NASA's human safety requirements and has a minimum driving range of 28.5 km, assuming no solar power availability to recharge the batteries.

The general operational concept of the vehicle allows crews on Earth or the Lunar Gateway to perform tedious and potentially dangerous terrain mapping in preparation to receive a crew on the Lunar surface. The rover identifies areas of interest that human crews will later examine for samples and water-ice collection for eventual return to Earth. Once the crew arrives, they will reconfigure the rover to operate as a human surface transportation system.

Crews, both on and off the Lunar surface, will be aided in Navigation by LIDAR, cameras, auto-drive features, and augmented reality. Most technologies are at a readiness level 9, and many have a flight-proven history. No significant advancements in technology must be made for the feasibility of the design

NOMENCLATURE

NASA	= National Air and Space Administration
ATHLETE	= All-Terrain Hex-Limbed Extra-Terrestrial Explorer
CNES	= Centre national d'études spatiales
ESA	= European Space Agency
HRI	= Human-Robot Interaction
JPL	= Jet Propulsion Laboratory
LIDAR	= Light Detection and Ranging
LRV	= Lunar Roving Vehicle
MUV	= Modular Utility Vehicle
RASC-AL	= Revolutionary Aerospace Systems Concepts Academic Linkage
TRL	= Technology Readiness Level
COTS	= Commercial Off-The-Shelf

1. INTRODUCTION

As NASA prepares to return people to the moon for the first time in nearly half a century, we will enter a place no human has ever visited before - the Lunar South Pole. A strange place of constant twilight, eternally dark shadows and eternally lit peaks; the sun always skirts the horizon and light and shadow differ by ~300°. But hidden within this eternal dusk lies a resource critical to humanity's next steps into the solar system: water. (10)

For astronauts to safely live and work in such an extreme environment will require major risk minimizing strategies. We must understand what is there, both as a reasonable method of ensuring our astronauts' safety, and also as laid forth within the RASC-AL requirements: must provide a method of transportation, create maps, develop infrastructure, find safe places to land, and identify and study areas of interest and high priority science.

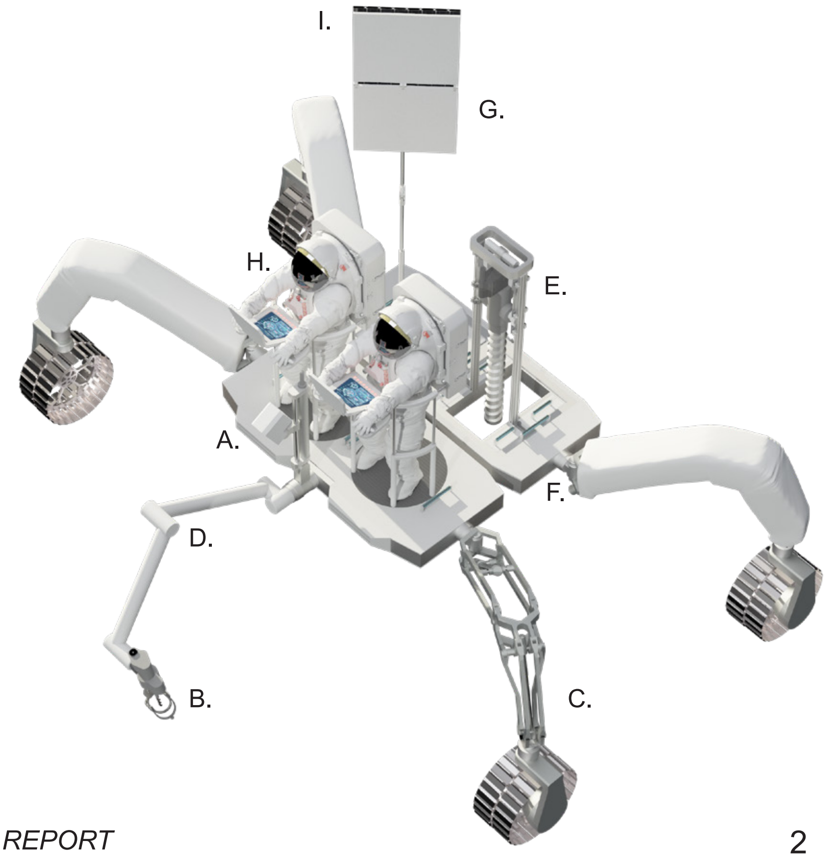
Responding to these unique challenges in such an unusual environment requires a unique, innovative, and flexible solution: modularity. We need to build a rover that has what we need, when we need it, and retain the capability to upgrade and improve the vehicle as the mission dictates. Split the operations between telerobotics and human interfaces, and capitalize on strengths that each mode presents.

In addition to the general usefulness and functionality on the Lunar Surface, the design must meet reasonable engineering requirements set forth by NASA and RASC-AL. The rover must be ready to meet the 2024 boots-on-the-moon deadline, weigh less than 300kg, and cost less than $300mil. All functions, manned and unmanned, must be included within these constraints. The rover is also to be unpressurized, able to transport two people, and function for a minimum of 6 days on the Lunar surface. After the crew departs, the rover is to revert back to robotic mode (RASC-AL).

Since the initial proposal, the team made several critical improvements in MUV design: the chassis design was upgraded after performing finite element analysis (4.2); we estimated power requirements per each payload and proposed power management with embedded redundancy (4.3); after acquiring mass properties for each of the MUV components and assemblies we performed a realistic mass estimate (4.1). We confirmed with providers of the proposed science package and MUV systems that all equipment is at least at TRL6 or higher.

COMPONENTS

A. ChemCam
B. Ropec Drill
C. 5-DOF Legs
D. Robotic Arm
E. Volatile Extractor
F. Hotdock Interface
G. Radiators (Deployable)
H. Control Post (Deployable)
I. Solar Panels (Deployable)



2. DESIGN CONCEPT

The MUV proposal uses modularity in a new and innovative way. Rather than building a vehicle in parts due to launch vehicle necessity, the vehicle is built for expandability and versatility. The Lunar South Pole presents unknown conditions, a place where we cannot even predict what we do not know. Rather than attempt to justify a large and expensive “do everything” rover, and solicit proposals for science packages, assemble, launch and integrate it all into the Artemis program within a 3 year limit, the MUV lays a foundation for growth and expansion. This allows for new science to be developed, delivered, and integrated into later Artemis missions without having to start design and development all over again. The discoveries of each mission will dictate the additions and science packages that fly in later missions so that the useful life of the vehicle becomes indefinite as parts are upgraded, added, and replaced as necessary.

Our team performed trade studies comparing advantages and challenges of building an all-up rover versus a modular one and discovered that while an all-up rover may be a considerably less challenging design, it will be significantly less useful and future-proof. It is not adaptable to future needs, technological improvements, or updated mission requirements.

A singular and more typical asset like NASA’s upcoming VIPER rover can function exquisitely for the job it is initially tasked for, but once that mission is completed the usefulness of the vehicle significantly diminishes without a possibility to integrate new functions or deploy new scientific payloads (13).
This uniquely expandable architecture allows for three mission Phases to grow and adapt along as the Artemis program progresses. The modularity likewise opens up new possibilities of human-robot interaction, exploration, safety, and redundancy.

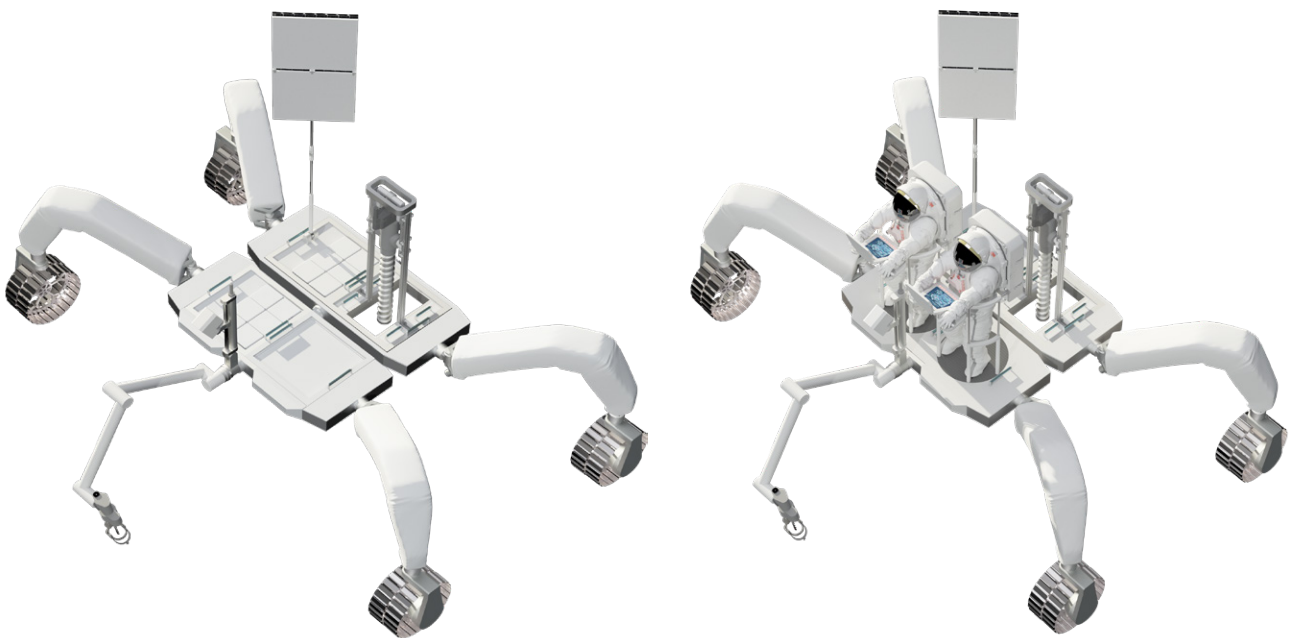


Fig 1. The two main configurations: Teleoperated (Phase I) and Manned (Phase II)

2.1 MODULAR ARCHITECTURE

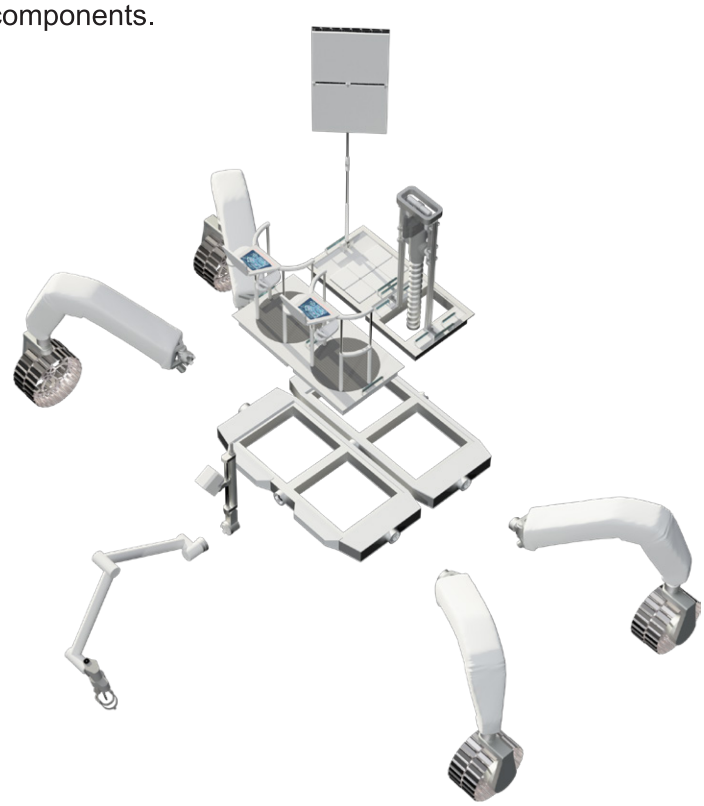
MUV Rover inherits the same modularity typical of the new generation military vehicles. The different subsystems are treated as independent, interchangeable units. To pursue this objective, MUV is based on a central chassis that is the main structural unit of the rover. The chassis includes two different kinds of interfaces, that are used to connect the modular hardware units to the structural core.

The Hotdock interface: a COTS docking system produced by Space Applications LTD. It provides structural connection, power and data transfer with the mobility units (Legs) and other modular Chassis. Each Chassis is provided with 4 Hotdock interfaces.

The Payload Slots: each square slot hosts the standardized 750mm payload Box. The slot also provides power, data and fluids exchange with the payload boxes and their content. There are two payload slots in each chassis. Both Payload Slots and Hotdock interfaces can be operated by human crews or robotically, to achieve maximum flexibility.

The modularity of MUV has two purposes: it allows mission specific requirements to be met, adapting the vehicle structure to new tasks and increasing reliability of the system, grants the capability to easily swap malfunctioning components.

Fig 2. Exploded view of the different MUV components



2.2 ATTITUDE CONTROL

The attitude control of the vehicle is granted by the mobility unit. Each unit is composed by a multi-terrain, independent wheel, developed by ODG LTD. and a 5 DoF robotic leg, directly derived from the original ATHLETE concept and the SherpaTT rover. The function of the mobility system is to provide a perfect attitude control on the steep slopes of the lunar craters, keeping the chassis always parallel to ground and providing real-time adjustments on the center of mass of the vehicle. Stable mobility is one of the main design drivers of MUV. This is a central matter for this project for many reasons:

- The new xEMU suits, developed by NASA and ILC Dover for the Artemis program are the heaviest suits ever built (around 200Kg) due to new rear access capability, which is heavily unbalanced on the backpack area. Managing this heavy payload (⅔ of the rover weight, without considering the astronauts weight) even a mild slope can become very dangerous for the stability of the entire vehicle.
- Even if greatly improved from the A7s Suits, the astronauts visibility is very limited, espe cially on the sides.
- MUV grants a greatly improved visibility, thanks to the ability to dynamically change the

height of its chassis.

- MUV can utilize its own weight to increase penetration power when using the Volatile Ext ractor by progressively lowering the chassis.
- The attitude control system is used to allow easy access to the control post for the crews.

Fig 3. The Mobility Unit attitude control

3. OPERATIONS CONCEPT

For the initial Phase I and Phase II of the mission, the rover will be primarily equipped to map the Lunar surface in preparation for crew arrival (Phase I), and perform ice-water sample analysis and collection for return (Phase II). A Phase III, used for base building and outpost establishment will not be covered here, but the modular design of the rover allows it to function as a truck, mobile science platform, or to perform new unforeseen functions.

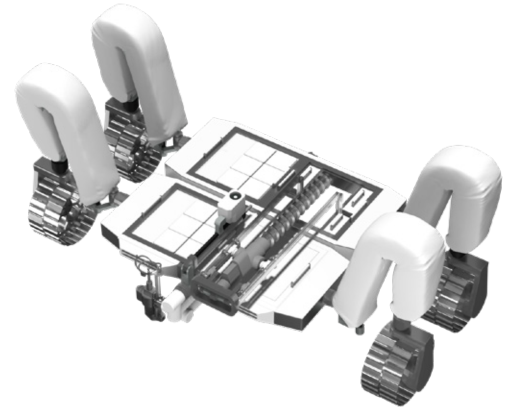
In *Phase I*, the rover will be initially controlled from Earth or the Gateway. Its primary function is to find areas of interest for later crew exploration, look for water ice, and perform geology and mineralogy analysis of the surrounding area. This is a similar function to tasks of NASA's Lunar Reconnaissance Orbiter, but at a more detailed level.

Phase II starts when the crew arrives on the Lunar surface, bringing with them the interfaces needed to drive the rover manually. The most of the water-ice analysis will occur at this phase. Since there is not much data about material properties of Lunar water-ice, it was decided that the best course of action will be to let the crew conduct the research. During this phase construction of an operational Lunar infrastructure will begin. The crew can deploy science packages, waypoints, material, and experiments not intrinsic to the rover itself. This, combined with the 3D map produced by the rover earlier will help to further integrate this area of the Moon into working domicile for humans as space faring species. The rover will not be deprecated after the Artemis crew departs. It will revert under telerobotic control and continue performing scientific investigations and mapping the area prior to the next crew arrival. The rover can be reused at the same landing site, or travel to the next landing site and wait for a new crew there, provided the traverse terrain is passable. Reuse of a rover for multiple missions and different landing sites was not possible during the Apollo missions. MUV will be the first multimission reusable rover.

3.1 INITIAL DEPLOYMENT

The MUV platform is delivered on the surface from a self-propelled Lander such as the one designed by NASA for the Viper Rover, or the Blue Moon commercial lander designed by Blue Origin.

MUV will land in a stowed configuration, to occupy less space and to reduce the effect of Launch forces and vibration on critical components. For the first phase, MUV is landed in the teleoperated configuration, composed by:



- 2 Chassis
- 4 Mobility units
- Volatile Extractor and analyzer
- 2 sample collection and storage containers
- Processing computer for autonomous science
- ChemCAM
- Robotic Arm and abrasion drill

Fig 4. MUV In stowed configuration

After the landing, the rover will be powered up and it will run a subsystem diagnostic. Once completed, MUV will start the nominal operations.
The first year of operations will be conducted using both the autonomous science computer and teleoperated scenarios using the first nucleus of the Lunar Gateway as local mission control.

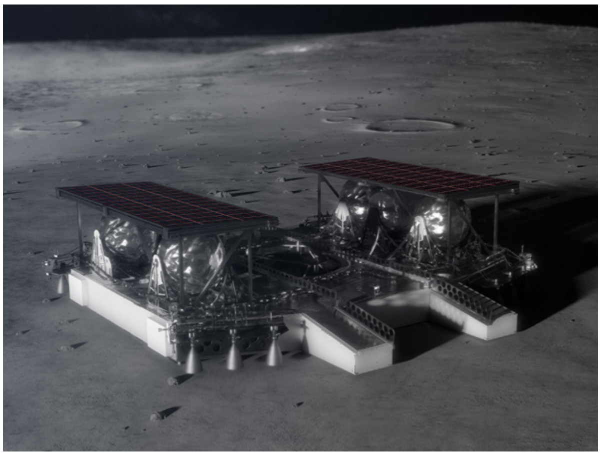


Fig 5. NASA VIPER Lander

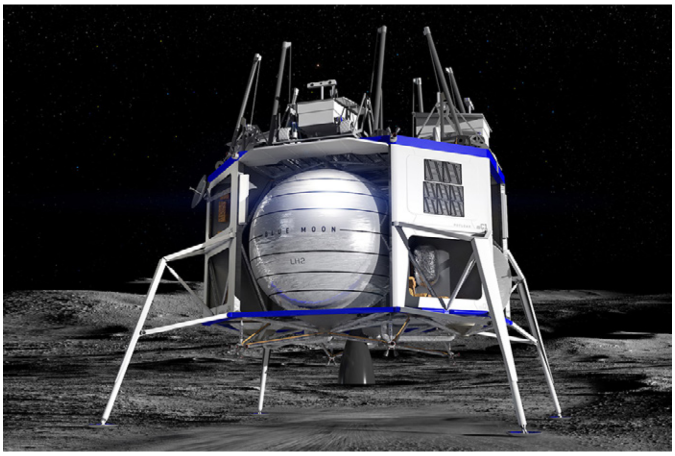


Fig.6 Blue Origin Blue Moon Lander

3.2 MODE SWITCH

After the first crewed moon landing, the astronaut crew will meet MUV near the designated landing area, carrying with them the two Manned Control Units.
Once reached the rover astronauts crews will disconnect BOX 1 and 2, in order to exchange them with the MCUs. The collected Central Processing Unit and Sample collection Container will be stored in the crewed lander in order to be sent back to the Lunar Gateway for further analysis. The two MCU are connected in stowed configuration, powered up and deployed. From that moment on, even if teleoperations will still be possible thanks to the internal computer of the chassis, autonomous operations cannot be performed anymore since the Autonomous Science Computer has been removed.
Each MCU includes a computer with a dual touchscreen, able to control both the rover telemetry or the scientific payload data and two physical 3 axis controllers for the direct control of the MUV mobility units or the robotic arm. The Touchscreen can be collapsed to preserve their functionality from the environmental action (sun, radiations, micrometeoroids and lunar dust) when they are not used to control the rover.

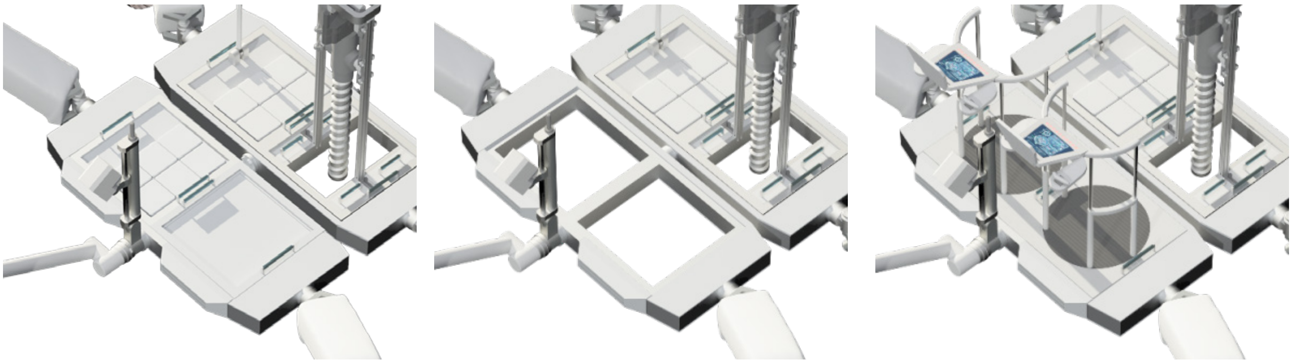


Fig 7. Mode Switch Sequence

3.3 CONTROL MODE TRANSFER

A unique and significant advantage of the MUV over a more typical rover is the ability to operate the rover both telerobotically from Mission Control or the Gateway (generally just referred to as Mission Control in this section), or to be driven directly by crew on the Lunar surface. This unique capability provides the rover a much longer useful lifespan, as it is capable of performing science long before the crew arrive, and long after they depart. Such capability saves money and reduces the need to launch more rovers or additional infrastructure to the Lunar Surface.
Switching between local control and telerobotic control modes is handled via software. That negates the risk of leaving a toggle switch in the wrong position and locking the ground out after the crew leaves the Lunar surface. It also works when the crew arrives. A broken toggle switch could prevent them from overriding ground control of the vehicle.

To activate telerbotic mode, a command will be sent from Earth or the Gateway prompting a notification on the MUV's interface panel. If the crew accepts the notification, or if the notification times out after 3 minutes of no crew input, the vehicle will transition into telerobotics mode. The timeout is included so that the command and method of gaining control remains the same regardless of crew availability. Crew also has the ability to reject the command.

The transition back to crew control works the same way with the option to keep payloads running during the handover. The crew selects the proper command from the vehicle's control panel. The vehicle calls home for approval. If Mission Control acknowledges the command or if the command times out the crew is given control of the vehicle. The timeout is intended to allow mode transitions during periods of no-comm, reduced staffing in Mission Control or other situations to give the ground time to react to the request.

Both the crew and Mission Control have the ability to reject mode transition commands, to avoid situations when one or the other mistakenly initiates transitions, and then calls up/down a request to ignore it. To minimize potential risks of errors, all nominal mode transitions will be scheduled and discussed between Mission Control, Gateway, and the Lunar surface crew.
Control can also be shared between the crew and Mission Control to allow non-interrupted scientific processes while the crew drives or during joint operations of different payloads.

For *emergency response*, there are 3 hardwired push buttons on each control panel to allow the crew to take immediate control of the MUV or shut it down. This is critical for crew safety - dangerous situations can develop rapidly without time for Mission Control to assist.
Emergency Stop ceases all motor functions, including wheels, legs, drills, and manipulators. The rover freezes in its current position. The rover may slide or jolt if used while in motion. The intent is to stop the rover from overcoming dangerous terrain, damaging a drilling payload, or creating a physical hazard to the crew.
Emergency Shutdown immediately cuts power to the vehicle's power busses. This is intended for cases of electrical arcing, overheating, or when the crew is faced with an electrical danger. Primary

avionics are shut down and the rover goes into standby-mode with reduced low power communications.
Emergency Control immediately provides direct control of the payloads and motor functions in their current state to the crew and can be used in conjunction with an Emergency Stop. It will be used if the crew needs to rapidly repack a payload or abort an EVA and get back to the lander as soon as possible.
All three modes can be overridden with a series of commands to restore nominal crew or telerobotic control once the situation is assessed to be safe. These commands can be executed by crew or ground, but in practice the ground will evaluate the situation with the crew before enacting any changes.

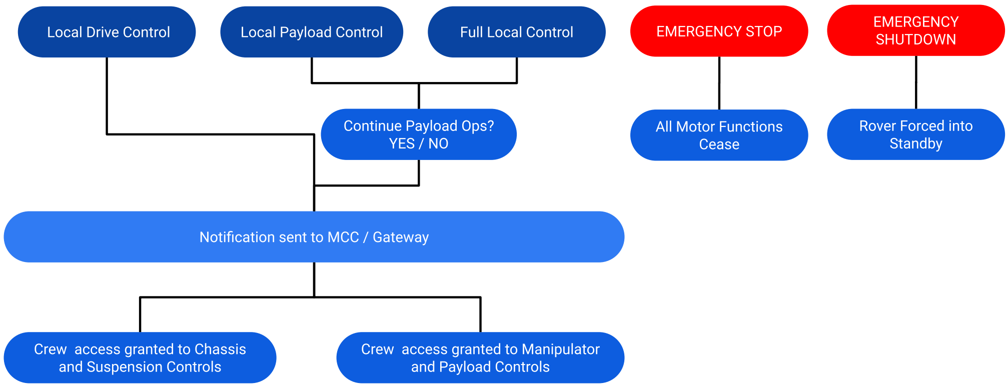


Fig 8. Crew Control flow chart

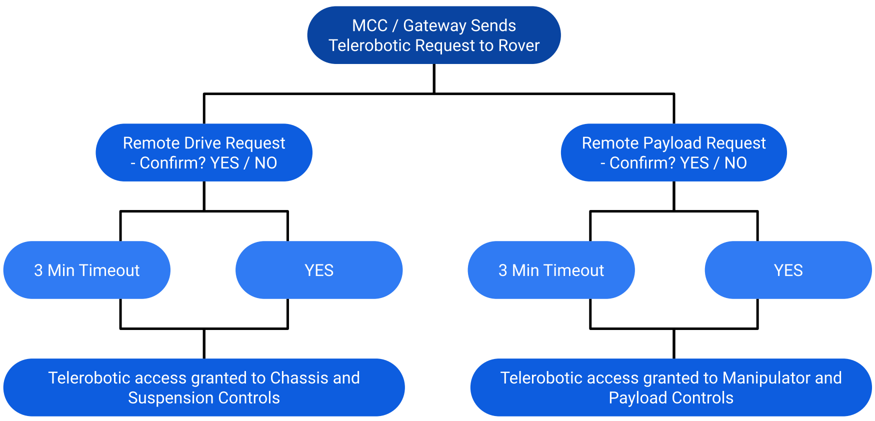


Fig 9. Remote Control flow chart

4. TECHNICAL SPECIFICATIONS

The basic vehicle design is made up of a single chassis that will nominally function in pairs of two. Each chassis has an outfitted mass of approximately 150kg and can support 30x its own weight while deflecting less than 1mm. Design and material testing was performed and verified using SolidWorks. Aluminum 7075 was initially selected as the standard material for aerospace applications, but this was later changed to Aluminum 2219. Though slightly heavier, Aluminum 2219 retains its material strength and properties when brought down to near absolute zero - the temperature at which MUV will operate in the crater floors harboring lunar water-ice (18). Nominally operated in pairs of two, each chassis provides two payload bays, two utility bays, 1.6kWh of batteries, computers, keep alive functions, communications, and four external connections to mate-up with more chassis, drive mechanisms, or robotic manipulators.

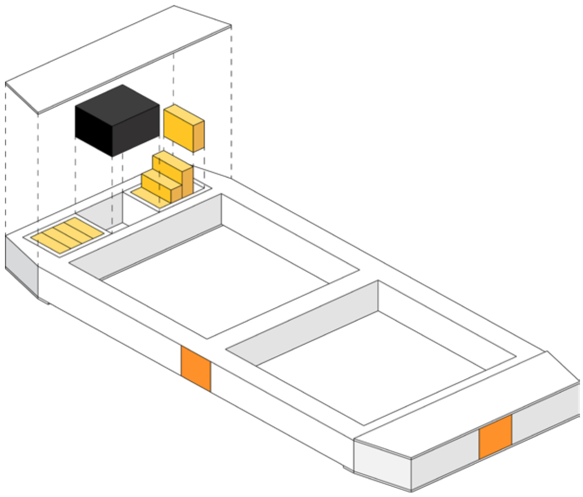


Fig. 10 Chassis Schematic

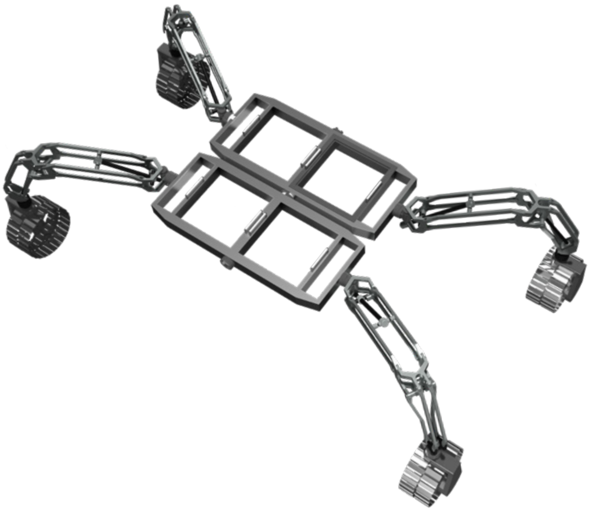


Fig. 11 MUV Core Structure

Primary external connections between chassis are provided by the Hotdock circular docking connectors. Each connector is capable of transferring power and data, and can withstand forces up to 8.0 kN (Linear) and 600 Nm (Bending). The notional configuration as proposed to RASC-AL is two Hotdock connectors and will be used for suspension and wheel connections. One connection will be used for a robotic manipulator, and the remaining connection will be used to connect the front chassis with the back chassis. The back chassis likewise has two connections to suspensions and wheels.

Each chassis has two 28V 10A-limited busses tied in parallel. Each bus is subsequently powered by two 2 Enersys ABSL 8s10p batteries rated at 28V and 15Ah each (11). This parallel configuration was selected for redundancy and to reduce load on the batteries, rather than power. Maximum power output is 560W and each bus can receive power from feed power to the other bus, other connected chassis, or a solar panel. This provides a conservative estimated minimum drive distance without recharging. Calculations are provided in the appendix section 4. The limiting factor of operational distance is not the batteries, but the maximum distance an astronaut can walk back to the lander in the unlikely case the vehicle gets stranded and is unable to be reconfigured to limp back to base.

The avionics package selected for command and control in each chassis is the Nvidia Jetson AGX that was chosen specifically because it was designed for neural network machine learning and object detection. During Phase I and other telerobotic operations phases the MUV will require a basic onboard intelligence to avoid obstacles and identify areas of interest. Same capability will be used during manned operations to accentuate and improve driver's awareness of the surrounding area using augmented reality and other drive-assist features. Using pre-designed off-the-shelf industry standard hardware reduces overall costs and simplifies programming and integration (15). Primary motive power is provided by a 4 wheel drive system with each chassis supporting the use of two (or more) wheel assemblies and motors mounted on the end of 3m long articulating leg structures. Each structure is actively managed by the vehicle and has 5 degrees of freedom, allowing the vehicle to translate sideways or pivot around itself if needed. Actively managed suspension also provides the ability to traverse slopes up to and beyond 30° while keeping the crew and science packages level to avoid rolling the vehicle. This is a key capability to access the water-ice located at the bottom of craters. Should the situation dictate the individual wheels can be locked and the suspension used as legs to 'walk' or 'climb' out of areas with low traction. Similar suspension capabilities have been proposed for NASA's ATHLETE and ESA's PERASPERA projects (2)

MUV Efficiency Estimate

- 1600 Wh per Chassis * 2 Chassis = 3200 Wh Total
- Assume 65% available for driving = 2080 Wh Available
- 2080 Wh / 67.68 Wh/km = 30.73 km
- 30.73 km / 1.4 (NASA 2016) = 21.95 km total usable distance without recharge*
- Rounded up to 22 km (additional 50m) for initial range estimate without recharge**

Drive Distance Estimates

- Total Distance per charge 22 km
- Roundtrip Outbound Distance = 22 km / 2 = 11 km
- Maximum Radial Distance from Lander with Astronauts = 11 km

Astronaut Walk-Back Capability Verification

- 2.7 km/h Apollo Spacesuit sustained walking speed (5)
- 8 hours nominal spacesuit life support limit (17)
- 2.7 km/h * 8 h = 21 km theoretical maximum walk-back distance
- 21 km walk-back distance > 11km max distance from Lander
- Astronauts can walk back to Lander if MUV were to fail

*NASA's 1.4 Ultimate Factor of Safety was applied to vehicle range for built-in margin.
**Estimated round number with built-in margin. Range capabilities will be further refined as design matures. Currently does not include constant solar recharge rate to baseline worst-case performance.

4.1 MASS BUDGET

For our nominal configuration, MUV consists of a total of 293 components. The entire rover was modeled using SolidWorks and the Mass Properties for each of the components and assemblies were obtained. All the components were grouped into the following categories, chassis, legs, wheels, power/electronics, and science. The mass of each group was tracked throughout the development of the rover to meet the established mass requirement. A summary of the mass properties can be seen below in Table.

4.2 CORE STRUCTURE

The core structure that makes up the MUV consists of two chassis and four mobility units. Each chassis was designed with modularity in mind to accommodate for any type of mission encountered when on the Moon. There are two slots for astronauts to use to operate the rover, place science equipment, and store samples collected from the surface. There are four hot docks as well that can be used to change the configuration of the vehicle if necessary. The mobility units have been designed to provide the rover with five degrees of freedom. By doing so, the rover can easily maneuver through any difficult terrain, maintain the astronauts in a balanced position, and even use the rover itself as weight to use certain equipment like drilling. Before making this decision, a series of finite element analysis was performed on the chassis and leg with the max loads that it would experience under the placed requirements.

First, two chassis were placed in their nominal configuration with a fixed restraint placed on the four hot docks located on the sides. Respective loads were placed along the vehicle using point load masses replicating the mass of the fully suited astronauts, science equipment, and electronics. Once the finite element analysis was completed, we found that there was very little deflection experienced and saw slight stress areas near the fixed location which was expected.

Next, analysis was performed on a single leg by placing a fixed restraint on the wheel and placing the respective load of the rover on the hot dock attachment of the leg. The leg was kept in its nominal configuration for this analysis. Once completed, areas of stress were found near the support of the wheel which was expected since the leg itself would experience a moment with the load applied at the hot dock. There was also very little displacement experienced at the hot dock where the leg is attached to the rover itself.

With this analysis completed, the team felt comfortable moving forward with the selected material and continued with the outfitting of the rover to meet the established requirements.

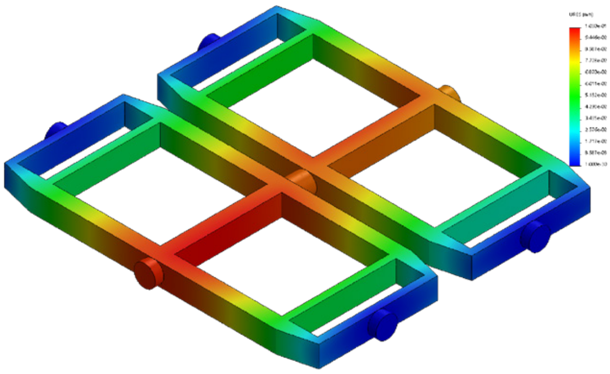


Fig.12 FEM Analysis Chassis

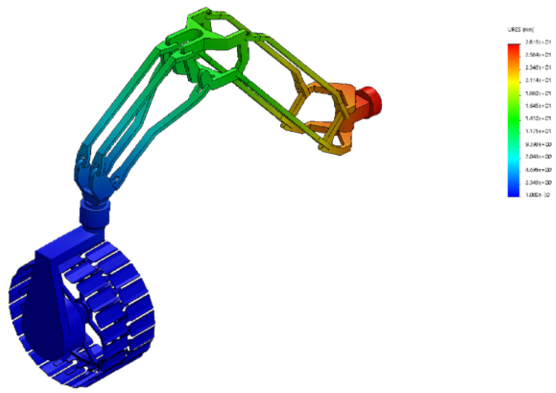


Fig.13 FEM Analysis Mobility Unit

4.3 POWER MANAGEMENT

Due to the modular nature of the vehicle, each chassis must be powered independently, but is nominally operated in pairs of two. Due to the dissimilar configuration of each chassis during nominal operations power sharing is enabled via the chassis HotDock interface to drive motors, recharge batteries, collect solar power, and power various payloads and experiments when and where as needed. The base power bus of each chassis remains the same and data provided in this section will be for the nominal two-chassis configuration.

Each chassis has two 28VDC 15A busses tied in parallel (A bus and B bus). 28VDC is a standard spacecraft voltage and 15A is enough power avionics, communication, thermal management, and two drive motors on a single power bus should one fail. Payloads can also be powered off of a single bus if the vehicle is not moving. Lower amperage also helps to increase astronaut safety during any required power system disconnects and reconnects and allows for narrower gauge wire as a weight saving measure.

The primary power source for each chassis is four (two per circuit) Enersys ABSL 8s10p batteries rated at 28V and 15Ah each (Enersys). Each chassis has a total power availability of 840Wh split evenly between the two busses. Secondary power is nominally provided by a single solar panel on one of the chassis. With an area of 2 square meters the panel can provide 500W at any given time, or 4000Wh over an 8 hour period (the maximum duration of an EVA). Due to the 28VDC and 15am bus limits, solar power is used to replenish or offload the batteries rather than increase total power output at any given time.

During nominal ops, equipment pulls power equally from both busses. With more than one chassis all the A busses are tied together and all B busses are tied together. It is possible to tie an A bus to a B bus, or operate all the chassis busses independently, but this is reserved for contingencies to protect for redundancy and fault protection during nominal operations.

Power requirements for payload and avionics usage was calculated using data provided directly from the various hardware manufacturers or estimated when that data was not available (Larson). Details on each of the payloads can be found in Section 5 - Science Package.

Assuming that most of the time during a manned EVA will be spent driving to the point of interest, and that the payloads will all be run all together at said location for approximately 25% of the total excursion time, that leaves 7092Wh available for driving.

Initial baseline range estimates are based on historical data from the Apollo Lunar Roving Vehicles (LRV) with an efficiency of approximately 81Wh/km (Iclodean). This data was selected due to the roughly similar scope and mass of both the LRV and MUV. Efficiency estimates were then reduced by nearly half to 150Wh/km for the MUV to account for unknowns and the increased spacesuit and payload weight over that of Apollo, and to provide engineering margin. With 7092Wh available and an efficiency of 150Wh/km, the MUV has an 8 hour range of 47km during manned operations. Without the 8 hour life support requirement this can be increased to 100km range during a 24 hour period for unmanned operations assuming sunlight is available.

In practice, manned operations will never range farther than 11km radial distance from the lander, and the farthest points of interest of the excursion will be explored first. This is to protect against a vehicle failure in which the crew must walk back to the lander.

Floodlightlights on the vehicle are powered independently and removable. This is for safety and redundancy. The crew can use them on EVAs as necessary and carry them back to the lander as a light source should the vehicle fail or become stranded.

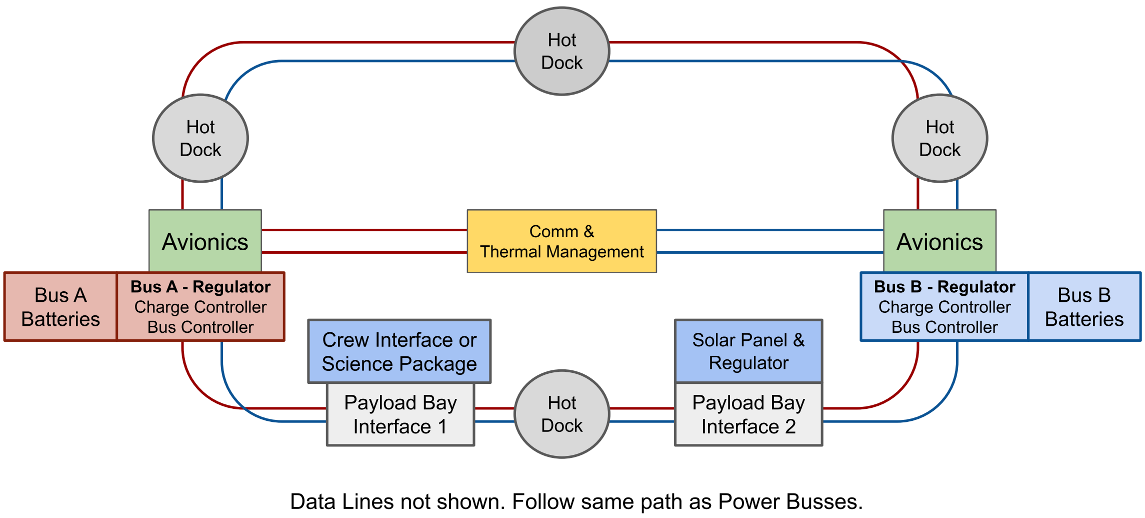


Fig 14. Chassis Power Diagram

4.4 HUMAN INTERFACE

During Phase II the MUV will host two crew members wearing Artemis spacesuits. Astronauts will secure themselves on the rover by clipping into waist-high support structures mounted on movable turntables. The supporting structure reduces the physical exhaustion of the operator by supporting the weight of the suit, managing the center of mass, and avoiding potentially awkward and difficult sitting down while wearing a spacesuit. The turntable provides an easy 360° field of view within the limited peripheral vision and mobility of the suit.
The suspension control previously mentioned enables the MUV to adjust its height for easy one-step on and off level to embark and disembark the vehicle - further reducing strain and effort of the astronaut.

Control is implemented via a screen and two throttle shaped joysticks mounted in front of the astronaut. Due to the harsh lighting conditions and difficulty in seeing grayscale terrain, the vehicle will use its suite of sensors, cameras, LIDAR, and hazard avoidance camera to display ground information to the driver. In case the driver chooses sensors-provided information and 3D mapping capabilities, he/she can see it as a real-time image of the terrain on the screen - simultaneously creating augmented reality on the Moon. While a specific interface still needs refinement, augmented reality itself is at a technology readiness level 9 and has been implemented in diverse consumer products.

Fig.15 Manned Control Unit

Fig.16 MCU Interface

5. SCIENCE PACKAGE

In order to meet the ever-changing needs for the mission, and to be flexible enough for initial use without the benefit of subsequent Artemis missions to outfit and upgrade it, the MUV will launch with the initial science packages installed below.

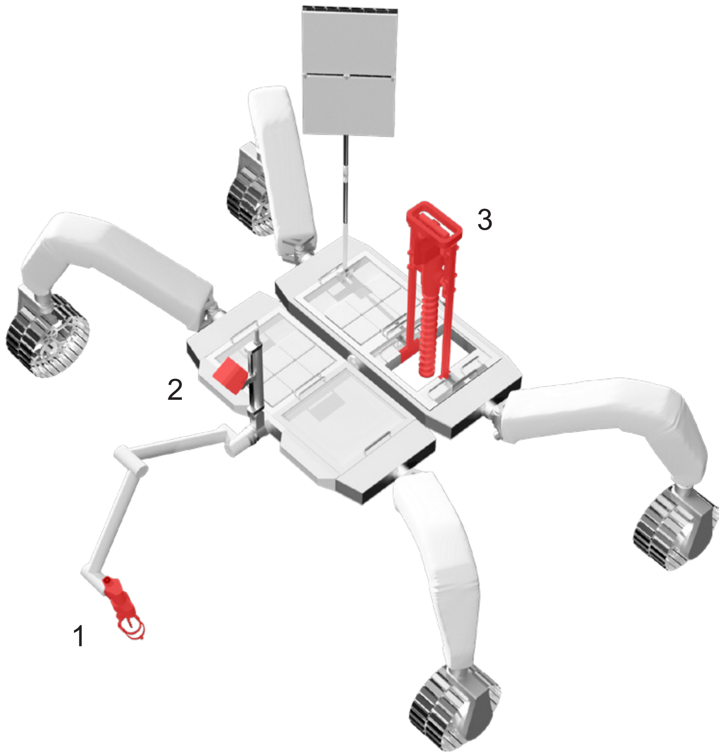


Fig 17. Position of Science payload on the rover

1.ROPEC Drill

2. ChemCAM

3. Volatile Extractor

5.1 MAPPING AND SENSORS

Camera Suite and LIDAR - The MUV utilizes several mature and well defined technologies for navigating on the Lunar surface, mapping the area, and sending images back to Earth and Gateway. Due to the harsh lighting at the Lunar South Pole visual-only navigation is not reliable. To overcome that issue, the MUV makes use of a suite of infrared cameras for cold sinks identification, and LIDAR, to produce a 3D map of the surrounding areas. LIDAR's laser beam will scan outward and measure the return time for the light to come back. This procedure estimates distance, size, shap, and slope to objects even in complete darkness. These technologies are all well developed with previous flight histories, and the maps produced will be fed to a human crew and ground to assist in navigation. These technologies all have a technolo- gy readiness level of 9.
The Neutron Spectrometer is used to detect water ice, and other areas of high Hydrogen content. As ubiquitous cosmic rays fall onto the Lunar surface, they pass right through the rock, but interact with Hydrogen-rich substances in the soil (such as water). This creates a neutron that bounces back up towards the surface where it is detected (16)

A neutron spectrometer was chosen over ground-penetrating radar because it is a passive device that does not need to emit anything to detect what is buried below it. This simplifies the design and power requirements, and allows it to look further into the ground. Neutron spectrometers have a proven history of use in space.

Neutron Spectrometers are tried and true technology, have flown on spacecraft before, and have a technology readiness level of 9 (16).

MiniPix - The miniPIX is a small postage stamp sized radiation detector with flight heritage on the International Space Station. The device has a simple USB interface and is easily integrated into structures and vehicles to measure the radiation environment. This is a simple experiment designed to help quantify the radiation exposure astronauts will actually be subjected to while on the Lunar surface. It has a technology readiness level of 9 (1).

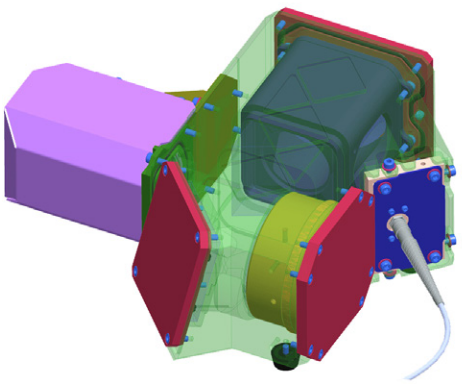


Fig.18 Neutron Spectrometer

Fig.19 MiniPix Sensor

5.2 GEOLOGICAL TOOLS

ROPEC Drill - The Rotary-Percussive Corer (ROPEC) Drill is a small hollow drill used to produce 1-2 cm diameter rock cores or abrasions. Mounted on a simple robotic arm, the drill primarily will be used during the unmanned Phase I and subsequent telerobotic periods of the mission. The robotic arm and drill will work in tandem with the Chem Cam to produce and analyze small samples determining the Lunar South Pole's geological history by accessing rock underneath surface contaminants from impacts, lunar dust, or radiation. Produced by Honeybee Robotics, the drill has a Technology readiness level of 6 (4).
Chem Cam - The Chem Cam is a laser spectrometer that has flight heritage on NASA's Mars Curiosity as well as the yet-to-launch Mars 2020 Rover. Produced by Los Alamos National Laboratory

with assistance from CNES in France, the device works by firing a laser onto a surface to analyze its material makeup. This enables studying rocks and (theoretically) water-ice samples without direct contact from a distance. When fired, the laser vaporises a small amount of material on the target object. producing a burst of plasma that glows at very specific wavelengths. By observing this flash and analyzing the wavelength of light emitted, the device can determine exactly what the material is made of (Wiens).
Mounted on the front of the rover, above and behind the ROPEC Drill mounted on the robotic manipulator, the device will have an access to a large unobstructed field of view of the surrounding area, as well as the samples provided by the ROPEC for analysis. The Chem Cam has a technology readiness level of 9 and will be used both during Phase I and Phase II of the mission.

5.3 SAMPLE COLLECTION

Planetary Volatiles Extractor - The planetary Volatiles Extractor is a new and innovative approach to access and analyze subsurface materials up to 1m in depth. This is the primary tool for accessing water-ice sources during Phase II. The device consists of a large hollow drill bit with a heated core. After drilling to the requisite depth and extracting the material, the sample is heated, causing volatile chemical compounds or water to evaporate out of the sample. This gas is collected via a pipe attached at the top of the drill for storage, re-freezing, or gas spectrum analysis to determine its chemical makeup. If desired to preserve the sample as collected, which is of particular interest when drilling into water-ice, the core can be extracted and returned as-is to Earth for analysis. The MUV is equipped with a small sample collection freezer to prevent ice-samples from melting upon first exposure to the sun on the way back to the lander. The Planetary Volatiles Extractor has a technology readiness level of 6 (4).

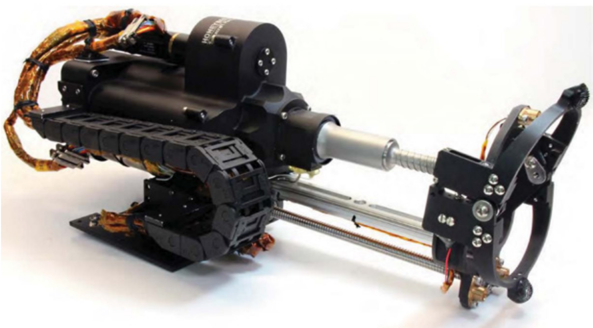


Fig.20 ROPEC Drill

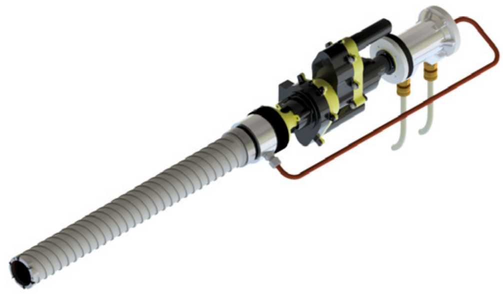


Fig.21 Volatile Extractor

6. BUDGET AND SCHEDULE

Despite the novel approach that MUV design represents in off-world human and surface telerobotics, it must still be ready to meet the first Artemis crew on the Lunar surface in 2024 and cost $217,306,000 (act from concept though assembly, testing, and launch). However, launch and landing costs are not factored into this price range.
Starting with the initial concept as originally developed in 2019 and further refined in 2020, the vehicle can be ready to fly in mid-2023. Following concept and design refinement through mid-2020, late 2020 can be allocated to design finalization and supplier and material procurement. Allowing for a 6 month lead time vehicle assembly can begin in summer 2021. This same year a launch and commercial lander provider will be selected and a flight scheduled for 2023. It is estimated that most of the time spent will be in testing, coding, and integration rather than physically building which takes the project into 2023. Final shipment and launch is estimated to be late 2023. Prices estimated and rounded up where applicable (Honeybee, Nvidia, Wiens, Space Applications, Solaero). Unverified component prices are currently listed as best guesses.

REFERENCES

1. ADVACAM. ADVACAM, *Imaging the Unseen*. ADVACAM (2019), from https://advacam.com/

2. Bartlett, P., Wettergreen, D., & Whittaker, W. Design of the Scarab Rover for Mobility and Drilling in the Lunar Cold Traps, *Proceedings of International Symposium on Artificial Intelligence, Robotics and Automation in Space*, (February 2008), Carnegie Mellon University

3. Bubble Technology Industries. (2019), http://bubbletech.ca/product/fns-100/

4. Honeybee Robotics, (2019), https://honeybeerobotics.com/***

5. Jones, E. M. Lunar Gaits. (November 2010), https://history.nasa.gov/

6. Lunar Roving Vehicle (LRV), AIR AND SPACE (2018), https://airandspace.si.edu/explore-and-le-arn/topics/apollo/apollo-program/spacecraft/lrv

7. Apollo Program Summary Report, NASA (1975)

8. NASA-STD-5001B, NASA (2016)

9. NASA Space Science Data Coordinated Archive (NSSDC). Lunar Prospector Image Collection. NASA (2019), http://www.tsgc.utexas.edu/spacecraft/lunar_prospector/

10. Enersys Power Full Solutions. (2019), from https://www.enersys.com/

11. Self-driving rovers tested in Mars-like Morocco. ESA (2018), https://www.esa.int/Enabling_Sup-port/Space_Engineering_Technology/Self-driving_rovers_tested_in_Mars-like_Morocco

12. Hautaluoma, G., & Johnson, A. New VIPER Lunar Rover to Map Water Ice on the Moon. (Octo-ber 2015), https://www.nasa.gov/feature/new-viper-lunar-rover-to-map-water-ice-on-the-moon

13. Moon's South Pole in NASA's Landing Sites. NASA (2019), https://www.nasa.gov/feature/mo-on-s-south-pole-in-nasa-s-landing-sites

14. Nvidia. Nvidia Autonomous Machines. NVIDIA (2020), https://developer.nvidia.com/embed-ded-computing

15. Neutron spectroscopy. *Science and Technology Facilities Council.* (2019), https://www.isis.stfc.ac.uk/Pages/Neutron-spectroscopy

16. Thomas, K. S., & McMann, H. J. (2007). *Us Spacesuits*. Berlin: Springer Science & Business Media.

17. Wilcox, B., Litwin, T., Biesiadecki, J., Matthews, J., Heverly, M., Morrison, J., Townsend, J., Ahmad, N., Sirota, A., Cooper, B. *Wiley InterScience*. (2007), from www.interscience.wiley.com

18. Williams, D. R. The Apollo Lunar Roving Vehicle. NASA (2019), from https://nssdc.gsfc.nasa.gov/planetary/lunar/apollo_lrv.html

APPENDIX

Power Specifications for 2 Chassis Operation

*P=V*I*
V=P/I
I=P/V

Battery Information

Enersys ABSL 8s10p	
Total Number of Batteries	8 (4 per chassis)
Amp Hour per Battery	15Ah
Bus Amps	15A (2 Bus per chassis)
Bus Voltages	28V (2 Bus per chassis)
Total Power Availability	3360Wh
	120Ah

Solar Panel Information

Efficiency	250W/m^2
Solar Panel Area	2m^2

Assume Solar Panel assumed pointed directly at Sun

Power Generated	500W
Power Generated 8 hours	4000Wh
Power Generated 24 hours	12000Wh

Total Power Availability

Batteries Only	3360Wh
Batteries + Solar Panel 8 Hours Sun	7360Wh
Batteries + Solar Panel 24 Hours Sun	15360Wh

Power Budget

Avionics	15W	0.5357142857 A	28V
Thermal Management	100W	3.571428571A	28V
Communication	100W	3.571428571A	28V
Avionics Sub Total	215W	7.678571429A	28V
Camera Suite / LiDAR	25W	0.8928571429 A	28V
MiniPix	5W	0.1785714286 A	28V
Neutron Spectrometer	25W	0.8928571429 A	28V
RoPeC Drill	50W	1.785714286A	28V
Planetary Volatiles Extractor	100W	3.571428571A	28V
Chem Cam	7W	0.25A	28V
Payload Sub Total	212W	7.571428571A	28V

Motor values represent maximum possible power draw, limited by ability for one 15amp bus to provide power to Avionics, Thermal Management, Communication, and two motors for contingency use. 2 Motor line item shown for reference, not included in the Total.

2 Drive Motors (one chassis)	205W	7.321428571A	28V
4 Drive Motors (two chassis)	410W	14.64285714A	28V
Total	837W	29.89285714A	28V

Communication value represents power draw from one chassis (not two) because only one communication system will be used at a time.

Drive Information

Drive Efficency 150Wh/km
5.357142857 Ah/km

	Battery	Battery + Solar 8 Hours Sun
Power For Driving 100% Payload Usage	2933Wh	6933Wh
Power For Driving 75% Payload Usage	2986Wh	6986Wh
Power For Driving 50% Payload Usage	3039Wh	7039Wh
Power For Driving 25% Payload Usage	3092Wh	7092Wh
Power For Driving 0% Payload Usage	3145Wh	7145Wh

	Battery	Battery + Solar 8 Hours Sun
Drive Distance 100% Payload Usage	19km	46km
Drive Distance 75% Payload Usage	19km	46km
Drive Distance 50% Payload Usage	20km	46km
Drive Distance 25% Payload Usage	20km	47km
Drive Distance 0% Payload Usage	20km	47km

	Battery	Battery + Solar 24 Hours Sun
Power For Driving 100% Payload Usage	2933Wh	14933Wh
Power For Driving 75% Payload Usage	2986Wh	14986Wh
Power For Driving 50% Payload Usage	3039Wh	15039Wh
Power For Driving 25% Payload Usage	3092Wh	15092Wh
Power For Driving 0% Payload Usage	3145Wh	15145Wh

	Battery Only	Battery + Solar 24 Hours Sun
Drive Distance 100% Payload Usage	19km	99km
Drive Distance 75% Payload Usage	19km	99km
Drive Distance 50% Payload Usage	20km	100km
Drive Distance 25% Payload Usage	20km	100km
Drive Distance 0% Payload Usage	20km	100km

Drive Distances rounded down to nearest whole number
Avionics, Thermal Management, Communication power usage always assumed to be 100% (not considered a payload)

Crew Walk Back Distance

Sustained Walking Speed	2.7km/h (Apollo Data)
Life Support Time limit	8h
Life Support Time limit 1.4 FoS	5.714285714h
Maxium Walk Back Distance	15.42857143km

Walk Back Distance 1.4 FoS 11.02040816km

Maximum radial distance from HLS during human mission 11km

COST ITEMS	PRICE
Camera Suite and LIDAR	$1,000,000
Neutron Spectrometer	$6,000,000
MiniPIX	$5,000
ROPEC Drill	$9,000,000
Chem Cam	$30,000,000
Planetary Volaties Extractor	$9,000,000
Chassis AL 2219	$5/Kg
Hotdock (Interfaces)	$200,000
Solar Panels	$50,000
Avionics and Communication	$2,000,000
Batteries	$50,000
Drive Motors, Wheels, and Attachments	$10,000,000
Assembly, Testing, and Personnel Costs	$100,000,000
Built-In Price Margin	$50,000,000
TOTAL	$217,306,000

COST DISTRIBUTION

Prices estimated and rounded up where applicable (Honeybee, Nvidia, Wiens, Space Applications, Solaero). Unverified component prices are currently listed as best guess and will be refined prior to final submission.

MUV COMPONENTS	EARTH KG
Chassis	84.91
Legs	89.45
Wheels	13.60
Electronics/Power	55.00
Science	55.10
TOTAL	298.07

Due to the modular nature of MUV, the weight range is very large. The presented table assume a basic configuration composed by: 2 Chassis, 4 legs, Science payloads and 2 Command post.

MUV

SICSA
Sasakawa International
Center for Space Architecture

REVOLUTIONARY AEROSPACE SYSTEMS CONCEPTS ACADEMIC LINKAGE
RASC-AL

UNIVERSITY of
HOUSTON

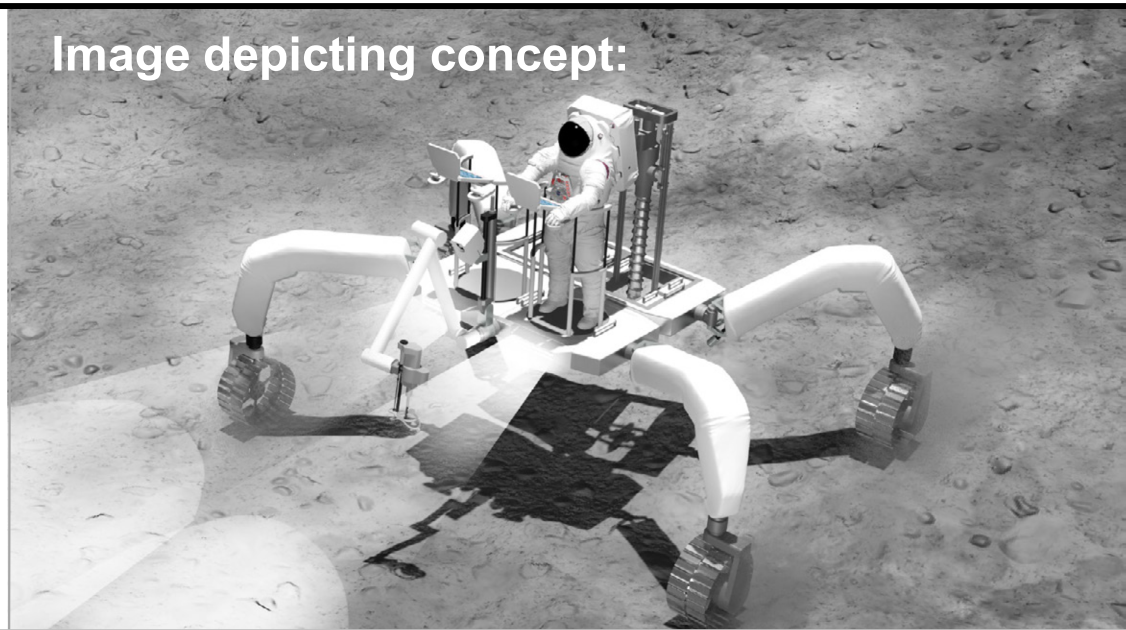
University of Houston
MUV: Multipurpose Utility Vehicle

Revolutionary Aerospace Systems Concepts Academic Linkage

Theme:

Theme 1 | South Pole Multi-Purpose Rover

Image depicting concept:



Innovations:

MUV modularity design allows:

- Expandability and versatility.
- Growth and adaptation for all three Lunar mission phases along with the rest of the Artemis program.
- New possibilities for human-robot interaction and human-robot exploration.
- Advancing mission safety.
- Increasing redundancy.

Concept Synopsis:

The Modular Utility Vehicle (MUV) is an unpressurized lunar multipurpose rover that utilizes a feasible design for a modular, upgradeable, telerobotically operated and/or manned rover for operating on the Lunar South Pole. Its capabilities include payload deployment, water-ice sample collection, geologic analysis, and terrain mapping. The defining aspect of this modular approach allows for diverse future mission requirements and objectives to be met.