National Aeronautics and Space Administration

Lunar Mobility Drivers and Needs

2024 Moon to Mars Architecture

White paper

Introduction

NASA's new campaign of lunar exploration will see astronauts visiting sites of scientific or strategic interest across the lunar surface, with a particular focus on the lunar South Pole region.[1] After landing crew and cargo at these destinations, local mobility around landing sites will be key to movement of cargo, logistics, science payloads, and more to maximize exploration returns.

NASA's Moon to Mars Architecture Definition Document (ADD)[2] articulates the work needed to achieve the agency's human lunar exploration objectives by decomposing needs into use cases and functions. Ongoing analysis of lunar exploration needs reveals demands that will drive future concepts and elements.

Recent analysis of integrated surface operations has shown that the transportation of cargo on the surface from points of delivery to points of use will be particularly important. Exploration systems will often need to support deployment of cargo in close proximity to other surface infrastructure. This cargo can range from the crew logistics and consumables described in the 2023 "Lunar Logistics Drivers and Needs" white paper,[3] to science and technology demonstrations, to large-scale infrastructure that requires precision relocation.

The current defined mobility elements — the Lunar Terrain Vehicle (LTV) and Pressurized Rover (PR) — are primarily for crew transportation, with limited cargo mobility functions. Conversely, planned near-term robotic missions — such as those being delivered through the Commercial Lunar Payload Services (CLPS) program — provide only small-scale mobility. This paper describes the integrated cargo mobility drivers for consideration in future architecture and system studies, with a focus on the human lunar exploration architecture. Scientific and uncrewed, robotic missions could necessitate additional mobility needs beyond those discussed here.

The cadence, mass, and number of cargo lander deliveries will be timed to meet the operational needs of NASA's lunar architecture, based on factors including science objectives, lighting conditions, and safety considerations. In many cases, cargo offloading and manipulation will need to be conducted before the crew arrives at each landing location (point of origin) and then again at local lunar exploration and habitation sites (point of use). These exploration and habitation sites will likely be located away from each landing location. This would require mobility capabilities to transport cargo of varying size and mass for full utilization within the architecture.

Current capabilities planned for lunar surface operations are limited to transporting approximately 1,500 kg of cargo. However, fulfilling other key exploration objectives could require cargo of sizes and masses beyond of these planned capabilities, creating the need for additional mobility capabilities.

Mobility Needs

One of the largest drivers of mobility needs on the lunar surface is moving cargo from its landing site to its point of use. Numerous factors drive cargo point of use, many of which necessitate separation from landing sites (e.g., darkness caused by a lander's shadow, point of use contamination by landers, or blast ejecta from lander plume surface interactions). These relocation distances can include the following factors:

- Separation from lander shadowing (tens of meters)
- Lander blast ejecta constraints (>1,000 m) due either to separation between the lander and existing infrastructure or lander ascent
- Support for aggregation of elements in ideal habitation zones from available regional landing areas (up to 5,000 m)

For more insight into lunar lighting considerations, see the 2022 Moon to Mars Architecture "Lunar Site Selection" white paper.[4]

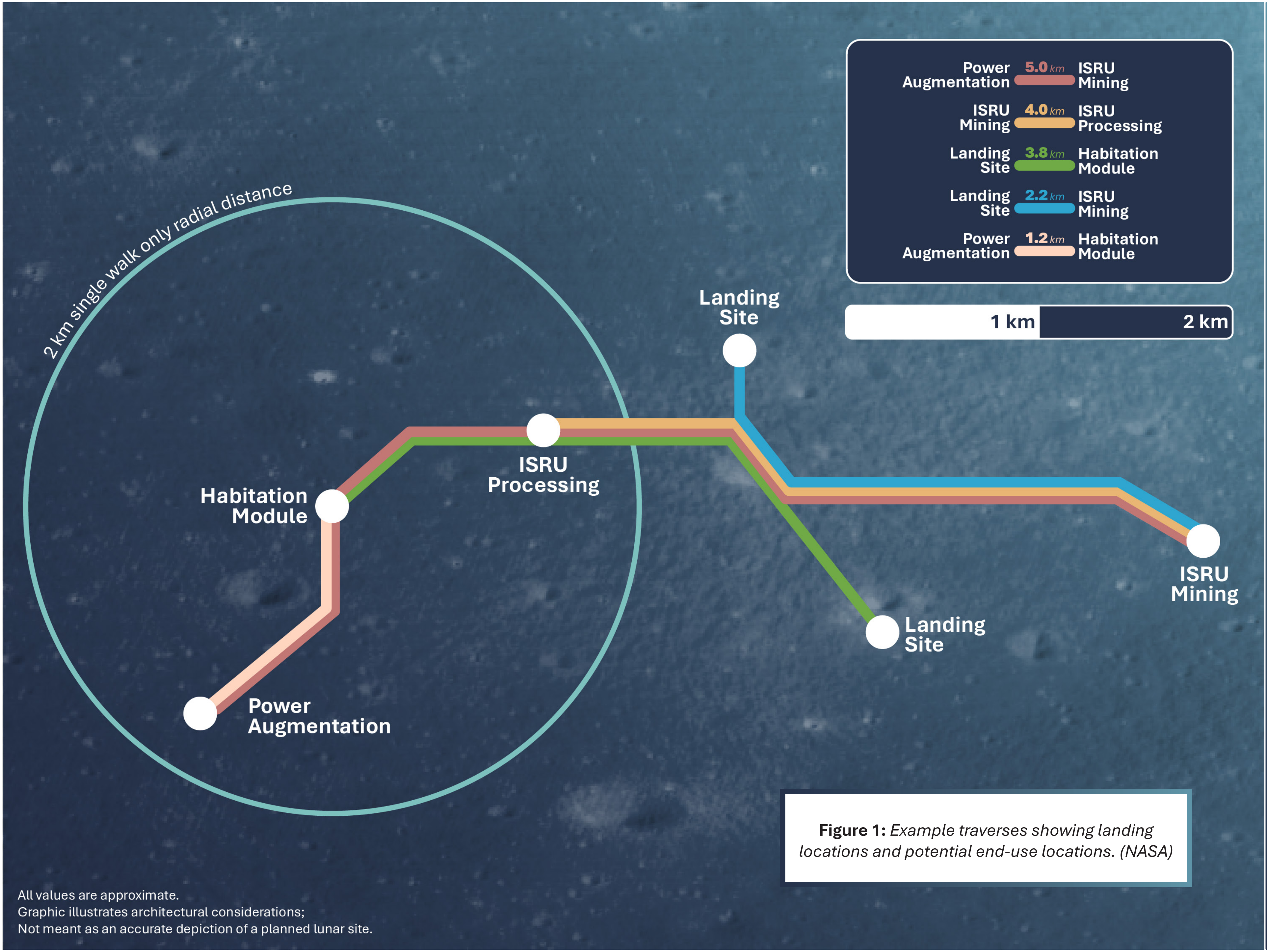

Figure 1: *Example traverses showing landing locations and potential end-use locations. (NASA)*

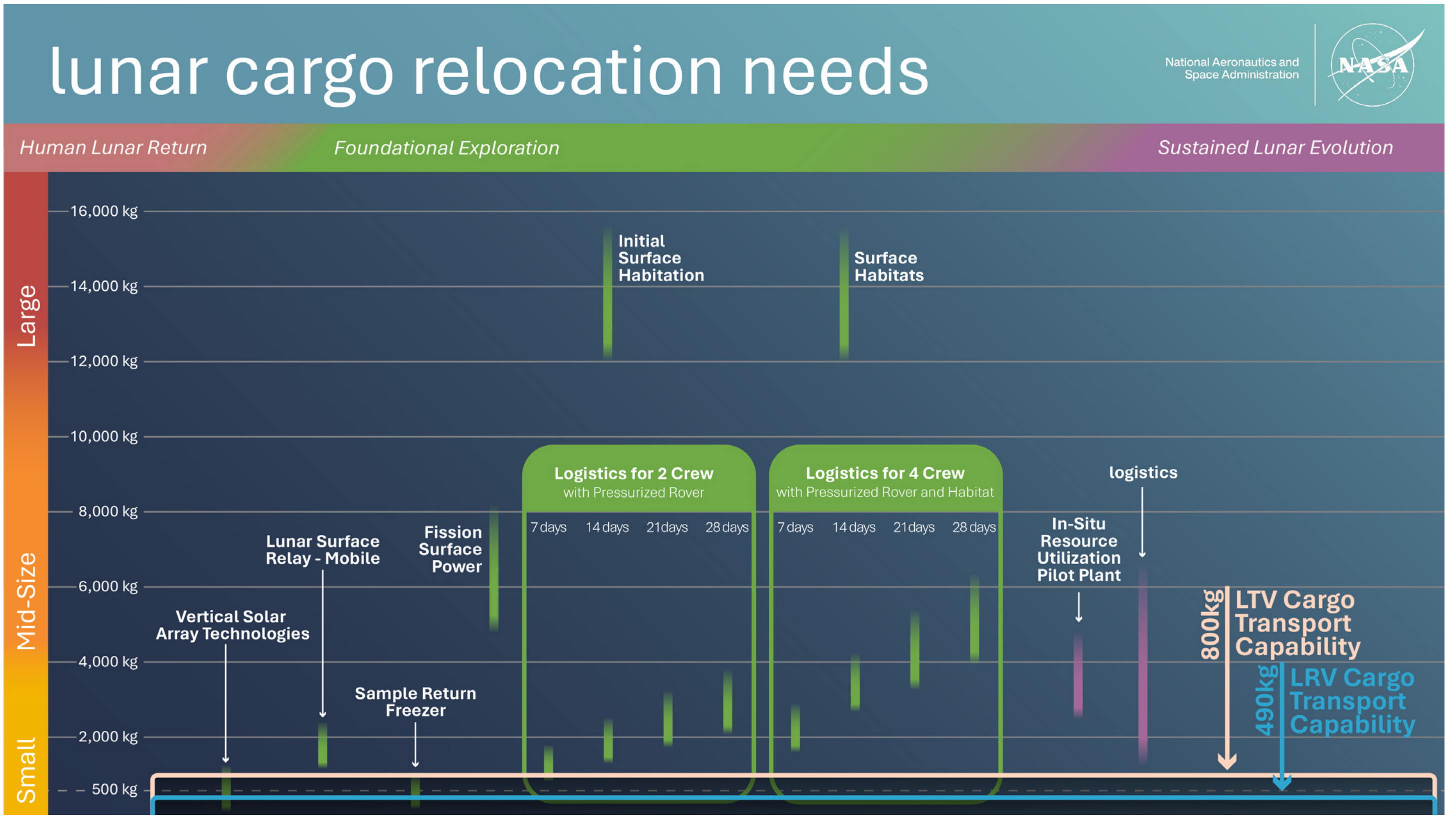

Figure 2: *Mobility demand forecast ranges compared to LTV and LRV transport capabilities. (NASA)*
Note: While contracts are in place for some cargo identified, this figure does not represent agency decisions to fly any item, nor does it reflect the order of flights for any of the items represented.

NASA will select habitation and seasonal hibernation points in the lunar South Pole region to minimize the frequency and length of periods of darkness from shadows caused by local topography and sun inclinations during lunar nights. These conditions are easiest to minimize at higher elevations and on top of ridges, driving elements with high energy needs to higher elevations, or upslope. Traverses from landing zones to habitation zones could encounter slopes of up to 20 degrees. **Figure 1** provides an example of this distribution.

NASA can meet these overlapping mobility challenges by providing capabilities for elements to move away from landers once on the surface. This could be done using independent or integrated mobility systems.

The frequency of traverses between downslope and upslope locations would be driven by the cadence with which landers deliver cargo to the lunar surface and the mass that a given mobility system can carry on each traversal. Integrated architecture operations will necessitate non-trivial relocation and aggregation ranges for cargo and assets.

Cargo and Asset Mass Demands

Currently, NASA expects that the Foundational Exploration segment of the Moon to Mars Architecture would require support for four crew members operating on the lunar surface for approximately 30 days. While this forms the basis for commodity and logistics demand, NASA expects to deploy additional science or technology demonstrations, infrastructure, and elements over time through various cargo lander capabilities. For more insight into lunar cargo landers, see the 2024 Moon to Mars Architecture "Lunar Surface Cargo" white paper published concurrently with this paper.[5]

Operational needs will require NASA to deploy many of these cargo deliveries and exploration assets, so they are available prior to crew arrival. This approach optimizes available crew time for tasks that require humans. **Figure 2** shows the mass ranges of potential cargo against transport capabilities.

The Foundational Exploration segment includes a wide range of potential mobility needs across the mass spectrum. Smaller deployed demonstrations are estimated in the 500-to-2,000 kg range. However, logistics elements needed on a recurring basis can total 2,000 to 6,000 kg per crewed surface mission. Further, the ability to aggregate infrastructure will be driven by larger crew elements — such as habitation systems — that could deploy in the 12,000-to-15,000 kg range.

Current mobility elements could provide some portion of cargo relocation capabilities. However, the LTV, for example — developed as a crew transportation element — is limited to 800 kg of uncrewed cargo mass. The Apollo-era Lunar Roving Vehicle (LRV) was designed to hold a payload of an additional 490 kg.[6] Studies indicate a significant near-term mobility demand in the Foundational Exploration segment beyond those capabilities. In total, current demand and mobility capacity are mismatched on the order of 1,000 to 15,000 kg per asset for ranges of 50 to 5,000 m.

The frequency of relocation needs can range from single operations for large elements to multiple trips per year for logistics containers or smaller scientific cargo. To allow for operations at the cadence and speed required to support crew, mobility assets will require sufficient autonomy and/or tele-robotic operation capability to operate throughout the year. Element planning should consider not just mechanical and electrical designs, but also operational paradigms and methods for automation and autonomy.

Mobility Technology and Drivers

Large-scale mobility demands require several considerations in technology and system development, including energy, surface conditions, control paradigms, and terramechanics (specifically the interaction between wheeled or tracked vehicles and lunar regolith). Energy demand for a system can be driven by many factors including operational considerations and payload masses, desired surface traversal speed, and the ability for the system to survive lunar night conditions.

Lunar surface conditions including terrain, lighting, and thermal environments are of extreme importance to mobility. Slopes of more than 10 degrees are common at the lunar South Pole (analogous to unimproved mountain passes), making slope traverses complex. Wheel and soil interactions for large mobility systems do not scale linearly with transported mass or the size of the mobility system. Transportation becomes exponentially more difficult at the upper end of the mass range.

Lunar regolith also poses a significant concern to the durability of autonomous mobility systems alone. Studies should consider regolith mitigation strategies to prevent wheel wear and overall system design should consider effects of lunar regolith and dust accumulation on all electro-mechanical systems.

This combination of factors creates a significant technological gap between existing systems and mobility demands for future exploration.

Mobility System Features

When considering lunar mobility technologies and capabilities, interactions between the mobility system, deployed cargo, and interfacing systems are critical. This can drive features for both interoperability and autonomous capabilities. A stated capability for mass relocation means little if the interfaces between the mobility element and the cargo are incompatible. Establishing shared standards that support autonomy would empower mission planners to better stage cargo and assets prior to crew arrival, increasing available crew utilization time.

The ability of mobility systems to manipulate cargo elements will be a key factor. Access to offload cargo landers, leveling to support surface docking of multiple elements, and support to mated power or other types of connectors could be key drivers for lunar surface mobility as well. The ability of multiple robotic mobility systems to work together may also be an enabling feature for future systems. This type of behavior would be additional motivation for standardization among robotic interfaces.

The operational independence provided by autonomous or semi-autonomous mobility has flow-down impacts on a wide variety of mission parameters. Navigation without human intervention can increase the speed of mobility elements, especially when crossing locations where terrain obscures communication links. Terrain and obstacle recognition, path planning, and mapping capabilities would empower year-round mobility independent of crew, offering increased flexibility for mission planning.

Summary

Mobility needs are driven by the requirement to move cargo and elements from their points of delivery to points of use for deployment in close proximity to other surface infrastructure or optimal locations. This means transporting 500-to-15,000 kg elements or cargo and across distances of up to 5,000 m to support even limited intra-regional operations at varying cadences.

Mobility on the lunar surface will need control paradigms that allow such traversal cadences to be met, the technology and systems development needed to achieve this goal must also consider several challenging environmental conditions. The Moon to Mars Architecture will include significant demand for mobility and relocation operations to provide effective and sustained human surface exploration.

More detail on architectural gaps for lunar mobility will be released at the close of the 2024 Architecture Concept Review Cycle, including in a white paper on NASA's lunar surface strategy.

Key Takeaways

Lunar exploration objectives require significant mobility of cargo and assets across the lunar surface from landing site to point of use at ranges of 5 to 5,000 m.

Currently, the surface mobility capability expressed in the architecture is limited to 800 kg. However, future mobility demands include aggregated logistics and larger elements as massive as 12,000 kg or more.

Large-scale mobility is not simply scaled up small-scale mobility; energy and environmental considerations are crucial to the design process.

Interoperability and autonomous or semi-autonomous capabilities on mobility systems enable mission planning flexibility and increase available crew utilization time.

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