CSA-ESM-RD-0004

Canadian Space Agency
Exploration Surface Mobility Project

Prototype Lunar Exploration Light Rover Requirements Document

Revision A
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1 INTRODUCTION

1.1 DOCUMENT SCOPE

This document defines the requirements on the Lunar Exploration Light Rover.

This document contains only requirements. For a definition of the context of the specified system from a systems point of view, see RD-6, and from an operational point of view, see RD-7. RD-6 also contains a definition of the internal components of the system, and of the interfaces of the system to other cooperating systems.

2 DOCUMENTS

This section lists publications of significance to this document. These documents are divided into two categories: Applicable Documents and Reference Documents.

2.1 APPLICABLE DOCUMENTS

The following documents of the exact issue date and revision level shown are applicable and form an integral part of this document to the extent specified herein.

TABLE 2-1 APPLICABLE DOCUMENTS

AD No.	Document No.	Document Title
AD-1	CxP 70024	Constellation Program Human-Systems Integration Requirements, Baseline 2006-12-15 Available at: https://ice.exploration.nasa.gov/Windchill/servlet/WindchillGW/wt.fv.master.RedirectDownload/redirectDownload/CxP%2070024%20-%20HSIR%20SRR%20Final.pdf?u8&HttpOperationItem=wt.content.ApplicationData%3A334238218&ContentHolder=wt.doc.WTDocument%3A334206699&forceDownload=true
AD-2	CMVSS	Canadian Motor Vehicle Safety Standards, as part of the Motor Vehicle Safety Regulations Available at: http://www.tc.gc.ca/acts-regulations/regulations/crc-c1038/menu.htm
AD-3	SAE J1100	SAE Recommended Practice, Motor Vehicle Dimensions
AD-4	SAE J2180	Tilt Table Procedure for Measuring the Static Rollover Threshold for Heavy Trucks
AD-5	ISO 2631:1-1997	Mechanical vibration and shock -- Evaluation of human exposure to whole-body vibration -- Part 1: General requirements

2.2 REFERENCE DOCUMENTS

The following documents provide additional information but do not form part of this specification.

TABLE 2-2 REFERENCE DOCUMENTS

RD No.	Document No.	Document Title
RD-1	-	The Lunar Sourcebook, a user's guide to the Moon, Heiken, Vaniman and French, 1991
RD-2	CSA-ESM-RD-0001	Canadian Space Agency Exploration Surface Mobility Project Rover to Payload Interface Requirements Document
RD-3		Larminie, J.C., "Modifications to the Mean Maximum Pressure System", Journal of Terramechanics, Vol. 29, No. 2, pp. 239-255, March 1992 (ISSN 0022-4898).
RD-4	CSA-ST-GDL-0001	Technology Readiness Assessment Levels and Assessment Guidelines
RD-5	MIL-STD-810G	Department Of Defense Test Method Standard. Environmental Engineering Considerations And Laboratory Tests
RD-6	CSA-ESM-DD-0002	Exploration Surface Mobility Project Reference System Architecture
RD-7	CSA-ESM-DD-0001	Exploration Surface Mobility Analogue Mission Scenarios

2.3 DEFINITIONS

2.3.1 Terminology

The following terminology is also used in this document:

a) The term “shall” designates a mandatory requirement
b) The term “should” indicates intent, desired or preferred option
c) The term “will” indicates a statement of fact or intent.
d) The term “equipment” is used in this document in reference to items of hardware at any level of assembly (i.e., unit, subassembly, subsystem, module, spacecraft).
e) The term "payload" is used to describe active equipment that interacts with the Lunar Exploration Light Rover via the standard interface of RD-2.
f) The term "cargo" is used to describe passive materiel (e.g. a science experiment package) that is to be transported by the Lunar Exploration Light Rover.
g) Maximum gross vehicle weight is used for the total mass of the vehicle when fully loaded with cargo and consumables (e.g. fuel).

2.3.2 List of Acronyms

ATSC Advanced Television Systems Committee

CMVSS Canadian Motor Vehicle Safety Standard

CSA Canadian Space Agency

ESA European Space Agency

ExDOC Exploration Development and Operations Center

EVA Extra-vehicular Activity

GPS Global Positioning System

IAWG International Architecture Working Group

IP Internet Protocol

MMP Mean Maximum Pressure

MTTR Mean Time to Repair

NASA National Aeronautics and Space Administration

SAE Society of Automotive Engineers

SOC Site Operations Center

TRL Technology Readiness Level

3 REQUIREMENTS

This section defines the functional and performance requirements on the Prototype Lunar Exploration Light Rover.

The intent is that the technology could be upgradeable for space and no technology fundamentally incompatible for space utilisation shall be used in the development of the rover (e.g. no combustion engine or hydraulic system).

3.1 Rover Capabilities

[EC-LMR-FNC-002] Crew Transportation: Nominal: The Lunar Exploration Light Rover needs to be designed in a way that is upgradeable to transport one EVA-suited crew member.

-[EC-LMR-FNC-008] EVA Embarcation: When upgrade to transport astronaut, the Lunar Exploration Light Rover shall provide convenient access for EVA crew to embark and disembark.

Comment: The term convenient is not precise because specific metrics are not in place to define this more precisely. The intent is that the crew not be required to make difficult movements nor take an unreasonable amount of time to embark, similar to entering a commercial passenger vehicle.

[EC-LMR-FNC-003] Cargo Transportation: The Lunar Exploration Light Rover shall transport cargo items.

Comment: Note that the sensor accommodation of [EC-LMR-PRF-380] Sensor Payload Accommodation is to be included within these values.

1. Cargo mass: The Lunar Exploration Light Rover shall support the transportation of up to 300 kg, including cargo, attached payloads and the nominal passenger complement.

2. Cargo Volume: The Lunar Exploration Light Rover shall support the transportation of cargo and attached payloads up to a volume of 1 m x 1.5 m x 1.5 m high.

[EC-LMR-FNC-006] EVA Tool Storage: The Lunar Exploration Light Rover provides a location for storing EVA tools.

1. EVA Access: EVA tools shall be accessible to the EVA crew.

3.2 Rover Functions

3.2.1 Locomotion

This section defines the requirements on the Rover's capabilities to drive on the terrain. These requirements apply under all passenger, cargo and payload conditions.

[ESM-LMR-DES-001] Propulsion: The rover needs to use electric propulsion.

[EC-LMR-FNC-200] Motion: Upon command, the Lunar Exploration Light Rover shall move forward, reverse, and steer.

[EC-LMR-FNC-017] Precision Drive: The Lunar Exploration Light Rover shall, upon command, place itself so that a target of interest is within the workspace of a contact sensor or sampling device.

[EC-LMR-FNC-180] Park: Upon command, the Lunar Exploration Light Rover shall put itself in a safe waiting state ("parked") in which locomotion is inhibited.

1. Parking Brake: The parked state shall hold the vehicle, at maximum gross vehicle weight, on a 31 degree slope facing in any direction. The vehicle shall be stopped on the slope, wheel motors or their equivalent turned off completely, and the rover held by the parking brake for no less than one minute in each direction.
   Rationale: The parking brake must be able to work in the same slope environment as the rest of the rover functions. A margin of 6 degrees is added.

[EC-LMR-PRF-010] Range: The Lunar Exploration Light Rover shall have a range of at least 15 km with a target of 30 km between refueling or recharging stops on a traverse where the vehicle is loaded to maximum gross vehicle weight, it is traveling over level terrain with a surface roughness defined using the equation in [EC-LMR-PRF-120] Maximum Speed on Natural Terrain with C=3.0E-05 and N=2.0, it travels at a constant speed of 10 km/h between stops and it makes 50 starts and stops.

Rationale: We use a different, less rough, surface for this requirement because the roughness defined in the referenced requirement is too severe; the lowest roughness surface, Surface 2, represents relatively rough terrain. Values with C=3.0E-05 and N=2 represent a near 'nominal' surface as defined by the Lunar Source Book (Fig 9.46) and R.J. Pike (Lunar Terrain and Traverse Data for Lunar Roving Vehicle Design Study)

[EC-LMR-PRF-018] Maximum Speed on Prepared Surface: The Lunar Exploration Light Rover, loaded to maximum gross vehicle weight, has to be capable of maintaining a speed of not less than 15 km/h on a smooth, level, prepared surface.

Comment: It is likely that a higher speed capability than this will result from other requirements, e.g. [EC-LMR-PRF-017] Gradeability. The intent is not to prohibit a higher speed, however, the safety requirements would have to be met at the maximum speed that the vehicle is able to achieve.

[EC-LMR-PRF-120] Maximum Speed on Natural Terrain: The Lunar Exploration Light Rover, when operated on the two specified surface roughness conditions (as defined by the Surface Roughness Equation and the constants listed in the table), shall be capable of travelling at the speeds shown in the following table.

Rationale: These values were developed through analysis of the lunar surface environment combined with assumed parameterized models of rover suspension systems over a range of possible designs. The rover suspension models were designed to be conservative (low damping). The lunar terrains are worst case estimates. The requirements here and in the Interface Requirements Document RD-2 were chosen to be reasonably achievable over the possible design space, and the speed limits were set to ensure that the driver comfort standard could reasonably be met, based on this analysis.

1. Chassis Environment: The Lunar Exploration Light Rover shall perform nominally in this environment.

2. Operator Environment: When occupied, the occupant's environment shall not exceed the vertical weighted acceleration value of 2.5 m/s^2 as defined by the International Standard ISO 2631:1-1997

3. Surface Roughness Equation: Surface Roughness (vertical), PSD (m^2/cycle/m) = C (Omega)^(-N) where Omega is spatial frequency (cycles/meter); C is a constant (cycles/meter); N is constant.

TABLE 3-1 SURFACE ROUGHNESS AND SPEED OVER TERRAIN

	Surface Condition	Surface Roughness constant 'C'	Surface Roughness constant 'N'	Load Condition	Speed to Achieve
		m^2/cycles/m		kg	km/h
max load	surface 1	8.350E-04	2.00	800	4.50
min load	surface 1	8.350E-04	2.00	500	4.50
max load	surface 2	3.600E-04	2.00	800	10.50
min load	surface 2	3.600E-04	2.00	500	10.50

[EC-LMR-PRF-068] Rock Hazard: The Lunar Exploration Light Rover running gear shall survive being driven over an obstacle (defined below), contacting along any lateral location of the running gear without failure or loss of fatigue life.

Rationale: The running gear (wheels or tracks) must be resistant to expected hazards of the lunar surface. The driver (human or machine) will have capability to avoid obstacles down to a certain size, depending on the speed, visibility from the cockpit or camera views, and vision system mapping accuracy. The values are selected based on what is expected on the Moon and what is reasonable to expect of the driver. Note that the different cases represent approximately similar contact severity, rather than correlating to detectability vs. speed (i.e. at lower speeds a smaller object should be detectable and avoidable). The choice of steel material reflects the likely testing scenario.

1. Obstacle: The obstacle shall be a right circular cone with the base fixed to secure the cone with the tip (apex) facing up. The tip of the cone will have a spherical profile with a radius of 3 mm. The cone angle shall be 30 degrees. The obstacle shall have the properties of medium-quality steel.

2. Case 1: For an obstacle height of 10 cm, the minimum speed shall be 5 km/h.

3. Case 2: For an obstacle height of 7 cm, the minimum speed shall be 10 km/h.

4. Case 3: For an obstacle height of 5 cm, the minimum speed shall be 15 km/h.

[EC-LMR-PRF-069] Soil Properties: The Lunar Exploration Light Rover is supposed to be able to negotiate soft soil and sand. The Mean Maximum Pressure (MMP)) calculated for operation on fine grained soils shall be no greater than 80 kPa when the vehicle is loaded to the maximum gross vehicle weight.

Comment:

Moon soil can be soft and some analogue terrestrial sites have similar characteristics. While there is no uniform way to specify the interaction between a vehicle and the soil for all different types of traction, one approach applicable for specific running gear and soil types is to use the Mean Maximum Pressure (MMP). This approach is selected to provide a clear design target and to differentiate between designs. The intent is to permit a variety of running gear solutions, be they wheels, tracks or other.

Comment: For reference, MMP is defined and calculated for wheeled vehicles as follows:

MMP = (K' x W) / { 2m x b^0.85 x d^1.15 x [Delta/d]^0.5 }

where K' =1.83 (axle factor: 2 axles, both driven)

W = maximum gross vehicle weight, kN

m = number of axles

b = tire width, unladen, m

d = tire diameter, unladen, m

Delta = tire deflection under vehicle weight W, m

a) For the purpose of standardization, tire diameter, d, shall be the diameter taken at the base of the tread.

b) Tire deflection, Delta, is as measured on a hard surface.

c) Complete information on this MMP formula and on other formulas for wheeled and tracked vehicles are contained in RD-3.

[EC-LMR-PRF-150] Reverse speed: The speed requirements apply in forward and reverse directions.

Rationale: There is no reason to make the design unique in each direction, and there may be operational utility to both.

[EC-LMR-PRF-063] Minimum Speed: The Lunar Exploration Light Rover has to be capable of operating at a minimum speed of not more than 0.1 km/h on level, unprepared regolith.

Rationale: This will ensure safe, very-low-speed movement of the vehicle. Initial autonomous driving in difficult terrain is expected to require very slow motion (< 1km/h) until algorithms are improved through testing. For this very-low-speed regime the minimum speed needs to be significantly smaller for good control. It is also important for precision driving in the manual and teleoperated control situations, where the requirement to place the rover accurately will require slow, precise motions.

[EC-LMR-PRF-065] Acceleration: The Lunar Exploration Light Rover, at maximum gross vehicle weight, on a smooth, level, prepared regolith surface, shall accelerate at 0.48 m/s^2 as a minimum.

Rationale: A certain minimum acceleration is needed for usability. The value is chosen with the intent not to be very demanding.

[EC-LMR-PRF-170] Stopping distance: The Lunar Exploration Light Rover, at maximum gross vehicle weight, on a smooth, level, medium hard surface with a peak friction coefficient of 0.58, shall stop on command from 15 km/h within 3.6 m without locking any wheel for a contiguous period of more than 0.1 s.

Rationale: This value is chosen to give the braking performance of a typical car, for safety purposes.

1. Lunar braking: The Lunar Exploration Light Rover shall, upon command, reduce the braking efficiency to simulate lunar performance to decelerate at 0.48 m/s^2 on level ground.

2. Override: The Lunar Exploration Light Rover shall provide an override for the lunar braking simulation that maintains operational safety.
   Comment: To comply to this requirement, the positioning and operation of this override must be carefully considered to ensure that the operator can engage it rapidly in an emergency situation. A possible solution would be an emergency stop button or pedal.

[EC-LMR-PRF-059] Consecutive Stops: The Lunar Exploration Light Rover, loaded to maximum gross vehicle weight, on a smooth, level, medium hard surface with a peak friction coefficient of 0.58, shall make five consecutive stops from 15 km/h without locking any wheel for a contiguous period of more than 0.1 s. The Lunar Exploration Light Rover shall accelerate back up to 15 km/h within ten seconds of stopping, and initiate each stop within ten seconds of reaching 15 km/h. For each of the five stops, the Lunar Exploration Light Rover shall stop within a distance of 4.2 m.

Rationale: This is similar to brake fade tests performed on earth, and is necessary for safe operations.

This will give the analog rover an ability to resist temperature-related brake fade in a manner similar to that defined in CMVSS 135.

Note, maximum speed is 80% of the maximum, consistent with the CMVSS 135 approach.

[EC-LMR-PRF-017] Gradeability: The Lunar Exploration Light Rover is required to drive at 10 km/h on natural terrain up to 10 degrees slope when at maximum gross vehicle weight.

Rationale: The system is not expected to go at full speed up to the full operational slope, but must be able to maintain speed on a non-trivial slope.

[EC-LMR-PRF-040] Obstacle Crossing: The Lunar Exploration Light Rover is required to drive at low speed over obstacles of up to 0.3 m wide, 0.3 m long, and up to 0.3 m high with edges rounded to a radius of 0.05m. Note that if wheels are not the design solution, then the intent is that whatever the ground interaction, be it tracks, hovering, etc., the Lunar Exploration Light Rover can pass over this obstacle size.

Rationale: The Lunar Sourcebook mentions rock sizes up to 80cm (p32). The Lunar Science Working grup found that the largest rock that would have to be crossed would be 30cm (Osinski et al, Manned Lunar Mission (MLM) Science Working Group (SWG) Technical Note 1, p48).

Rounding the edges gives the obstacle a more rock-like shape.

[EC-LMR-PRF-060] Ground Clearance: The Lunar Exploration Light Rover needs to be able to pass over an obstacle with a height of 0.35 m and a width of 0.7 m. No projection of the Lunar Exploration Light Rover shall be closer to the ground than 0.35 m, other than the wheels, suspension and drivetrain components.

Rationale: The Lunar Sourcebook mentions rock sizes up to 80cm (p32). The Lunar Science Working group found that the largest rock that would have to be crossed would be 30cm (Osinski et al, Manned Lunar Mission (MLM) Science Working Group (SWG) Technical Note 1, p48). Rounding the edges gives the obstacle a more rock-like shape.

[EC-LMR-PRF-090] Maximum Gradient: The Lunar Exploration Light Rover shall be able to start and stop in a controlled fashion while ascending or descending a 25° slope at maximum gross vehicle weight.

Comment: Note that this requirement is not intended to be applied for low-friction surfaces such as concrete, which would require rubber for traction.

1. Performance: There shall be no stalling, slipping, overheating, upsetting or hesitation.
2. No Leaks: There shall be no leaks of fuel, lubricants or coolants.
3. Shear limit: The requirement shall be met on dry sandy slopes where the angle of internal shearing resistance exceeds 36°.
   Rationale: This is on the high end of shearing angle for earth soils (lunar soils are stronger). The 11 degree difference between shearing angle and the actual slope climbing angle provides some soil strength margin to actually support the vehicle. Tracked vehicles are able to achieve up to 5 degrees, but wheeled vehicles are only typically able to achieve 10 degrees.

[EC-LMR-PRF-110] Side Slope: The Lunar Exploration Light Rover shall drive across slopes with a tilt angle of 25 degrees. Performance may be reduced (e.g. speed) but safety (human and equipment) must not be compromised.

Comment: Note that this requirement is not intended to be applied for low-friction surfaces such as concrete, which would require rubber for traction.

Rationale: Given a standard vehicle layout, the transverse stability is likely to be lower than the longitudinal stability, so the requirement is lowered compared to the maximum gradient. The Rollover requirement covers both cases for safety.

1. Performance: There shall be no stalling, slipping, overheating, upsetting or hesitation.
2. No Leaks: There shall be no leaks of fuel, lubricants or coolants.
3. Shear limit: The requirement shall be met on slopes where the angle of internal shearing resistance exceeds 36°.

[EC-LMR-PRF-160] Turning circle: The Rover needs to be able to turn in a circle where the turning circle diameter is lesser or equal to 1.3 times the wheelbase length. The turning circle is the path traced by a point at the centreline of the vehicle, halfway between the front and rear axles or their equivalent, as the vehicle travels around in a low-speed, steady-state turn.

Rationale: A tight turning radius is desirable for manoeuvrability to position the sampling systems on targets plus alignment for docking operations to payloads, handling systems and eventually pressurised modules.

Most military and passenger vehicles have a sharper turning radius than R/L=2. (R/L=2 requires just 29° of Ackerman angle on one axle). The Army LUVW (G-wagon) essential requirement for R/L is 1.35 (42°), and desired R/L is 1.18 (48.5°).

R/L=1.18 is achievable with steering of one axle alone. Steering with the front and rear axles together means that R/L=0.59 (48.5° front and 48.5° rear) is possible.

The proposed value of D/L=1.3 is equivalent to R/L=0.65. This will require Ackerman angles of 44° on both the front and the rear axles.

Other solutions not relying on Ackerman mechanism but meeting the requirement are acceptable.

[EC-LMR-PRF-061] Angle of Approach: The angle of approach (H106 in SAE J1100) for the Lunar Exploration Light Rover shall not be less than 40 degrees.

Rationale: This is needed to make sure the vehicle can approach steep ramps or slopes without bottoming.

[EC-LMR-PRF-062] Angle of Departure: The angle of departure (H107 in SAE J1100) for the Lunar Exploration Light Rover shall not be less than 40 degrees.

Rationale: This is needed to make sure the vehicle can exit steep ramps or slopes without bottoming.

[EC-LMR-PRF-066] Ramp Breakover Angle: The ramp breakover angle (H147 in SAE J1100) for the Lunar Exploration Light Rover shall not be less than 34 degrees.

Rationale: This is needed to make sure the vehicle can crest over ridges (and especially crater edges) without bottoming.

[EC-LMR-PRF-064] Rollover Threshold: The rollover threshold of the Lunar Exploration Light Rover shall be at least 36.9° (0.75 g) when measured in accordance with SAE J2180. Equipment and Payloads will be in a stowed configuration for travelling, but their Center of Mass shall be permitted to be at least as high as the center of the Cargo volume, and anywhere horizontally on the surface of the interface plates controlled by RD-2.

Rationale: This will provide an adequate margin between the operation-on-side-slopes capability of 25° specified previously, and actually rolling over.

[EC-LMR-FNC-067] Driveline Configuration: The Lunar Exploration Light Rover has to have all-wheel-drive capability if it is wheeled, or all-tracks-driven capability if it is tracked.

Rationale: When operating on firm surfaces with small slippage, torque-based operation ensures that wheel/track wear is minimized, for instance in turning when the speeds of each may vary. When operating in soft ground where substantial slippage occurs, operating in equal-speed mode will ensure optimal traction, and avoid spinning individual wheels/tracks.

1. Power modes: The power shall be delivered to individual running gear in an equal-torque mode when operating at low slips, and in an equal-speed mode at high slips.

2. Smooth transition: Transition between low and high (and high and low) slip modes shall be smooth and gradual.

3. Turning: The equal-wheel-speed mode shall provide left- and right-side wheel speeds that vary in proportion to the turning radius being demanded by the steering command.

[EC-LMR-PRF-011] High Manoeuvrability Options: The Lunar Exploration Light Rover needs to have the following manoeuvring capabilities (in the horizontal plane).

Rationale: These capabilities are likely not required to implement the scenarios, however this is not clear. Situations exist where they would be useful: manoeuvring in a tight space between rocks to place a target within reach of an arm, or to place a drill close to an obstruction; manoeuvring up to a docking port; manoeuvring around a target while maintaining pointing towards the target. NASA's design solution, Chariot/Lunar Electric Rover, has these capabilities. The benefit of the capability to perform these tasks versus the extra cost of the system is not subject to a simple trade-off. By having these capabilities in the prototype, CSA can more easily evaluate them, but this is not critical to the success of the prototyping project.

1. Turn-in-place: The Lunar Exploration Light Rover should be able to rotate about any point within or external to the chassis.

3.2.2 Imaging and Sensing

[EC-LMR-FNC-044] Imaging: The Lunar Exploration Light Rover shall, upon command, take imagery of itself and the surrounding terrain.

Rationale: This function is for situational awareness especially during teleoperated driving, for recording events and activities in all modes, for problem solving during teleoperation and for providing images of terrain and targets for science evaluation and decision-making.

1. Spectral Bands: The Lunar Exploration Light Rover shall image in visible wave bands.

2. Panorama: The Lunar Exploration Light Rover, upon command, shall take a 360 degree panoramic image in any of the supported wave bands.

3. Two views: The Lunar Exploration Light Rover has to be able to provide at least 2 views continuously, at least one of which must be color.
   Rationale: This ensures that the teleoperating remote driver is not limited to a single forward-looking view which may not be sufficient. Colour is needed for scientific characterization, but may not be needed for driving. Requiring colour increases the needed bandwith for downlink.

4. Resolution: The Lunar Exploration Light Rover shall provide video at a resolution of at least 640x480 pixels, with a goal of 1920x1080 pixels.
   Rationale: Resolution is chosen to be within digital video standards (e.g. ATSC). The best resolution possible is desired but may be subject to constraints. High resolution may require lossy, high compression under some circumstances where real-time streaming is required in a small bandwidth, but higher quality images could be downloaded more slowly when time is available, e.g. for area surveying.

5. Azimuth Coverage: The Lunar Exploration Light Rover imaging shall cover 360° in azimuth around the rover.
   Rationale: This supports manipulator operations around the side of the rover and locomotion forward and reverse. It also supports path planning and science.

6. Elevation coverage: The Lunar Exploration Light Rover imaging shall cover the top of the Lunar Exploration Light Rover and up to at least 90° degrees elevation.
   Rationale: Rover deck coverage will assist with manipulator operations plus problem solving. High elevations will be required in science exploration operations near cliffs. It can also be used for atmospheric observations if desired.

7. Manipulator workspace: The Lunar Exploration Light Rover imaging, separate from any imagers mounted on the manipulators, shall cover the manipulator workspace.
   Rationale: This provides a separate viewpoint for manipulator operations which, based on International Space Station robotics experience, will be needed. The zoom requirement is to ensure that the end-effector can be precisely monitored. It should be covered by the general zoom capability.

   1. Zoom: The Rover imaging shall zoom in on the manipulator workspace to provide a full-screen image with a maximum diagonal dimension of 15cm in the object space. The range to the edge of the workspace should be no less than 2 m.

8. Zoom: The Lunar Exploration Light Rover imaging shall, upon command, change the field of view in a range of 2 degrees to 30 degrees diagonal dimension, in steps of 1 degree maximum.
   Rationale: Zoom capability is in general to support detailed imaging of distant targets while also supporting driving and other close-by operations which require a wide field. It appears that a 15x zoom ratio should be commercially available.

[EC-LMR-FNC-047] Lighting: The Lunar Exploration Light Rover is required to provide lighting for night-time conditions for robotic operations and potential proximity EVA operations within 10m of the vehicle, and for driving (i.e. in front and behind) up to 50 m from the vehicle.

[EC-LMR-FNC-049] Basic Digital Terrain Mapping: The Lunar Exploration Light Rover, upon command, takes a digital range/position measurement of the area around it.

Comment: Line-of-sight measurement is acceptable, there is no need to look behind obstructions from a single location. The field of view vertical span was set to be achievable with a commercial product. The 360 degree azimuth supports driving forwards and backwards with rapid turns.

1. Range: The range shall be at least 50m.
2. Resolution: The resolution shall be 4 cm or better in all 3 spatial dimensions at 5 m range.
3. Accuracy: The positional accuracy shall be better than 2 cm in all 3 spatial dimensions at 5 m range.
4. Frame Rate: The measurement shall be updated at least twice per second.
5. Field of View: The measurements shall cover at least 2 degrees elevation above the horizontal to 24 degrees below, and 360 degrees azimuth.

[EC-LMR-FNC-052] Sensor Height: Basic digital terrain mapping and terrain imaging from at least one imager are done from an adequate height to see over obstacles of 1 m height.

Comment: The precise height is left to the contractor to optimize for the requirement to see over obstacles. The height is chosen specifically for the sensor payload case to ensure that a design baseline is set for mating systems.

Rationale: The Lunar Sourcebook mentions rock sizes up to 80cm (p32), with potentially larger rocks mentioned elsewhere. The Lunar Science Working group found that the largest rock that would have to be crossed would be 30cm (Osinski et al, Manned Lunar Mission (MLM) Science Working Group (SWG) Technical Note 1, p48). The selected rock size is based on these. The terrain mapping needs the capability to see beyond such obstacles to allow route planning in their vicinity, especially if the route has to avoid several while maintaining a consistent direction.

[EC-LMR-PRF-380] Sensor Payload Accommodation: The Lunar Exploration Light Rover needs to provide a mounting location for sensor payloads (e.g. the Advanced Vision Systems and science instruments) at 2m above ground level.

Rationale: There will be boulders in lunar sites and possibly analogue sites. The Rover will have to steer around them and they should not obscure the science instruments. The parent requirement specifies the obstacle size. This requirement defines a useful height to look over nearby obstacles.

1. Mass: The Lunar Exploration Light Rover shall accommodate 30 kg at this location.
2. Volume: The Lunar Exploration Light Rover shall accommodate a volume of 40 cm x 40 cm x 40 cm at this location.

3.2.3 Control

[EC-LMR-FNC-023] Crew Control: When upgraded to transport astronaut, the Lunar Exploration Light Rover needs to provide interfaces for the on-board crew to control all functions. Interfaces may be combined where there this does not degrade the effectiveness of the control function.

1. Driving Console: When upgraded to transport astronaut, the Lunar Exploration Light Rover shall provide a workstation for driving and navigation.

2. Camera display: When upgraded to transport astronaut, the Lunar Exploration Light Rover shall, upon command, display the camera views on the driving console.

3. Standard Interface: The crew control station shall use the standard Rover-Payload interface, as per RD-2.
   Rationale: This ensures modularity so that the console can be removed to increase payload capability or removed and replaced with an upgraded system.

4. Payload control: The Lunar Exploration Light Rover shall provide a workstation that supports the payload user interfaces including hosting the payload user interface software.
   Comment: The initial concept is for this interface to be the same as at Exploration Development and Operations Center, hence requiring no special services beyond a laptop.

[EC-LMR-FNC-015] Crew Navigation: When upgraded to transport astronaut, the Lunar Exploration Light Rover has to support on-board crew navigation by providing digital terrain maps and localization aids.

[EC-LMR-RCS-010] Remote Control: The Lunar Exploration Light Rover shall have a Remote Control Station at the Exploration Development and Operations Center.

[EC-LMR-RCS-030] Remote Commanding: The Remote Control Station needs to accept and send commands at a rate sufficient to perform teleoperation of the Lunar Exploration Light Rover.

[EC-LMR-RCS-040] Remote Control Station Usability: The Remote Control Station human interface shall permit the operator to formulate and enter commands at a rate sufficient to perform teleoperation of the Lunar Exploration Light Rover.

Rationale: Commands must be sent at a rate that is sufficient to not impact performance of the Rover when commanded remotely. The operator interface has to be designed in an efficient, ergonomic manner or else the difficulty of entering commands will prevent the operator from being effective.

[EC-LMR-RCS-020] Remote Operator Displays: The Remote Control Station needs to provide operators with telemetry and video displays with update rates sufficient to perform teleoperation of the Lunar Exploration Light Rover.

Rationale: The remote operator will have difficulty controlling the Rover if the update rate of the video and telemetry is insufficient.

[EC-LMR-RCS-060] Multiple command sources: The Lunar Exploration Light Rover shall accept commands from and send telemetry to the Site Operations Center, Exploration Development and Operations Center or via a direct wired connection (external port).

Rationale: Exploration Development and Operations Center is for teleoperated execution. Site Operations Center is for setup, checkout, driving to the test location and problem solving. Direct connection is for debugging.

[EC-LMR-RCS-070] Command Source arbitration: The Lunar Exploration Light Rover needs to prioritize and arbitrate the commands received from multiple sources to ensure that the most appropriate source is used. The priority shall be: direct wired connection comes before the Site Operations Center, which comes before the Exploration Development and Operations Center.

Rationale: It would be easy under debugging conditions to receive commands from multiple sources. This must be handled.

[EC-LMR-RCS-080] Site Operations control: The Lunar Exploration Light Rover shall provide a Remote Control Station at the analogue site with the same control capabilities as the Exploration Development and Operations Center, described here as the Site Operations Center (SOC).

Rationale: The set up and maintenance of the rover, and set up of the scenario, will require close interaction with the local support team.

[EC-LMR-FNC-210] Tele-operated control: The Lunar Exploration Light Rover shall have a Tele-Operated mode of control.

Rationale: Derived from the operations concept. In the Tele-Operation mode, the Rover is driven by crew at the Site Operations Center or Exploration Development and Operations Center (simulating a control center on the ground on Earth). Situational awareness is provided by camera views, sensor data and telemetry displays on the operator console.

1. Teleoperated speed: When in tele-operated mode, the Lunar Exploration Light Rover shall drive safely at a speed of up to 5 km/h with a target speed of 10 km/h.

[EC-LMR-FNC-014] Autonomous Control: Upon command, the Lunar Exploration Light Rover shall perform activities autonomously to achieve high-level goals provided through simple commands and command scripts.

Rationale: Derived from the operations concept. In the Autonomous mode, the Rover is driven by crew at the Site Operations Center or Exploration Development and Operations Center (simulating a control center on the ground on Earth) by providing high-level goal-oriented commands (e.g. drive to a certain location). Other systems also behave autonomously (e.g. moving an instrument to contact a certain rock and take a measurement). Situational awareness is provided by camera views, real views (if possible), sensor data and telemetry displays on the operator console.

1. Autonomous Navigation: Upon command, the Lunar Exploration Light Rover shall perform autonomous navigation to drive to a defined location.

2. Autonomous Speed: When in autonomous mode, the Lunar Exploration Light Rover shall drive safely at a speed of up to 3 km/h with a target speed of 5 km/h.

3. Alternate Vision System: When using digital terrain data, the Lunar Exploration Light Rover shall allow the information provided by the basic vision capability of [EC-LMR-FNC-049] Basic Digital Terrain Mapping to be either replaced by an external data source, or used together with it.

3.2.4 Navigation

[EC-LMR-FNC-022] Navigation: The Lunar Exploration Light Rover has to be able to determine its position, heading and orientation.

Rationale: The position is needed for driving to aid the operators in assuring that the planned path is followed. The orientation is needed for provision to payloads (e.g. manipulators and drills) so that payload operations can be correctly implemented and also for vehicle safety to determine rollover risk and slippage risk on hills.

[EC-LMR-FNC-026] Navigation self-sufficiency: The Lunar Exploration Light Rover shall navigate without reference to external navigational aids (e.g. GPS).

Rationale: Lunar navigation is likely to have no assistance from infrastructure at least in the initial phases. This needs to be simulated in the analogue missions. More accurate localization may be performed by the site support team.

[EC-LMR-PRF-340] Absolute localization: The Lunar Exploration Light Rover has to be able to determine its absolute location to within 100 m.

Rationale: Design choice by CSA based on scenario needs. The intent is to be able to place the Exploration System "close enough" to a feature of interest to be able to recognize and home in on it using sensors.

Absolute localization is the ability to locate oneself relative to the planetary coordinate system, i.e. in latitude and longitude, given a minimum of prior information. This may be done, for example, by triangulating features from the terrain.

[EC-LMR-PRF-350] Relative localization: The Lunar Exploration Light Rover shall determine its location to within 1 % of the distance from its starting point for the scenario.

Rationale: Design choice by CSA based on scenario needs.

[EC-LMR-FNC-019] Self-Location: Construction: The Lunar Exploration Light Rover needs to implement a function to estimate its location while performing construction tasks within 1 m accuracy relative to a fixed point in or near the construction zone.

[EC-LMR-FNC-021] Image and Sample Geo-referencing: The Rover needs to provide position and orientation information to other payloads on request.

Rationale: This allows the other systems to compute and record the location of imagery, contact measurements and samples.

3.2.5 Communication

[EC-LMR-COM-001] Communication: The Lunar Exploration Light Rover shall be able to communicate with the Site Operations Center and with Exploration Development and Operations Center.

1. Received Data: Data to be received by the Lunar Exploration Light Rover shall include but is not limited to:
    1. Plans: Mission plans, detailed procedures and automated command scripts.
    2. Telecommands: Telecommands for the Lunar Exploration Light Rover and its subsystems.
    3. Maps: Digital maps and localization data, annotated per mission plans e.g. with destinations and regions of interest.
2. Transmitted Data: Data to be transmitted by the Lunar Exploration Light Rover shall include but is not limited to:
    1. Received Data: Any data that is received can be retransmitted for verification or to provide updates.
    2. Systems telemetry: Health and status monitoring data for all subsystems.
    3. Imagery: Imagery generated by instrument subsystems such as cameras and vision systems.

4. Navigation: Speed, distance, pose, self-computed geo-localization data (e.g. from vision system).

5. Geo-location: The data shall include geo-referencing information.

3. Real-Time: The communication system shall transmit and receive data in real time to support teleoperation.

    1. Delay: Lunar Exploration Light Rover-induced communication delay shall be < 0.5 s.

[EC-LMR-COM-010] Network: Communication between the Lunar Exploration Light Rover, Site Operations Center and Exploration Development and Operations Center is supposed to use the CSA-provided wireless IP network, via a Lunar Exploration Light Rover-mounted, CSA-supplied wireless node.

Rationale: CSA plans to provide a communications system separately.

[EC-LMR-COM-020] Delay Tolerance: The Lunar Exploration Light Rover control shall be tolerant to delays up to 3 seconds round-trip. This includes designing the teleoperation user interface to be effective with this delay.

Rationale: Demonstration of lunar light delay tolerance.

[EC-LMR-COM-030] Rover-to-ExDOC bit rate limit: The Lunar Exploration Light Rover shall not require more than 0.7 Mbit/s telemetry downlink capability for control.

Rationale: This is an allocation of the parent requirement to the rover. The rover is assumed to get the largest portion of the bandwidth during driving operations.

Comment: It is likely that most of this bandwidth will be used for compressed video in support of tele-operation mode which needs high situational awareness. [EC-LMR-COM-001] Communication: Imagery is expected to be implemented in real-time to support this mode.

[EC-LMR-COM-040] ExDOC-to-Rover bit rate limit: The Lunar Exploration Light Rover shall not require more than 0.7 Mbit/s telemetry uplink capability for successful control.

Rationale: This is an allocation of the parent requirement to the rover. The rover is assumed to get the largest portion of the bandwidth during driving operations.

[EC-LMR-COM-050] Continuous telemetry: The Lunar Exploration Light Rover shall continuously transmit engineering and health information to the control stations whenever it is on.

Rationale: Telemetry is needed, and power-up is commonly a phase that highlights any problems. It is expected that the CSA-provided network will provide routing to the different control sites.

[EC-LMR-COM-055] Telemetry Reconfigurability: The Lunar Exploration Light Rover shall, upon command, configure the telemetry stream to provide specific requested data.

Rationale: The downlink capability is not infinite. Certain data will be more important than others at different points in a mission, or in different missions. Allowing control over the telemetry ensures that the limited bandwidth can be used to best effect.

[EC-LMR-COM-120] Data storage: Upon command, the Lunar Exploration Light Rover shall store video, still images and telemetry of up to 60 minutes.

1. Capacity: The Lunar Exploration Light Rover shall provide 100 GByte of on-board storage.
   Rationale: 100 Gbyte is compatible with modern commercial systems. This will provide considerable margin for storing video data (1 hour of 640x480 monochrome video compressed at 10:1 is 27 Gbyte). A single Lidar image is expected to be around 30 Mbytes.

[EC-LMR-COM-150] Concurrent Operation: When commanded from two separate stations at the Exploration Development and Operations Center, 2 Lunar Exploration Light Rovers shall be controllable concurrently.

Rationale: This will permit simultaneous experiments to be run, reducing operations overhead. This will also allow testing a higher operational tempo. Two rovers are expected to be delivered.

3.2.6 General Functions

[EC-LMR-FNC-012] Power-up: Upon command, the Lunar Exploration Light Rover shall perform the following sequence.

1. Power: apply power to all subsystems,
2. Test: check the status of the built in test program of each subsystem to determine its functional status.
3. Operation: upon successful completion of all the built in tests the Lunar Exploration Light Rover shall switch to operational mode.
4. Failure response: in the event of the failure of a built in test the Lunar Exploration Light Rover shall transmit the status information of all subsystems and enter a "wait" mode.

[EC-LMR-FNC-011] Self-test: Upon command, the Lunar Exploration Light Rover shall

1. Test: execute a self-test to check the function of all subsystems
2. Status: transmit the status information of all subsystems
3. Reset: upon successful completion of the tests, reset subsystems to the previous operating state
4. Failure response: in the event of the failure of a built in test, transmit the status information of all subsystems and enter a "wait" mode.

[EC-LMR-FNC-013] Power-down: Upon command, the Lunar Exploration Light Rover shall switch to a keep-alive state which consumes minimal power, or to a fully off state in an orderly manner.

[EC-LMR-FNC-150] Standby: The Lunar Exploration Light Rover shall be configurable to a low-power configuration when not in use which minimizes the time to power up systems.

Rationale: Derived from the operations concept. The rover will be kept in a low-power state when not being used. The term "minimizes" is not clear, but the intent is that there be a significant (factor of 5 to 10) improvement in the time to get to an operational state compared with starting from completely unpowered.

3.3 Interface Requirements

[EC-LMR-INT-020] Payload support: The Rover needs to provide mechanical support, power, data and video transfer function for payloads.

Rationale: This function is required to support the non-locomotion functions of the Exploration System. The specific requirements are in RD-2.

[EC-LMR-INT-010] Payload power: The Lunar Exploration Light Rover shall be capable of providing a total average power of 250 W to all payloads and instruments during all mission phases.

Rationale: Payloads and instruments cover a wide range of systems from payloads that only require keep-alive warmth (minimal in normal analogue environments) to power-hungry subsystems like drills. The value was chosen somewhat arbitrarily. Note a single automotive battery contains about 500 W-hr.

[EC-LMR-INT-011] Payload power boost: When parked, the Lunar Exploration Light Rover shall increase the available power to the payloads and tools by at least 100%. The Lunar Exploration Light Rover should be capable of providing all unused power to the payloads.

Rationale: Some subsystems such as a drill or robot arm, will require substantial power to operate, and when parked the Rover should not need its full power capacity. The value of 100% is selected to allow considerable leeway to the payloads. Initial estimates of rolling resistance for rover locomotion suggest that the cruise power of the rover will be in the 5 to 20 kW range, so the payload power boost is quite small relative to this, and will not affect rover range significantly.

3.4 Safety

[EC-LMR-SMA-002] Maximum Speed: For safety requirements in this document, the speed to be used needs to be the maximum speed achievable by the vehicle

[EC-LMR-SMA-001] Safe Environment: When upgraded to transport astronaut, the Lunar Exploration Light Rover shall provide a safe environment to crew and maintenance personnel who are on-board or working on the exterior.

[EC-LMR-SMA-250] All-Stop: Upon command, the Lunar Exploration Light Rover shall immediately conduct a graceful stop of all mechanical systems and safe all systems. This includes safing attached Payloads.

Rationale: All-stop is required for safety. Several situations could cause a hazard which would require safing the system. (a) a loss of situational awareness by the operator, especially in tele-operation, due to camera malfunction or poor lighting or other confusing situation, (b) an internal failure, (c) concurrent operation of multiple payloads with unforeseen results, (d) unexpected change in the environment.

Comment: Ideally the All-stop should be an easily-accessible button that has direct hardware connection to the systems to ensure that no delays or failures can impede the execution. A possible solution would be for the rover to cut all power to payloads and apply maximum braking. If the crew would work from several locations, then there would need to be several buttons.

1. Rapid Access: The All-stop command shall be easily accessible to ensure a minimum of delay from the operator recognizing a hazard to executing the stop.

2. Insensitivity: The All-stop function shall not be affected by software delays and hangups.

[EC-LMR-SMA-010] Driver Impact Protection: If the Lunar Exploration Light Rover is equipped with a steering column, it is supposed to comply with the requirements of CMVSS 203 (Driver Impact Protection and Steering Control System).

[EC-LMR-SMA-011] Anchorage of Seats: When upgraded to transport astronaut, the seats of the Lunar Exploration Light Rover shall comply with the requirements of CMVSS 207 (Anchorage of Seats).

[EC-LMR-SMA-012] Occupant Restraint: When upgraded to transport astronaut, the Lunar Exploration Light Rover includes a crew restraint device that secures the crew within the vehicle. The Lunar Exploration Light Rover shall comply with the crash protection requirements set out in subsection (22) of CMVSS 208 (Occupant Restraint Systems in Frontal Impact). The maximum speed shall be according to the maximum speed determined by [EC-LMR-PRF-018] Maximum Speed on Prepared Surface (not 48 km/h as per Section 23(b) of CMVSS 208). Compliance to CMVSS 208 may also be demonstrated through computer simulation in lieu of physical testing.

Rationale: Operating safety

[EC-LMR-SMA-040] Restraint operation time: When upgraded to transport astronaut, the Lunar Exploration Light Rover crew restraint device shall be capable of being engaged or disengaged in 15 seconds or less.

Rationale: Convenience.

[EC-LMR-SMA-031] Crew freedom: When upgraded to transport astronaut, the restraint shall not limit the movement of the crew’s arm’s, hands or feet while operating controls, nor restrict the crew’s vision.

[EC-LMR-SMA-032] Restraint usability: When upgraded to transport astronaut, the restraint system needs to be easily adjustable to fit different crew height, mass and additional crew suit add-ons for various mission roles.

[EC-LMR-SMA-015] Seat Belt Assemblies: If the Lunar Exploration Light Rover is equipped with seat belts, the seat belt assemblies on the Lunar Exploration Light Rover shall comply with CMVSS 209 (Seat Belt Assemblies).

[EC-LMR-SMA-016] Seat Belt Anchorage: If the Lunar Exploration Light Rover is equipped with seat belts, the seat belt achorages on the Lunar Exploration Light Rover shall comply with CMVSS 210 (Seat Belt Anchorages).

3.5 Environment

[EC-LMR-ENV-001] Analogue Site Environment: The Lunar Exploration Light Rover needs to meet its requirements in the analogue site environment.

Rationale: This is the high-level goal. The other requirements in this section specify the details of the environment and trace to this statement.

[EC-LMR-ENV-002] Operating Temperature: The Lunar Exploration Light Rover shall meet its requirements between -10 and +40 degrees C, and should meet its requirements down to -20 degrees C.

Rationale: Traced from Exploration Surface Mobility system requirements.

[EC-LMR-ENV-012] Storage Temperature: There is no requirement for an expanded range of temperature for storage. Deployment operations are expected to be planned to control the storage temperature within the operating range.

Rationale: Storage in the analogue environment or during transportation cannot assume a controlled environment be provided to the system. The intent is to minimize special design for the system by allowing the solution to include supporting equipment that can control the environment.

[EC-LMR-ENV-003] Weatherproofing: The Lunar Exploration Light Rover is not required to meet operating requirements in precipitation (snow, rain, etc.) The Lunar Exploration Light Rover shall resist rain and snow, but is not required to be water-proof.

Rationale: Traced from Exploration Surface Mobility system requirements.

[EC-LMR-ENV-005] Humidity: The Lunar Exploration Light Rover shall meet all requirements in relative humidity of 20% to 100%, with a goal of 3%.

Rationale: Traced from Exploration Surface Mobility system requirements.

[EC-LMR-ENV-006] Cloud: The Lunar Exploration Light Rover shall meet its performance requirements under partial or complete cloud cover.

[EC-LMR-PRF-330] Day/Night Capability: The Lunar Exploration Light Rover needs to meet all performance requirements in full sunlight and at night.

Rationale: Night-time or shadowed operation of the lunar rovers is a requirement, and needs to be demonstrated.

[EC-LMR-ENV-007] Mud: The Lunar Exploration Light Rover needs to meet all requirements if it is splashed with moist soil or mud.

Rationale: Operation after rain means that there is the potential for getting mud on the rover. The intent is not that the rover operates in mud.

[EC-LMR-ENV-004] Sand and Dust: The Lunar Exploration Light Rover shall meet its requirements while resisting small-particle dust and blowing sand.

Comment: Lunar regolith has unique and challenging properties. There is a wide range of particle size in the regolith down to nano-particle sized dust. Regolith and dust can be magnetic. They can be electrically charged by the solar wind. The particle shapes are very different from those typical of Earth, being more extended and jagged due to a lack of weathering. For more information, see for example "Lunar Sourcebook".

The intent is that the analog prototypes withstand the dusty environments of potential analogue sites (e.g. Moses Lake, Washington) and also show the path to space flight lunar dust resistance. The latter will not be tested on the prototype.

Rationale: Dust can impinge on the Rover from mechanical action, and it can be airborne by wind.

[EC-LMR-ENV-008] Solar Radiation: The Lunar Exploration Light Rover shall meet its requirements under expected solar radiation conditions in the analogue environment. This includes all sun angles.

Rationale: The Rover needs to operate outdoors and hence will be in sunlight.

3.6 Reliability and Maintainability

[EC-LMR-SMA-210] Life: The Lunar Exploration Light Rover shall be designed for a mission life of 3000 km driving and 3 years use and storage. Maintenance may be used (lubrication, limited life part replacement, etc.) to achieve this requirement.

Rationale: This is computed from assuming a high rate of utilization on 3 deployment tests. Assuming 8 h of operation during each of 20 days (approximately 1 month) for 3 deployment seasons gives 480 h. Assuming an average speed of 5 km/h, the total distance travelled is 2400 km. The value chosen includes some margin. Note that the values are based on an assumption that the system will not be used after the third deployment, or if it is, CSA takes the risk that parts will wear out.

[EC-LMR-SMA-220] Reliability: Except for nominal servicing (e.g. battery charging), the Lunar Exploration Light Rover shall operate as per performance requirements for at least 48 hours and 240 km continuously without failure in a relevant deployment environment and nominal operation.

Rationale: This requirement sets a minimum trouble-free operation time so that deployment testing is not undermined by failures. The requirement is set to allow a week of testing without interruption. 48 hours supports 6 days of testing at 8 hours per day. The distance is computed using an average speed of 5 km/hour over 48 hours. It is envisaged that this could be verified by demonstration over 2 days of continuous operation.

Comment: Relevant deployment environment

[EC-LMR-SMA-230] Replaceable Units: Corrective maintenance of the Lunar Exploration Light Rover is done through the use of Replaceable Units (RU).

Comment: A Replaceable Unit is intended to be a module that can be replaced with minimum effort, having simple mechanical, electrical and software interfaces.

There is an intent that in the future for Replaceable Units to be upgraded to be robotically compatible.

[EC-LMR-SMA-240] Modularity: The Lunar Exploration Light Rover should be of a modular design such as to facilitate corrective and preventive maintenance, and future upgrade

[EC-LMR-SMA-050] Field maintainable: Critical Lunar Exploration Light Rover components shall be maintainable or replaceable in the field.

Rationale: CSA needs the prototype to be maintainable in the field to control cost and delay when problems occur. Analogue site operations will likely be remote and difficult to access.

Comment: Critical here means key components that support multiple functions whose loss would terminate the analogue test campaign. The idea is that the campaign can tolerate some failures without being halted, particularly within payloads where a complete spare is planned, but functions such as mobility are fundamental and their loss would cripple the campaign.

[EC-LMR-SMA-260] MTTR: With the use of on-site available RUs, the Mean-Time-To-Repair (MTTR) the Lunar Exploration Light Rover under field deployment conditions should be no longer than 4 hours.

Comment: The requirement is set as a target so that it does not unreasonably affect the prototype development and divert attention from the basic technology development.

Rationale: Compliance to this requirement would ensure that deployment testing is not substantially delayed by a single failure. To support this requirement, a set of spare RU's would be required to be ready, on-site.

[EC-LMR-SMA-270] Standard Tools: The standard and non-standard tools from the list provided by the contractors shall be sufficient to perform all servicing, maintenance and RU replacement on the Lunar Exploration Light Rover.

[EC-LMR-SMA-080] Freewheel: Upon command, the Lunar Exploration Light Rover should allow any wheel (or track) or a combination thereof to freewheel.

Rationale:This is one approach to ensure reliability. This can be used in the event of a failure in the drive mechanism in order to continue operation with the remaining wheels or to allow towing for demonstration purposes or for real failures. Allowing commanding means failures can be simulated.

1. When off: The freewheel function should maintain its state when the Lunar Exploration Light Rover is powered off.
   Comment: In other words, the intent is that the Rover can be set to freewheel when powered, and then when power is removed, the Rover is still in a freewheel mode. This allows the Rover to be towed unpowered.

[EC-LMR-SMA-150] Remote restart: The Lunar Exploration Light Rover shall provide the ability for its on-board computer(s) to be restarted from a remote location without the need for a command to be processed by the main on-board computer software.

Rationale: This is to ensure that there is no situation where the software needs to be reset but cannot be reset because the software is required to process the command, but it is not working properly.

[EC-LMR-SMA-160] Software upload: The Lunar Exploration Light Rover shall have the ability to have new software uploaded and executed from the Remote Control Station.

Rationale: Prototype testing will inevitably mean discovering software problems and enhancements that need to be installed rapidly. This capability is a requirement also for space, so the software infrastructure needs to be designed with it in mind.

3.7 Resource Requirements

[EC-LMR-RES-010] Rover mass: The dry mass of the Lunar Exploration Light Rover shall not exceed 500kg with a target mass of 300kg.

[EC-LMR-RES-020] Rover volume: The shipping requirements for the Lunar Exploration Light Rover have not been determined. The Lunar Exploration Light Rover should be compatible with normal shipping methods at minimum cost and no or minimal unique equipment.

Rationale: The Rover needs to be compatible with the shipping approach to the analogue mission site, whether it be via trailer, C-130 or Twin Otter. The site not having been chosen, the requirement cannot be specified.

[EC-LMR-RES-050] Recharge time: Lunar Exploration Light Rover battery recharge or replacement, or refueling, is not supposed to take longer than 30 minutes.

Rationale: Executing multiple scenarios or very long scenarios will likely demand more power than the rover can supply, especially if test setup is time-consuming. Limiting the time needed to re-energize the Rover will help operational efficiency.

[EC-LMR-RES-060] Deployment Time: The time to assemble the Lunar Exploration Light Rover from its shipping configuration shall not exceed 3 hours.

Rationale: Preparation time needs to be limited to a reasonable value for operational campaign.

[EC-LMR-RES-040] Power self-sufficiency: The Lunar Exploration Light Rover shall have sufficient power generation and storage capabilities in order to meet mission requirements without requiring power from ancillary sources.

Rationale: The intention is that the Lunar Exploration Light Rover be completely self-sufficient during execution of the analogue mission scenarios and tests, including providing power to payloads, but not during ancillary activities.

[EC-LMR-RES-045] Charging Equipment: The Rover needs to include equipment to recharge the power supply.

Comment: The charging equipment is not expected to be part of the Rover unless this can be achieved with minimal penalties of mass, volume and other issues.

Rationale: Recharging the system will be necessary under all foreseeable rover designs. This will have to be done in remote locations without electrical service, but where such service is available, it will be very convenient to use it.

1. Remote Locations: The equipment shall be able to recharge the system in remote locations without support from electrical utility infrastructure.

2. Use of Infrastructure: The equipment shall use electrical utility infrastructure when it is available.

[EC-LMR-RES-046] Electrical Utility Converter: The Lunar Exploration Light Rover has to include equipment to convert electrical utility power for input to the external power feed described in RD-2 [ESM-IRD-ELE-015].

Rationale: The capability to use electrical utility power will allow test, debugging and evaluation without using up battery life cycles or using consumable fuel. It is not expected that conversion equipment would be part of the Rover. This capability implies an umbilical which means locomotion would have to be minimal. Payload integration testing will benefit from this capability.

3.8 Human-Systems Integration Requirements

Note: The human-system integration requirements are applicable only if the rover is upgraded to have crew

[EC-LMR-HSI-190] Operators: If applicable, the Lunar Exploration Light Rover shall be compatible with crew operators either fully suited in an EVA suit or simulation of one, or dressed in normal indoor or outdoor clothing.

Rationale: The EVA suit will add some volume and mass to the crew, changing the relationship to the controls. Operation by personnel not wearing the suit is needed also for operational convenience.

[EC-LMR-HSI-060] Operator display: If applicable, the Lunar Exploration Light Rover has to provide situational awareness data to the on-board operator to assist in navigation of the vehicle, as a minimum: heading, speed, power reserve, terrain map display, vehicle location, obstacle identification.

Rationale: To test operator situational awareness needs.

[EC-LMR-HSI-070] Anthropometrics: If applicable, the Lunar Exploration Light Rover shall provide fit, access, reach, view, and operation of human system interfaces in crew functional areas for pressurized- suited crewmembers as defined in Appendix B, Tables B-7A & B-7B of CxP 70024, Constellation Program Human-Systems Integration Requirements.

Rationale: Rover should be compatible with suited astronaut for complete simulation of lunar scenarios.

[EC-LMR-HSI-090] Crew Mass: If applicable, aspects of the Lunar Exploration Light Rover with which a pressure-suited crewmember may physically interact during planned simulated tasks shall accommodate a pressurized-suited crewmember's mass of between 72 and 139 kg.

Rationale: Rover should be compatible with suited astronaut for complete simulation of lunar scenarios. Values taken from Table B-11 in Appendix B of CxP 70024, Constellation Program Human-Systems Integration Requirements.

[EC-LMR-HSI-100] Maximum Crew Loads: If applicable, Lunar Exploration Light Rover components and equipment that will only be operated by the pressure-suited crew should withstand the forces in the "Maximum Crew Operational Loads" column of Table B-17B in Appendix B of CxP 70024, Constellation Program Human-Systems Integration Requirements without sustaining damage.

Rationale: Rover should be compatible with suited astronaut for complete simulation of lunar scenarios.

[EC-LMR-HSI-110] Minimum Crew Loads: If applicable, Lunar Exploration Light Rover components and equipment that are intended to be operated by pressure-suited crew should require forces no greater than the "Minimum Crew Operations Loads" as defined in the appropriate data in Table B-17B in Appendix B of CxP 70024, Constellation Program Human-Systems Integration Requirements.

Rationale: Rover should be compatible with suited astronaut for complete simulation of lunar scenarios.

[EC-LMR-HSI-120] Crew Contact Loads: If applicable, Lunar Exploration Light Rover components and equipment exposed to crew contact needs to withstand a crew-induced load of 262 N over any 10 cm x 10 cm square, without creating a hazard to nearby equipment or crew.

Rationale: Rover should be compatible with suited astronaut for complete simulation of lunar scenarios.

[EC-LMR-HSI-160] Dust Kick-up: The Lunar Exploration Light Rover is designed to limit dust from being kicked up on to the suited astronauts, console displays, cameras, and other equipment.

Rationale: Ease of use.

[EC-LMR-HSI-200] Shock Exposure: When upgraded to transport astronaut, shock accelerations resulting from traversing a single bump at 15 km/h shall not exceed 2.5 g (measured on the floor at the occupant's feet.) This requirement shall be satisfied by the Lunar Exploration Light Rover throughout its operating weight range.