Uncrewed Lunar Surface Operations and Support Activities

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A sustained human presence on the surface of the Moon and future missions to Mars require increased independence from surface crews and Earth-based mission control to operate efficiently, safely, and reliably. The number of astronauts and the availability of the surface crew to perform tasks will be limited, and extravehicular activities are burdensome and time-consuming. A balance of crewed and uncrewed surface operations will maximize crew exploration time by reducing their time dedicated to routine maintenance and support tasks. Certain sustaining activities that consume valuable crew time and preparation tasks such as staging and prepositioning equipment and materials can be performed without the crew, either before their arrival on the lunar surface or after their departure, thus improving task efficiency and mission effectiveness. This paper will define uncrewed operations and support activities and examine the functions, features, and capabilities that support sustained human and robotic surface operations. It will also discuss the extreme environmental challenges and the complexities associated with the development and operation of autonomous systems, as well as some suggested methods, techniques, and tools to overcome these challenges.

I. Introduction

NASA's human exploration plans focus on landing astronauts, including the first woman and the first person of color, on the Moon [1]. NASA will collaborate with commercial and international partners to establish a sustainable, long-term lunar presence and to test, demonstrate, and prove the technologies and capabilities needed to accomplish the first human Mars mission. The sustained lunar exploration and development plans are based on a multi-phased approach. Presented in this paper is an attempt to organize and comprehend lunar operations and support activities across the Artemis Era—a period that begins in this decade of the 2020s and will sustain a long-term human presence

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and extend to the emergence of bold new science projects and new commercial markets on the surface of the Moon. We begin with an overview of Artemis in Section II.

Section III defines the context and terminology of commonly used expressions, such as *Uncrewed Surface Operations* and *Support Activities*, through example scenarios. For this paper, *uncrewed surface operations* occur when the crew is absent or remotely controlling a system at some distance, or when the operations are independent of surface crew timeline activities and require no oversight or intervention by the surface crew. *Support activities* include the tasks and surface infrastructure that enable surface operations.

Section IV discusses how developing a diverse mix of human-machine systems can improve architectural sustainability, crew task efficiency, and mission effectiveness.

Sections V through VII outline a notional context for the lunar architecture, surface functions, and concepts of uncrewed surface operations and logistical support activities.

Sections VIII and IX describe the extreme lunar environmental impacts on integrated surface operations planning, and the technology and development challenges for uncrewed surface operations and support activities.

Finally, in Section X, a summary is provided, along with a conclusion that addresses the achievement of sustainable lunar operations through human-robotic capabilities.

II.Artemis Overview

Artemis builds upon ongoing human spaceflight efforts and sets the stage for future deep space programs, including the first human mission to Mars. The architecture will evolve and expand over time and is a collection of crewed and uncrewed elements and services that work together to achieve maximum mission effectiveness. Early missions establish foundational capabilities to launch and transport crew to lunar orbit. This includes the use of the Orion spacecraft, the Space Launch Systems (SLS), the Lunar Gateway, and the Human Landing System (HLS) (see Fig. 1). The first mission, Artemis I, is a flight test of the SLS and Orion without a crew. After Artemis III, the first human lunar return mission, the plan is to conduct operations on and around the Moon that help prepare for the duration and activities of the first human Mars mission, while also emplacing and building the infrastructure, systems, and robotic missions that can enable a sustained lunar surface presence [2]. As these missions continue to progress and land at the same lunar region, an outpost called Artemis Base Camp (ABC) near the South Pole will be gradually established. ABC will be the first sustainable foothold on the lunar surface.

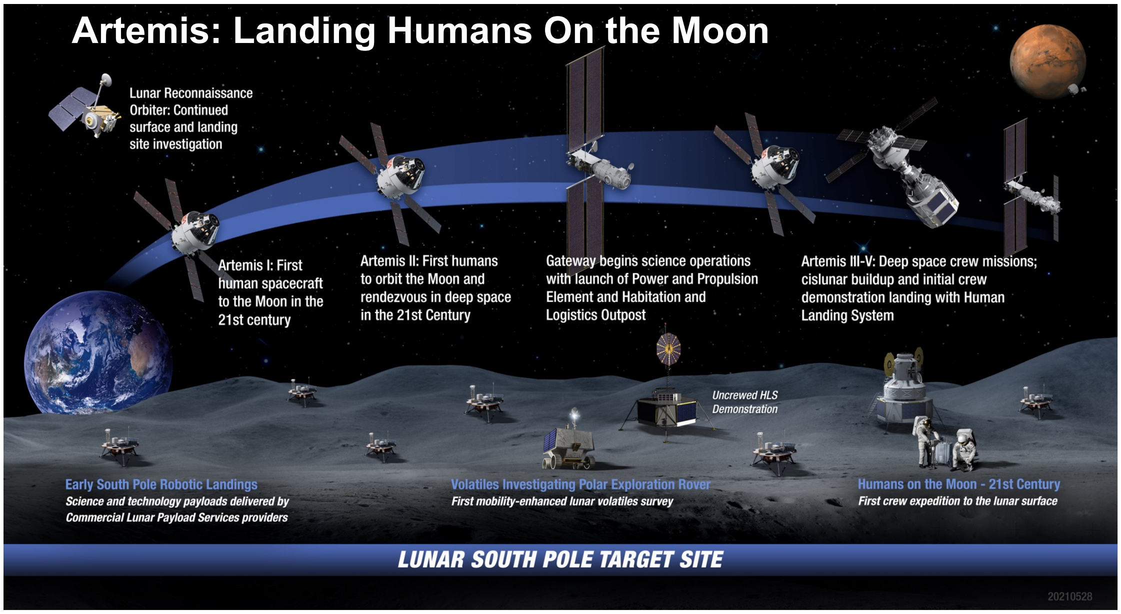


Fig. 1 ARTEMIS: Landing Humans on the Moon

The central elements are an unpressurized Lunar Terrain Vehicle (LTV), which will transport crew around the site, a Pressurized Rover (PR), which will transport crew on long-duration trips, and a Surface Habitat (SH), which will enable longer stays of four astronauts on the surface [2]. Supporting surface infrastructure, such as communications, power, radiation shielding, a landing pad, construction equipment (excavators, etc.), and waste disposal, can be added over time.

Candidate ABC sites are being selected (see Fig. 2) based on, but not limited to, the collective merit of the science, availability of information (maps) and usable resources, and any operational challenges (terrain, seasonal variations, illumination, etc.) associated with the site. Base camp concepts are considering different areas (zones) where specific systems are located, and services are rendered. The launch and landing areas are being identified to support human transport, cargo deliveries and offloading, and the potential to support propellant/commodity services, if needed. Surface construction of berms near landing zones are also being considered to protect surface assets against regolith blast ejecta from landing spacecraft. Construction of paths can improve mobility to and from different locations of the outpost, reduce the liberation of lunar dust, and extend the life of surface mobility systems. A separately delivered surface habitat is conceived to be emplaced in a habitation area to support crew habitation and health, and other cross-functional services. Specific concepts for sustainable food production areas are expected to emerge from early, on-site research at the base.

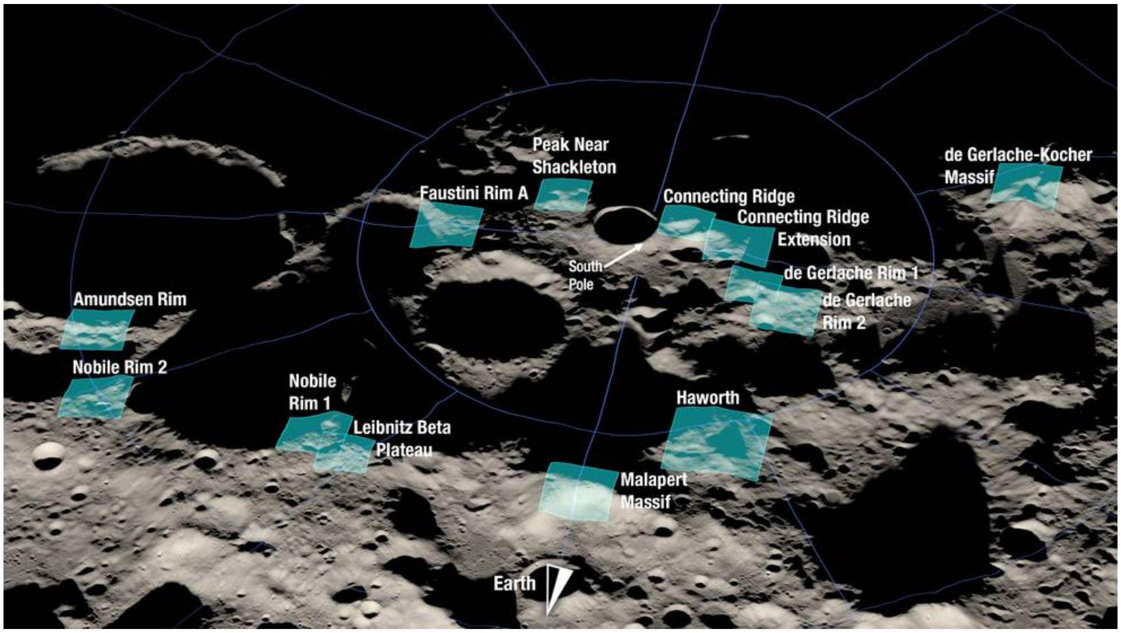


Fig. 2 Candidate Regions for Artemis III [3]

Lunar surface activities consist of a balance of lunar science, resource utilization, and technology and operational surface system demonstrations. These activities aim to promote science, create new economic opportunities, reduce risks for extended stays, and enhance the success and safety of future missions to Mars and beyond. Early missions will be sorties of up to 6.5 days duration with a crew of two residing in and performing extravehicular activities (EVAs) from the lunar lander. Subsequent missions will evolve to a crew of four with surface stays of up to 30 days. As the lunar missions continue to advance, more sites will be visited, and more capabilities will be added as needed. The surface architecture is envisioned to evolve towards a sustainable network of destinations, including a permanent base camp. Surface operations will eventually increase in complexity with the accumulation of distributed sites, assets, and associated activities augmented with greater intelligence.

The number of astronauts and their availability to perform tasks will be limited. Once on the surface, one of the objectives will be to maximize the crew time to perform science and exploration activities. This means that there will also be a desire to minimize the crew time for other activities, such as maintenance and support tasks. Additionally, initial missions will only see crew on the lunar surface for short periods of time. As the cost per mission is initially high, this means that every hour and minute of surface crew time is of extreme value. EVAs are also burdensome and time-consuming, and therefore, even more valuable than time in a pressurized volume. Moreover, some tasks may not be possible for humans to accomplish manually by hand. Rovers and crew-tended capabilities on the surface will be designed to operate autonomously and serve as robotic assistants to the crew [2]. Therefore, a balance of crewed and uncrewed surface operations will maximize crew exploration time by reducing the time dedicated to routine maintenance and support tasks.

Identifying and balancing human/automation roles and tasks and infusing automation and autonomy practices early in a system's lifecycle will be essential to achieving mission objectives. Among these objectives are attaining a sustained human presence, improving performance and mission effectiveness, reducing operations and maintenance (O&M) costs, increasing the availability of surface infrastructure, and ensuring operations are robust to communication delays. This will be crucial in achieving the architecture's effectiveness and reducing lifecycle costs. Therefore, an operational shift toward increased automation and autonomy with less reliance on humans is needed.

III. Defining Uncrewed Surface Operations and Support Activities

The lunar surface architecture supports a variety of activities during crewed and uncrewed periods. Human surface operations commence with the arrival of the crew, proceed through the crew mission on the surface, continue through crew departure and ascent, and progress through a period of uncrewed activities in preparation for the next crewed mission. When the crew is on the lunar surface, operations may consist of crewed, uncrewed, and collaborative operations.

Before discriminating between crewed and uncrewed activities, it is helpful to define what is meant by *operations* and what is meant by *support.* Then, characterizations of activities in terms of how these tasks are performed come into focus.

A. Surface Operations

For this paper, *surface operations* are *direct actions* occurring with surface systems and equipment to accomplish the primary functions of the surface architecture. These primary functions are discussed in more detail later in *Section VI*. Example surface actions, systems, and resulting operations include:

- Actions: *Lifting and handling, servicing, powering, traversing, scouting, surveying, prospecting, transferring, inspecting, pressurizing, cleaning, maintaining, safing, etc.*
- Systems: *Habitats, rovers, landers, logistics containers, excavators, etc.*
- *Surface Operations: Lower habitat, power-up rover, transfer container, inspect equipment, safe system, etc.*

With *surface operations* now defined, consider the operating agent(s) responsible for carrying out the actions.

Uncrewed operations are more complex to define, unlike manual crewed surface operations, which are better understood and more clearly definable as a result of direct actions. Two primary reasons are noted for the complexity of defining "uncrewed" operations. The first is a sliding scale of collaborative human/machine interactions, and the second is the continuum from remote-controlled to fully autonomous operations. In addition to these reasons, there is also ambiguity with the many definitions and interpretations of autonomy. To avoid confusion for this paper, a brief definition and example use cases are provided.

As initially identified in Section I, uncrewed surface operations are performed on the surface when the crew is absent or remotely controlling a system from a surface location distant from where the end actions occur, or when the operations are independent of surface crew timeline activities and require no oversight or intervention by the surface crew. This means that uncrewed operations could be defined by two dimensions: the location of the operator (i.e., spatial continuum), and the degree to which the operator controls the activity (see Fig. 3). Consider the following four example modes:

1. *Crewed/Manual Mode*

   Local Operator: Manual operations performed by humans where the end actions occur on the surface. In crewed tasks, the crew members are intended to be actively engaged and are the prime controlling entity for performing the task or replanning the task as necessary.

- Example Crewed Surface Operation: The crew manually drives the LTV.

2. *Uncrewed Modes*

A lunar surface system may be capable of operating in one of several different uncrewed modes, or even a mix of operational modes. These modes are determined by various factors, including a system's cost, functional criticality, reliability, and operational requirements and scenarios, along with other aspects such as task complexity, communications latency, bandwidth, availability of sensory information, anticipated Remote Operator workload, and demonstrated operational trust. The degree to which a system has integrated intelligence, such as sensing, acting, and planning capabilities, defines a control continuum.

Remote Operator/Supervisor: Where communications are feasible and latency (time delay) is acceptable, teleoperations permit human control over surface elements. This *teleoperation* is conducted from surface assets (e.g., crew cabin), from Gateway, and/or from Earth. It assumes a sliding scale of operator (human) involvement from remote control of a surface system to incremental automated pre-programmed sequences. With *supervised autonomous operations*, a remote operator intermittently commands and supervises the surface system, intervening only when necessary. These operations rely on sensory information/data to observe the environment and make decisions based on these observations.

- Example 1 Uncrewed Surface Exploration: Earth-based mission operators remotely control the Volatiles Investigating Polar Exploration Rover (VIPER) for exploration.
- Example 2 Uncrewed Surface Operation: Gateway crew or Earth-based mission operators preposition the LTV before HLS landing to televise the event.
- Example 3 Uncrewed Surface Operation: The crew in the SH supervises the autonomous navigation of the LTV that is following the PR.

Machine as the Operator: Fully autonomous operations are performed (ideally) by the surface asset(s) without human supervision within a defined scope to accomplish assigned objectives while adapting to changing operational and environmental conditions. In simplistic terms, an automated system performs tasks exactly as it's programmed to do, while an autonomous system decides what actions to take depending on its knowledge and understanding of the available information. *Autonomy* is the ability of a system to achieve goals while operating independently of external control [4]. The National Institute of Standards and Technology (NIST) provides additional insight that *autonomy is the condition or quality of being self-governing, enabling a system's own ability of integrated sensing, perceiving, analyzing, communicating, planning, decision-making, and acting, to achieve its goals as assigned by its human operator(s) or by another system* [5].

- Example 1 Uncrewed Surface Monitoring: Autonomous base camp environmental monitoring of dust, contamination, radiation, and seismic activity.
- Example 2 Uncrewed Surface Survive-the-Night Operation: The LTV subsystems autonomously operate during long periods of darkness at a predetermined low-power energy-saving mode for system monitoring and thermal management.

3. *Collaborative Modes*

Collaborative Human/Machine Operator(s): Cooperative operations conducted by humans on the surface augmented with robotic assistance to accomplish a task. In this mode, a human could locally control the robotic assistant, the assistant could be remotely controlled from another location by another human where necessary time-critical control of the robotic assistant is maintained, or the assistant could operate autonomously with limited interaction and supervision by humans. Combining the unique and complementary capabilities of humans and robotic systems enables a greater set of goals to be met effectively, cost-efficiently, and safely, and extends flexibility for unforeseen circumstances [6].

- Example 1 Collaborative Surface Operation: A habitat surface crew conducts sample acquisition with a robotic mobile equipment cart that assists in bagging, tagging, and storing samples, enabling the EVA crew to focus on the acquisition tasks and not the curation tasks.
- Example 2 Collaborative Surface Operation: An EVA crew operating out of a pressurized rover remotely controls an unpressurized rover to conduct reconnaissance of the route ahead.

  - Example 3 Local Collaborative Operation: An EVA crew provides high-level commands to a robotic arm on the rover (e.g., for sampling, where the crew inspects camera images to determine sample results for disposition).

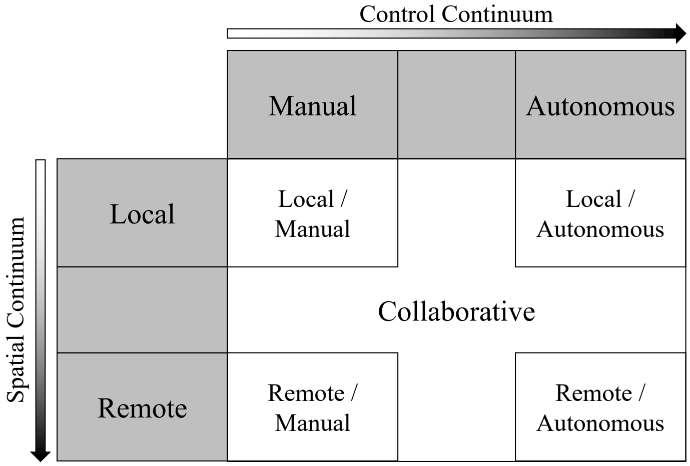


Fig. 3 Simplified View of Human-Machine Spatial and Control Continuums

4. *Special System Modes*

There are also special system modes that an operator may initiate or encounter during surface activities. Some examples include *learning*, *maintenance*, *safing* (e.g., E-Stop), and *energy-saving/hibernation* modes.

B. Surface Support Activities

Surface support activities are tasks needed to *sustain* surface equipment and *enable* surface operations. *Surface support infrastructure* is the collection of facilities, systems, services, and resources (e.g., human workforces and their machines/tools) needed to enable and/or sustain the primary functions of the surface architecture (see *Section VI)*. In general, surface support refers to what it takes to make the primary surface capabilities available. That is, providing the necessary materials, tools, support equipment, and personnel (both on-site and remote) when and where they are needed to conduct the exploration, development, and sustaining activities on the surface. Examples of surface-based support (which also may be crewed, uncrewed, or collaborative) include:

- EVA and human surface mobility support
- Power production, storage, and distribution
- Logistics management
  - Supply and resupply
  - Inventory tracking
  - Storage and staging (e.g., spares, material, and utility equipment)
  - Calibration and fabrication
  - Waste management
- Ops Planning & Control
  - Planning and scheduling
  - External and multi-element coordination and execution
  - Health management (e.g., inspection, maintenance, and repair)
  - Resource management (e.g., personnel, equipment, materials)
  - Emergency management
- Fluids and gas servicing
- Environmental protection and control (e.g., monitoring, cleaning, shielding, and sheltering)
- Safety support and security (e.g., hazard control and access, information technology security)
- Handling, access, and transfer
- Construction and excavation (e.g., site preparation and maintenance)

- Support for in-the-field modification, upgrading, and expansion
- Training and certification

IV. Attributes Influencing a Sustained Long-Term Lunar Presence

A key goal of Artemis is to lay the foundation for a sustained long-term presence on the lunar surface and use the Moon to validate deep space systems and operations before embarking on the much farther voyage to Mars [7]. This section addresses the influence of *operability* and *supportability* attributes on architectural sustainability, and how investments in developing a robust mix of human-machine systems can improve these attributes and the effective use of surface crews.

***Long-Term Sustainability and the Influence of Operability*—**Lunar surface systems must be robust (highly operable) and capable of conducting both planned and unplanned operations for lunar exploration and development while keeping the surface systems available for continued use. The human-machine infrastructure needs to be able to execute planned operations dependably, which means the systems and the procedures need to be highly reliable and trusted. When unplanned troubleshooting or one-off upgrade tasks are performed, there must be flexibility in the system design and confidence in the operators to perform any type of contingencies that may be encountered. These planned and unplanned activities require attributes such as accessibility, repairability, maintainability, expandability, and safety to operate them effectively. To be affordable and efficient, the operations must be simple to perform (i.e., as few executable steps as possible) while requiring minimum support equipment and resources. The architecture must, however, not be so minimal to not satisfy all the stakeholders' objectives.

For planned operations, consider as an example the operability of subsurface surveying. This consists of mapping geological layering and locating the presence of frozen volatile ice for scientific purposes. These operations are time-consuming, highly repetitive, and effectively performed by rovers navigating grid-like patterns across the surface with minimal human supervision (supervised autonomous operations). Rovers may be equipped with ground penetrating radar to map the top 100m of regolith or a neutron spectrometer to investigate polar volatiles in the top meter of regolith. Performing subsurface surveying would be more costly and burdensome for surface crews. The benefit of augmenting surface crews with robotic surveying is that it can focus the crew's work on promising discoveries.

For unplanned operations, consider the example of troubleshooting and repairing a failed rover. An effective embedded rover health management capability can quickly isolate the problem to a faulty battery module. The assigned robotic caretaker is then informed of an upgraded, newly standardized battery module available in logistics storage to replace the outdated unit. The updated unit has improved performance and predictive remaining useful life (RUL) capabilities. The caretaker obtains and delivers the replacement unit and installation kit (e.g., tools and cables) to the rover, rapidly gains access to the rover's battery compartment, replaces the failed unit, and closes out the repair. The rover performs functional checks and verifies nominal operation.

The allocations of roles and functions to the operators (e.g., surface crews, remote operators/supervisors, and autonomous machine operator(s)) are frequently overlooked during the formulation and design phases of a mission unless the mission's emphasis is on robotics and autonomous operations. Job design, roles, responsibilities, and how agents (human and otherwise) are allocated to these must balance mission design attributes such as affordability, safety, reliability, operability, maintainability, supportability, and resilience to off-nominal situations. Implementing these capabilities after systems are designed and manufactured impact cost, schedule, and performance. Identifying architectural features and labor-intensive operations early in the design process, which robotic/autonomous agents should efficiently perform, will improve mission effectiveness, and reduce crew burden.

Long-Term Sustainability and the Influence of Supportability—As humans extend farther from Earth for longer periods of time, supportability becomes a much more significant factor. Supportability describes the ease with which a particular system can be ensured to remain operable in a given context, as a function of a broad set of system characteristics that drive the amount of logistics and support resources required to enable safe and effective system operations [8, 9]. For an affordable, cost-effective, and sustainable surface architecture, it is essential that a supportability strategy be an integral part of the architectural design to ensure robust availability of elements while maintaining low life cycle costs. For example, Space Shuttle operations and maintenance activities were complex and expensive to support, in part due to a lack of interchangeability and accessibility for certain components [10]. The need for a supporting infrastructure will also exist for the Moon-to-Mars enterprise. Fully addressing and accounting for Earth-based, in-space, and surface-based support needs will be the key to long-term sustained Artemis and Moon-to-Mars operations.

A supportability approach is required throughout the life cycle to influence the operational effectiveness. Operational effectiveness is a composite of performance, availability, process efficiency, and life cycle cost, and is best achieved by influencing early design of the architecture. During the design phase, supportability-focused analyses ensure that the systems and components that are most likely to require maintenance can be serviced quickly and efficiently. During the operational phase, supportability functions such as spares acquisition, system maintenance, training, and planning activities are major contributors to life cycle costs. Failure to consider supportability from the beginning of design can result in system support requirements that cannot be satisfied within performance capabilities. Optimal operational effectiveness requires balance between system effectiveness, life cycle cost, logistics mass, crew time for maintenance, and risk to achieve mission objectives in a safe and cost-effective manner.

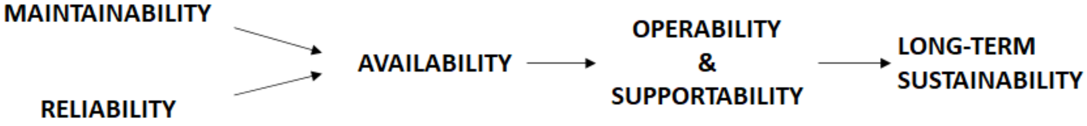


Fig. 4 Simplified Path to Sustainability

While Fig. 4 does not show all the influences, understanding these cause-and-effect relationships in decision-making during development and deployment of the surface architecture will greatly increase the probability of success in achieving the objective of long-term sustainability. There are several ways this can be approached. One way is to implement commonality, standardization, and interchangeability whenever possible. For example, standardizing interfaces, components, processes, procedures, tools, and repair kits creates an effective, cost-efficient, and sustainable architecture throughout its lifecycle and will greatly improve interoperability [11]. In this case, any single spare can address the greatest number of potential failures. Two notable concerns with this approach are the compatibility of using common design components in different applications within extreme lunar environments and the potential for common cause failures. A second approach is to enable repair at the lowest feasible hardware level, thus resulting in the physically smallest possible spares. Another method is to enable repair of failed items either as an alternative to removal and replacement or as a means of recycling a failed item to later serve as a spare. A fourth approach is aimed at significantly improving the long-term reliability such that the need for maintenance is reduced. For example, the addition of self-correcting systems may be a viable option. Finally, another approach uses a multi-supplier acquisition approach that brings in the factor of competitiveness. A combination of these approaches provides a robust supportability strategy.

Effectively applying reliability, maintainability, and availability (RMA) design principles during the design phase of a surface architecture can avoid significant costs and improve supportability throughout its life cycle. Rework of any system to retrofit operational efficiencies (operability) can be costly when identified late in the life cycle. A lack of RMA will be evident in unexpected failures, higher maintenance costs, and longer downtimes resulting in reduced system availability. Therefore, a well-executed, integrated, and balanced approach that addresses RMA across hardware, software, and the entire architecture can provide meaningful cost efficiency and improve system availability.

Availability is a function of Reliability and Maintainability (R&M). It is the probability that a repairable item will perform its intended function at a given point in time (or over a specified period) when operated and maintained in a prescribed manner [12]. In other words, design first for reliability. If reliability is not sufficient, then design-for-maintainability techniques must be employed. The performance metric of availability is a mathematical function of reliability and maintainability [13]. To illustrate this performance metric, Table 1 dramatically demonstrates the importance of this relationship by showing the order-of-magnitude of availability relative to down time.

Table 1 System Availability Percentage Performance Metric

Availability %	Downtime per year	Downtime per month	Downtime per week	Downtime Mission to Mars (1200 days)
90% (one nine)	36.5 days	3 days	16.80 hours	120 days
95% (one and half nines)	18.25 days	1.5 days	8.40 hours	60 days
99% (two nines)	3.65 days	7.20 hours	1.68 hours	12 days
99.9% (three nines)	8.76 hours	43.20 minutes	10.08 minutes	1.2 days
99.99% (four nines)	52.56 minutes	4.32 minutes	1.01 minutes	2.88 hours
99.999% (five nines)	5.26 minutes	25.92 seconds	6.05 seconds	17.28 minutes
99.9999% (six nines)	31.54 seconds	2.59 seconds	0.60 seconds	1.73 minutes

Based on these guiding principles, an approach for uncrewed lunar operations and support will be described in the following sections.

V. Lunar Architecture Context

For this paper, a notional top-level context diagram (see Fig. 5) relates architecture environments to functional interfaces. Within a larger Moon-Mars context, the lunar architecture functions and interfaces are encompassed within several major environments: Earth, cislunar, and lunar surface. Additionally, the Mars environment is also important in this context. Certain Earth-based functions interact directly with the lunar surface, while other ground functions interact with the cislunar environment. The lunar surface also interacts with the cislunar environment.

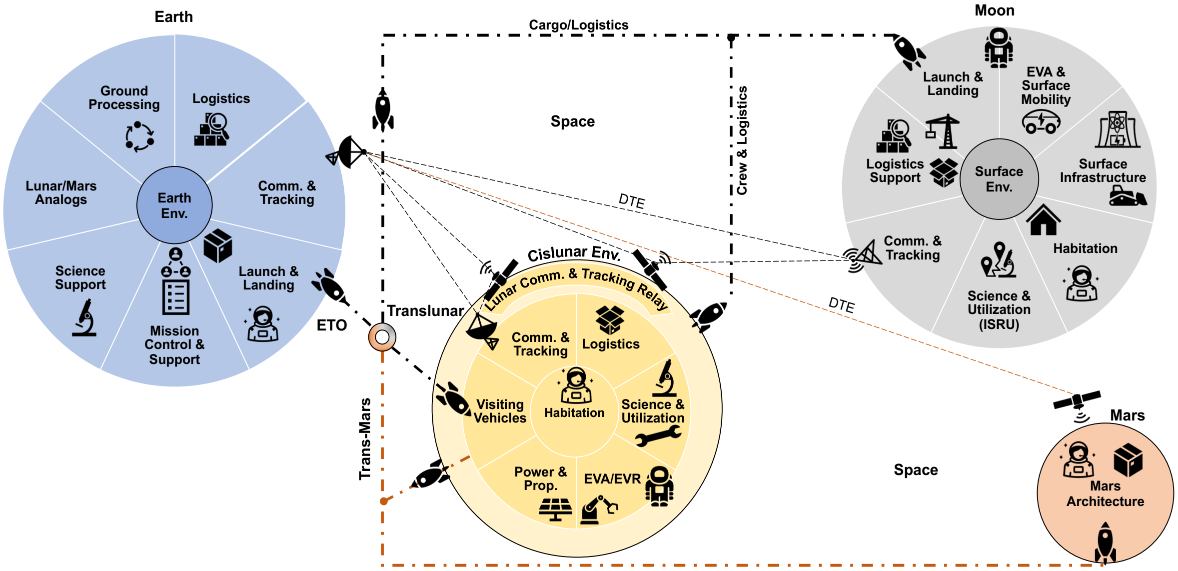


Fig. 5 Notional Lunar Architecture Context Diagram

Earth Environment—An environment of functional capabilities supporting and sustaining the lunar architecture, including ground support to both cislunar and surface environments. Typical Earth-based functions are itemized in the above diagram.

Cislunar Environment— An environment of functional capabilities that are aggregated in cislunar space, such as those embodied in a lunar Gateway. Cislunar-based functions are itemized in the above diagram.

Lunar Surface Environment— An environment of functional capabilities that support human and robotic activities on or from the lunar surface, while also an extreme space environment analog for living and working on other worlds, such as Mars. Lunar surface-based functions will be further described in Section VI.

Mars Vicinity—An environment of functional capabilities that support human and robotic activities in Mars vicinity. Note: Mars-based functions will not be covered in further detail in this paper.

Within these environments are specific functions that interface with other environments and among themselves. Depicted in Fig. 5 are the types of interactions typically found across these environments, which involve the routine movement and exchange of material, energy, information, and personnel. This presents both an unprecedented deep space logistical support challenge, and limitless and exciting opportunities for innovation.

Within this context, the next section describes in further detail one way to begin conceptualizing lunar surface operations and support—and that is by first laying out the general functions.

VI. Concepts of Lunar Surface Operations and Support by Function

This section summarizes specific areas of lunar surface operations and support activity, but does so across a broad timescale. Regardless of the timeframe of interest, the operational features and capabilities of the envisioned lunar surface architecture promote a balance of lunar science, resource utilization, and technology and operational demonstrations.

The functional coverage must include what is anticipated for early mission planning such as the initial sortie missions, which are planned for up to 6.5 days duration with a crew of two residing in and performing EVAs from the lunar lander. Following the initial period of human activity, a series of human missions will return to the Artemis Base Camp or perform sortie missions to nearby sites in the South Pole region. With under 2% of the total mission duration per year spent with the crew on the lunar surface, the envisioned surface architecture aims to provide effective and efficient utilization of periods of availability for deployed surface assets to accomplish mission objectives without crews, thus enabling surface crews to focus on higher priority tasks upon their arrivals. This presents opportunities to explore greater surface functionality.

To assure functional coverage across the intended scope of the Artemis effort, the major functional areas are first defined for the surface architecture in a long-term, sustained presence context. Then, each of these major areas are described in more detail, but are not restrained to early mission planning and development commitments. These descriptions present a brief *functional description*, a *system description* that includes both near-term mission plans and prospects for sustained presence, and a *concept of operations and support* activities.

The surface architecture can be sorted into five major functional categories: *Launch and Landing*, *Habitation*, *Science and Exploration*, *In Situ Resource Utilization*, and a set of *Shared Functions* that support the other four major functions (see Fig. 6). Additionally, there are functional interfaces and interactions that occur which are also depicted in the diagram. In general, these functional interfaces address the flow of materials, commodities, equipment, energy, information, and personnel across the surface.

Identifying these functions and interactions, free of system design specificity, allows future innovation across the surface architecture and across broad timeframes that extend into periods of sustained presence, and are general enough to reach into the future emergence of surface markets in a lunar economy. In other words, the functions should endure, and even be applicable for planning and organizing other extraterrestrial surface architectures, such as on the surface of Mars.

After the general functions are identified, then siting and master planning can be performed, along with specifying system designs, operations, and support infrastructure which together form the architecture. These function-by-function descriptions follow according to the diagram in Fig. 6.

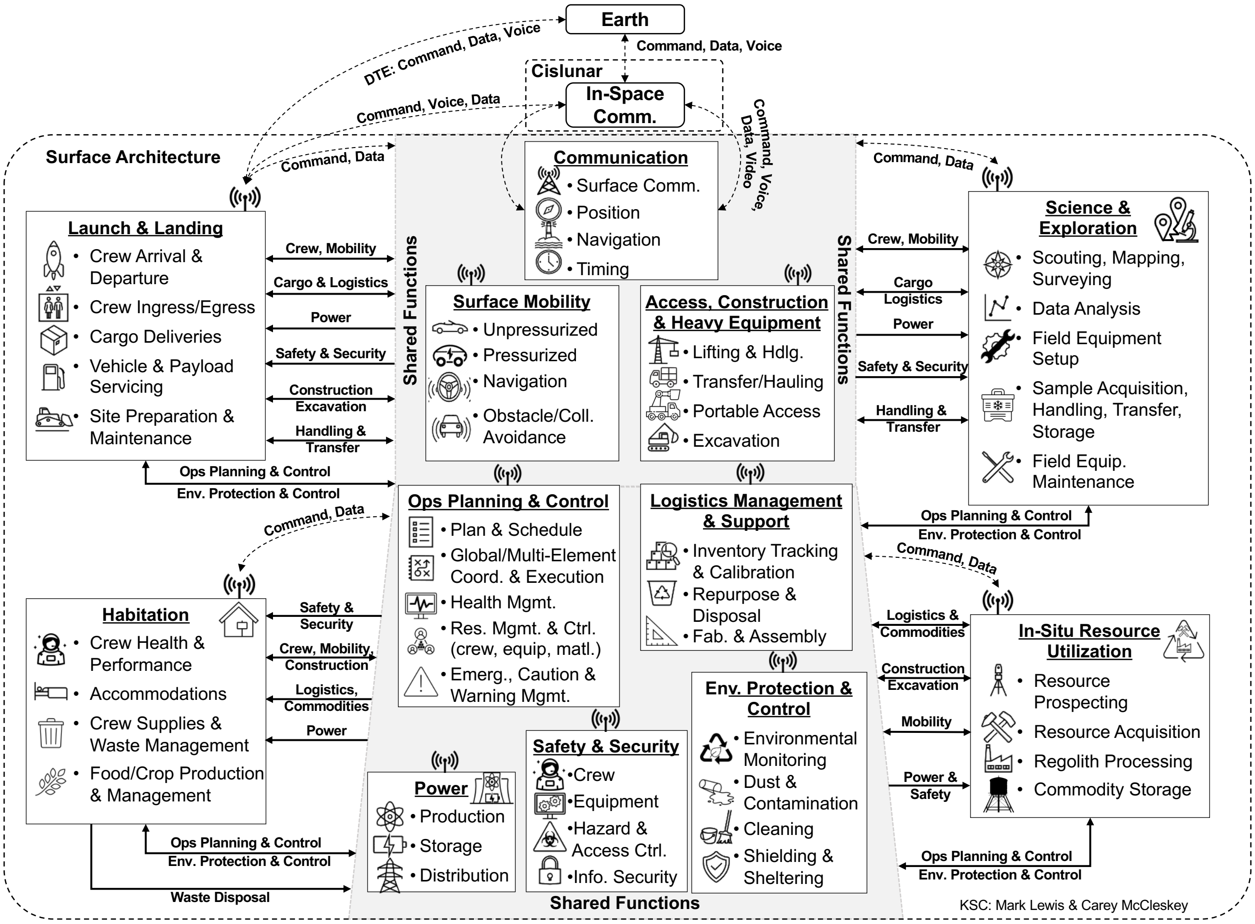


Fig. 6 Lunar Surface Architecture Functional Context Diagram

1. *Launch and Landing*

Functional Description—Launch and landing supports the arrival and departure of vehicles, such as crewed landing and ascent and uncrewed cargo deliveries. It also involves vehicle and payload servicing prior to departure, vehicle and system safing following arrival, ingress and egress of lunar surface crews, offloading and loading of payload and cargoes, and site preparation and maintenance of the launch and landing area(s). It will evolve from an unimproved site at the beginning of the exploration campaign to a more sustainable landing and launch area that can support repeated arrivals and departures.

System Description—Launch and landing systems include any surface-based elements, fixed or mobile, that are located at or near the landing zone. Currently, the Artemis architecture up to the initial human missions has not identified any dedicated launch and landing elements.

Landers themselves are not considered a surface element, but rather a transportation element. However, they could be repurposed for other functional uses. For example, a lander could be converted to a surface habitat or a commodity storage facility, becoming a surface-based element for the rest of its life cycle.

For the future, it is recognized that sustaining routine and critical arrivals and departures at the launch and landing site(s) may require improvements such as protective berms, prepared surfaces to mitigate plume ejecta effects, and dust control. Also, it may be useful for surface-based handling and access equipment to routinely load/offload cargo and for surface operators to access and maintain large vehicles. Additionally, equipment may be needed to reposition landers. To implement efficient vehicle servicing, methods for intelligent optimization of propellant/commodity long-term storage, preservation/conditioning, transfer, and loading will be needed. Active propellant servicing and conditioning equipment for cryogenic propellant preservation would need support services, such as power and communication, at the launch and landing area. Furthermore, these support services would be needed when ISRU surface-based liquid oxygen transfers become feasible.

Concept of Launch and Landing Operations and Support—Launch and landing operations may include emplacement of navigation beacons and communication equipment, real-time video and photography of landing/liftoff events, and element repositioning, such as portable utility power (applicable for other landed assets at other areas). Safing operations involve protecting the crew, critical vehicle systems, and any nearby emplaced surface systems. Site preparations, such as surface leveling, soil compaction, and berm/path construction, may be needed for a more sustainable launch and landing area capable of accommodating vehicles that are increasingly more reusable, and to reduce the effects of plume surface interactions and ejecta impacts on nearby surface assets. During surface missions, cargo and logistics may be delivered to the lunar surface via robotic cargo landers before the crew arrives or delivered with the crew in large landers. These shipments, which can arrive in pressurized logistics carriers, will deliver the supplies necessary to support crewed missions and include items such as food, water, equipment spares, etc. Providing the capability to retrieve, offload, and transport the logistics closer to the base of operations or remote field sites before the arrival of the crew will increase the overall efficiency of crew operations once they arrive [14]. In the sustained phase of exploration, other supporting services may be needed, such as lander propellant servicing, surface power services, commodity refreshes, and additional inspection, maintenance, and repair capabilities, to sustain a cadence of extended personnel stays and cargo arrivals and departures.

2. *Habitation*

Functional Description—Habitation includes crew health and performance, accommodation of living and working activities, crew supplies and waste management, and may also include food and crop management (production, distribution, storage, recycling).

System Description—Habitation system elements include both integral crew cabins in the lander and separately deployed surface habitats. A Surface Habitat (SH) is identified in the Artemis architecture and will be deployed following the initial human landings.

In the future, specialized habitats may emerge in the architecture, such as habitats for large-scale food and crop production, or workshops for fabrication, repair, maintenance, storage, calibration, and analysis in a conditioned environment for human sheltering (safe haven) and work activities.

Concept of Habitation Operations and Support—Surface habitation may involve supporting activation and pre-entry operations of habitats while the crew is in orbit at the Gateway preparing for landing. Operations may include bringing cabin environments (e.g., SH or large lander cabins) to a habitable temperature and air mix and activating other critical crew support systems. Potential crop production tasks could also include autonomous watering and tending. Additionally, when the crew departs, habitats may enter dormancy for the long period of uncrewed operation. A logistical staging area could also be collocated with nearby habitats. If so, staging operations for crew supplies, waste re-location, and recycling operations may be opportunities for uncrewed operations.

3. *Science and Exploration*

Functional Description—Science and exploration examples include scouting, surveying, and mapping; data analysis; field equipment positioning, setup, and testing; sample acquisition, handling, transfer, and storage; and field equipment maintenance.

System Description—Surface-based science and exploration elements are currently being identified in the Artemis architecture. Exploration is performed through rover traverses. Science instruments and supporting equipment are deployed at locations of interest. Science racks may be also collocated within the crew cabin (either on the lander or in the SH).

In the future, a habitat design could be repurposed as a dedicated science laboratory by outfitting it with scientific platforms. This approach provides an isolated environment for surface-based chemical analysis, non-destructive and destructive testing of samples, and other hazardous activities best performed separately from living quarters. These laboratory activities could be performed robotically or robotically assisted.

The location of science field equipment may be determined by criteria such as ease of surface crew access, specific geological features, terrain (permanently shadowed regions, PSRs), or others. Some science systems may be relocated and combined with other deployed elements. For example, a spent descent stage with residual propellant could be repurposed as an uncrewed science hopper that departs sub-orbitally to a new exploration site out of reach by practical rover traverses.

Concept of Science/Exploration Operations and Support—Surface exploration may involve scouting, surveying, and mapping of terrain associated with science-driven investigations. Scouting operations involve searching, imaging, and traversing the surface for potential scientific sites of interest for future missions. Surface mapping operations are broad in scope and consist of localized charting of the environment, such as illumination, temperature, and seasonal variations, and topographical mapping of the terrain. These operations will aid in determining optimal surface asset emplacements, navigational paths, and night-survival locations. Data analysis may be performed in the field before transport, identifying potential finds of scientific interest. For more detailed analysis, on-site laboratory facilities may be available. Data results may be transmitted to Earth-based scientists for evaluation and to help select samples to be returned at the end of a human mission. Science deployment operations will emplace and maintain field equipment.

4. *In Situ Resource Utilization (ISRU)*

Functional Description—ISRU functions include prospecting for resources, resource acquisition, processing of regolith into materials and commodities, and commodity storage.

System Description—The Artemis program is currently considering technology demonstrations and pilot plant systems for ISRU. Concepts for small prototype excavators and processing equipment are being developed. Sites are being investigated for the acquisition, transfer, and processing of regolith into resulting products.

Concept of ISRU Operations and Support—Resource prospecting, mapping, and characterizing possible resource sites are likely to be time-consuming and represent an opportunity for uncrewed operations between crewed missions. Mobile equipment operations may be needed in the extreme environments of permanently shadowed locations where resource extractions occur. Resource acquisition involves the extraction of the prospected resources utilizing various techniques such as excavation, microwave heating, and drilling, among others. Regolith processing operations involve methods to transform regolith material into useful products. These methods may include crushing/size-sorting/beneficiation, transfer into and through processing systems, extraction of target products (water, oxygen, metals, etc.), or others. The waste tailings generated during excavation and regolith processing would also need to be transported and deposited at a dedicated location. Any produced commodities can be stored at a centralized storage location for future use. Supporting ISRU operations and infrastructure are shown in the interfaces in Fig. 6, and are described in general below.

5. *Shared Functions*

Shared functions crosscut the lunar surface infrastructure for the primary functions listed above. Details of these functions and support activities are outlined below.

Communications

Functional Description—The communications function includes exchanging information from, to, and across the surface, and provides specific capabilities for positioning, navigation, and timing (PNT) information to all operators, local and remote.

System Description—NASA is engaging international and commercial partners to develop an extensible and scalable lunar communications and navigation architecture, known as LunaNet [2]. The LunaNet architecture will enable robotic landers, rovers, and astronauts on the Moon to have network access similar to networks on Earth [2]. It will provide users with three services: networking, PNT, and science utilization. The architecture encompasses a wide variety of topology implementations, including surface and orbiting provider nodes. LunaNet will provide users with an operational experience analogous to that experienced by users of the Internet on Earth.

In the future, surface-based communication relays may be needed and are presently under investigation. The results of these investigations may impact surface operations and support activities. Intelligently reconfiguring communication networks for optimized data management is envisioned.

Concept of Communications/PNT Operations and Support—NASA is presently developing the LunaNet Interoperability Specification and Concept of Operations. Once defined, the necessary uncrewed operations and support will be determined.

Surface Mobility

Functional Description—This function involves transporting crew, supplies, and equipment in unpressurized and pressurized surface vehicles, and navigation and obstacle/collision avoidance.

System Description—The Artemis architecture currently includes human surface mobility systems such as an unpressurized LTV for the initial exploration and a PR for extended multiday traverses. Therefore, the PR satisfies many of the critical habitation functions. Use of these vehicles to conduct crewed, uncrewed, and collaborative human-robotic operations for exploration and other surface support activities are being formulated (see Section III for definition of these operations and modes).

In the future, there may be fleets of such rovers across multiple field sites. These future rovers may feature advanced human-robotic interfaces (e.g., robotic arms with end-effector tools, augmented with vision systems, lighting, sensors, etc.) to support collaborative human-robotic mobility. Various mobility support facilities, equipment, and services could emerge into a surface mobility market as surface exploration and development activities grow. To sustain this future mobility market of rovers, a need for sheltered and conditioned service garages is likely. For example, supporting equipment may include jack and lift stands, and outfitting kits for specialized work packages, such as manipulators, mobile tool kits, hitches, trailered add-ons, and so forth.

Concept of Surface Mobility Operations and Support—Following delivery by a lander, the LTV will be activated, perform functional checks, and be deployed to the surface. The LTV will be ready for human and robotic exploration. It will extend the range of exploration on the lunar surface by scouting future landing sites, deploying experiments, collecting scientific data and samples, and conducting research. The LTV will also be available to transport cargo and crew supplies. It will be prepositioned in advance of subsequent landings and departures.

Following delivery by a lander, the PR will be activated, perform functional checks, and be deployed to the surface. The PR will be ready for human and robotic exploration. It will further expand exploration capabilities beyond the LTV, with increased surface performance (e.g., multiday crew traverses, speed and load carrying capacity).

Common features of human surface mobility systems that enable uncrewed operations include autonomous navigation in extreme environments (i.e., dusty, starkly lit, and high-grade terrains), obstacle/collision avoidance, and transport of surface logistics (see Section VII). Additionally, these systems may be deployed to support collaborative human-robotic operations for EVA crew rescue (i.e., incapacitated crew rescue). Such operations may necessitate bringing life support and/or medical resources, and/or retrieving a crew member and providing life support during transit.

Access, Construction, and Heavy Equipment

Functional Description—This function involves access for surface crews and robotic systems to connect between surface systems in the extreme lunar environment, and/or to provide portable access as needed. It also includes portable illumination, access lighting, environmental monitoring, lifting and handling (including rotating, reorienting, repositioning, grappling, manipulating, and handling associated with large-scale assembly operations, etc.), and transfer of large/heavy loads across the surface. Surface construction and excavation functions encompass tasks such as site preparations that include grading, soil compaction, and berm and path construction; excavation consisting of material handling, digging, trenching, tunneling, and drilling; and object manipulation for positioning, moving, and handling items needed during site preparation and operations.

System Definition—Surface-based access, construction, and heavy equipment elements are currently being identified. Davit cranes and roll-off ramps are being considered for certain landers and the SH.

In the future, large landers and their cargo will be arriving. As a result, heavy loads are expected to be handled and transferred, which will create the inevitable need for what is often referred to in ground architectures as heavy equipment. These systems may include telescoping buckets for access by surface crews and robotic equipment, portable/collapsible access tunnels, automated scaffolding and specially constructed access, utility and/or service towers, and lifting, moving, grabbing, and other handling devices. These may be fixed or mobile devices, such as cranes, hoists, jibs, davits, surface flatbeds, haulers, and self-propelled modular transporters (SPMTs).

Concept of Construction and Heavy Equipment Operations and Support—While not anticipated for early Artemis missions, it is foreseen that portable access, construction, and other heavy equipment will need to be made available to surface operators in the future. Equipment for loading and offloading large, prefabricated elements, as well as for other construction and assembly tasks, may be more efficient through surface-based handling and transfer means than burdening commercial lunar lander transport services. Surface-based mobile cranes, haulers, drilling, boring, and other devices, or work packages are envisioned to arrive, while their number of uses is expected to grow. Such equipment is also envisioned for long-term sustainment and expansion of capabilities at surface sites, and thus may begin to form another market of activity. Emplacement of additional power units and expansion of ISRU capabilities is also expected to grow, further requiring such heavy equipment support services. Excavation operations, preferably performed by remote operators, involve preparing small prototype areas at first, but then removal of large quantities of regolith material for resource utilization, site preparation, and construction is expected. Excavation may be performed by multiple robotic vehicles and will require high operational cycles. Beyond the normal use of this equipment, supporting the repair and maintenance tasks and determining efficient and effective methods and techniques for inspection, maintenance, and repair of heavy equipment assets will need to be included in large-scale services as that market emerges.

Power

Functional Description—This function produces electrical power at the surface and distributes the power to various surface users. It also includes deploying power cables, mating/demating electrical connections, and storing energy.

System Description—Systems under consideration in the Artemis architecture include Fission Surface Power (FSP) element(s) with associated surface distribution lines, and portable power units.

In the future, power demands will grow in scale. Meeting these demands will involve power distribution (fixed and portable) where needed. As such, a market for fixed and mobile surface power, energy storage, and distributed power services will grow. The ability of surface crews to keep up with this demand represents an area for highly autonomous power technologies and optimization for the most efficient collection, storage, and distribution.

Concept of Surface Power Operations and Support—The FSP element and its supporting distribution equipment provide power to surface elements as needed across the ABC to supplement day-to-day operations and survive lunar nights. Uncrewed support of this power system includes any initial LTV-assisted deployments of cables and other distributed equipment, associated electrical connections, and system testing and activation operations. Robotically performing some inspections, maintenance, or repair tasks on the power distribution equipment could reduce the surface crew workload. Construction of berms would provide protection from radiation produced by the FSP where the terrain does not provide such protection.

Operations Planning and Control

Functional Description—Surface operations planning and control involves preparing, prioritizing, scheduling, and executing tasks driven by the functions (those that have been implemented) in Fig. 6. This function also includes global/multi-element coordination and execution, health management, resource management and control (crew, equipment, and materials), and emergency and caution/warning management. Additionally, the health management function addresses the assessment and restoration of functional integrity through inspection, maintenance, and repair of faults within the surface architecture. These operations planning and control functions may be performed by a combination of remote operators, surface crew, robotics, and/or automated systems. They enhance decision-making and help to ensure that constraints are not violated. The operations planning and control function must also coordinate with supporting logistics functions (see Section VII).

System Description—While this function is mostly considered as software and algorithms managed by supporting personnel, the need for a system of control consoles, servers, and facilities to support this function may emerge in the future. In the future, an operations planning and control system is envisioned to fully support a Logistics Management System (refer to the logistics management function and Section VII).

Concept of Planning and Control of Surface Operations and Support—An operations planning and control system is employed where tasks are planned during continuous periods of uncrewed operations using a flexible set of tools to comprehensively manage, control, and adapt to an everchanging configuration while coordinating and allocating the supporting resources when and where needed. Integrated, automated surface planning, scheduling, and decision-making tools are used to automate the process of determining, prioritizing, deconflicting, and scheduling the surface activities (those that have been implemented in Fig. 6). The lunar surface health management system detects, predicts, and anticipates faults/failures within the architecture. It can reconfigure and restore lost functionality and maintain system integrity while still in use. Preventive maintenance operations are performed as needed or on-demand. Prioritization of assigned tasks and resources depend on the availability of supplies, commodities, equipment, and personnel (remote and on the surface). Critical operations (such as life support) take precedence over non-critical tasks. The surface health management system oversees and coordinates with robotic devices to perform inspection, maintenance, and repair activities of deployed surface systems with minimal human interaction required. Repair activities include restoring and re-verifying the functional system integrity by performing physical inspections and/or self-checks, troubleshooting and isolating the failure, gaining access to replace/repair the faulty asset, restoring (closing out) disturbed area(s), re-servicing or recalibrating as needed, and performing post-closeout verification of all restored functionality. These maintenance and repair activities are supported by a cataloged set of standard tools and supplies such as cameras, grippers, screwdrivers, socket wrenches, scissors, drills, pliers, cutting wheels, and others. Standard maintenance and repair procedures are nominally initiated by remote operators, or initiated through executive control, and performed by robotic caretakers with minimal human oversight. However, the health management system does not preclude the surface crew, at any point, from taking control to complete these activities if necessary. A learning capability is envisioned for surface operations planning and control. This advanced learning capability monitors operational and/or environmental state data to develop process models by employing machine learning strategies that optimize surface activities. It also predicts surface system performance, determines relationships among disparate data sets, adjusts system parameters, etc.

Logistics Management

Functional Description—The logistics management and support functions are essential for sustainable surface architectures. These functions provide material, information, and supplies to sustain other surface functions as well as inventory management, asset tracking, calibration, repurposing, fabrication, assembly, and disposal of materials as needed. Logistics management and support functions are also tightly coupled with surface operations planning and scheduling functions to maintain, reconfigure, or repair other surface systems.

System Description—Integrated Logistics Management consists of the following: a logistics management system, a supply chain management system, cargo containers and packaging, surface logistics delivery systems and services that make supplies and equipment available to surface operators, and surface transportation and storage systems that perform packaging, unpacking, handling, tracking, transporting, and delivering of items to, from, and across the surface. It also addresses end-to-end waste management, including recycling. Packaging systems and containers are used for both pressurized and unpressurized supplies and equipment. Additionally, concepts are under development for robotic umbilical transfer of fluid and gas commodities (water, breathing air, propellants, other commodities). Under consideration for Artemis missions' logistics needs are Small Pressurized Logistics Containers (SPLCs). Standardization of logistics management and supporting systems are currently under consideration. Logistics systems will be further discussed in Section VII.

In the future, more optimized logistics management systems will be required to sustain an efficient flow and transport of materials, equipment, energy, information, and personnel. Increases in component commonality, reuse, and multi-use capabilities can significantly reduce the dependence on resources sent from Earth, while improving self-reliance. Inventories may be distributed and stored in surface depots or caches. Efforts to reduce, reuse, or recycle items should be incorporated.

Concept of Logistics Management Operations and Support—Surface logistics are managed by identifying and quantifying resupply needs in terms of material and energy supply across the surface architecture. The surface logistics management system has the knowledge of supply constraints, storage constraints, and disposal, recycling, and boneyard requirements, as well as distribution constraints. It also has the capability for exchanging information with off-surface logistical tools (e.g., Earth, Gateway, HLS). Further discussion of lunar surface logistics and support can be found in Section VII.

Safety and Security

Functional Description—Surface safety focuses on the consideration of risks resulting from hazards that can affect the crew, the environment, or the surface assets, and ensures safety controls are directed toward risk drivers to reduce or mitigate the risks to an acceptable level throughout all phases of the surface architecture. Surface security encompasses both physical and information access control, privacy, and security functions.

System Description—Systems for implementing safety and security needs are being investigated. Efficiently and effectively establishing physical controls for any lunar surface areas and associated hazards are under consideration. At this time, no specific dedicated equipment needs have been identified for near-term Artemis missions. Information technology security is, of course, needed, and is being addressed in the Artemis architecture.

Concept of Safety and Security Operations and Support—For safety consideration, establishing keep-out zones, restricted access for hazardous operations, and the use of robotic systems to minimize human exposure to hazards are important. For security consideration, access control of physical surface assets may be included as part of operations processes and procedures to ensure integrity of the items. Sharing information among governmental, commercial, and international users necessitates the imposition of rules and policies, such as export control, to manage data security and privacy concerns. Security measures for user access enhances user privacy.

Environment Protection and Control

Functional Description—Environmental protection and contamination control is a critical crosscutting function necessary to minimize environmental impacts on planetary surfaces during exploration activities, and in habitats. Functions include environmental monitoring (e.g., space weather forecasting affecting surface operations), dust and contamination control, cleaning, and shielding/sheltering.

System Description—Systems associated with environmental protection and control are being accommodated in the currently identified Artemis elements (landers, PR, SH, LTV, and EVA suit systems).

In the future, advanced electrodynamic dust shields and coated surfaces, along with other environment monitoring and control technologies, are likely to become standard equipment as experience proves their effectiveness. There could be a market for lunar surface cleaning and contamination control services, much like the ones in existence on Earth. Highly autonomous cleaning equipment, methods, and techniques are likely to be incorporated over time as surface activities grow. Concepts for shelters and shielding materials constructed of lunar materials are being researched for sustained habitation and sheltering of major surface-based assets.

Concept of Environment Control and Protection Operations and Support—EVA and ISRU operations and extensive long-term human settlement will affect the surface environment. Monitoring and managing biological and organic contaminants are especially required to protect the science conducted on a planetary surface. Geological samples and resource extraction experiments need to be pristine and free from any contamination by other samples, habitat gases, dust, or other human-generated materials.

VII.Concepts of Uncrewed Lunar Surface Logistics and Support

A critical component of enabling sustainable scientific exploration on the lunar surface and Mars is a robust, repeatable, and reliable lifecycle logistics and supply chain architecture. Scientific exploration is constrained by the breadth and scope of the logistics necessary to support it. During the design phase for key systems supporting the sustained lunar architecture, decisions need to be made concerning long-term operations including supportability, reliability, system repair, and maintenance, as were previously discussed in Section IV - *Attributes Influencing a Sustained Long-Term Lunar Presence* and in Section VI - *Operations Planning and Control*. In addition, supply support activities such as sparing approaches, cargo packaging, handling, storage, and transportation cannot be made independent of logistics life cycle considerations. Sustainability of this endeavor is contingent on a robust and resilient surface logistics system capable of providing Integrated Logistics Support (ILS) by pulling together all these functions into a coordinated support capability. Thus, the surface logistics system is critical in supporting the Operations Planning and Control System.

For Surface Logistics, the ILS consists of a complex interconnected system of processes, software, hardware, and best practices that can enable the efficient and effective development of a commercial lunar surface logistics supply chain in the decades to come. It will need to be designed to minimize the logistics footprint and the amount of crew time needed to transport, load, unload, pack, and unpack logistics items, leveraging autonomous operations and/or teleoperations to the maximum extent possible. The ILS will need to support lunar surface logistics resupply with sustainable solutions that enhance the lunar system's support posture, and ensure a viable industrial base for reliable sources of quality spaceflight hardware that can be reconfigurable or offer hardware commonality across multiple systems.

To better conceptualize the requirements for this support system, the ILS can be categorized into several general capabilities that are critical to a successful ILS solution that will support both the scientific utilization community as well as human habitation. These capabilities are currently in definition as the Artemis Program evolves its requirements from development to the sustaining phase of lunar and Martian exploration include:

- Logistics Management: End-to-end logistics system management focusing on maintainability, supportability, and reliability, including campaign-level logistic modeling and planning,
- Supply Chain Management: Data system(s) and tools for supply chain management including tracking and location identification of surface bound inventory, and maintaining supply chain resiliency,
- Cargo Containerization/Packaging: Pressurized and unpressurized cargo carriers extensible for human consumables as well as scientific experiments, payloads, tools, spare parts, etc.,
- Surface Delivery: Delivery options to the lunar surface for cargo and commodities encompassing the various lander options envisioned for the Artemis Program,
- Surface Transportation and Storage: On-surface cargo transportation capabilities including robotic and autonomous operations (e.g., payload off loading, movement, transfer, and final storage of cargo), and
- Waste Management: Methods and processes for collecting, storing, and potentially re-using or recycling trash and waste.

Lunar Surface Logistics Management is very broad in scope and encompasses the entire life cycle of the surface architecture: development, deployment, sustainment, and disposal. It includes the managing, storing, and tracking of crew consumables (food, clothing, etc.), life support system consumables (breathing air, water, etc.), and supplies and materials to sustain surface assets. The logistics management function also plans, schedules, and coordinates surface transportation and other support functions, such as robotic assistants, to unload and transport logistics service modules, unpack, and stow their contents, and retrieve needed tools, supplies, and materials, as well as provide instructions in support of maintenance activities. In addition, it also identifies materials, structures, systems, assemblies, and components that can be recycled or repurposed for another use, contains hazardous and non-hazardous waste, manages the disposal of waste generated from crewed (dry and wet trash) and uncrewed activities (waste products such as packaging materials; old, broken, and unrepairable tools and parts; and spent and unwanted materials), and locates disposal areas (boneyards). Other support services may include inspection, cleaning, calibration, and storage of processed ISRU resources.

Supply Chain Management is one of the key capabilities to an ILS objective of enhancing system operational availability. This long-term operational availability posture, however, is ultimately determined early during the systems design phase of the lifecycle. It is during the early design phase that the logistics inherent availability is determined, from which the recurring support requirements and costs can be estimated. This makes it critical that logistics requirements are identified during the design phase for improved upfront logistics planning and optimal supply chain development. A supply chain consists of an integrated network of materials and information flow, supporting a common hardware spare and repair philosophy throughout a program for long-term support of space exploration. This process consists of the suppliers and pre-positioned logistic nodal points, in addition to field centers and facilities with consistent product data taxonomy, needed to support the Artemis mission that will support Artemis elements throughout the program's life. For lunar surface, it is anticipated that significant portions of this supply chain will be supported by uncrewed operations to minimize crew time needed to distribute and preposition commodities, spares, and other supplies.

Cargo Containerization and Packaging includes a standardized capability of logistics carriers for transporting cargo. For a sustained presence on the lunar service, objectives for the design of these carriers would include optimal logistics carrier mass and volume for cargo transportation (i.e., reduced tare weight); minimal amount of crew time needed to locate, transport, load, and unload logistics from lunar landers; minimal amount of crew time needed to pack, unpack, and store cargo items from any logistics carriers; minimal risks for hazardous logistics operations in extreme surface environments (e.g., pressurized gas transfers, logistics carrier crew handling, minimize dust transfer); minimal logistics footprint and maximal reuse of logistics carriers; maximal common interfaces and interoperability; and maximal sustainable solutions with reliable sources that can support on-time and reoccurring requirements for sustained logistics deliveries. These containers would be incorporated into operations architecture in such a way to maximize the ability for use with uncrewed operations.

Surface Logistics Delivery, including pressurized and unpressurized logistics service modules and commodities, will be delivered periodically to the lunar surface by commercial or international partners. Offloading these logistics will be accomplished by an offloading capability that maximizes the use of uncrewed operations. Since the lunar surface will be unoccupied by humans most of the time, robotic caretakers capable of precision positioning, aligning, and manipulation of objects may be used to remove, install, and stow supplies and equipment.

Surface Transportation & Storage includes packaging, handling, storage, and transportation of cargo and commodities. Pressurized and unpressurized logistics service modules will be delivered periodically to the lunar surface by commercial or international partners. Offloading the logistics containers and commodities will be accomplished by cargo and commodities offloading capability, while transporting them to a central logistics depot at or near the Artemis Base Camp or to a staging location in the field will be performed by the LTV and PR. Since the lunar surface will be unoccupied by humans most of the time, robotic caretakers capable of precision positioning, aligning, and manipulation of objects may be used to remove, install, and stow supplies and equipment. Resupply of certain consumables with ISRU derived products (e.g., water, oxygen, propellants) produced on the surface and requiring storage is also possible.

Waste Management is vital for a long-term sustainable human presence on the lunar surface. Many waste management activities are anticipated to be performed by humans; however, the use of automation and robotics can greatly reduce the burden on the crew. In the SH and PR, the crew will be responsible for cleaning up their own wastes after each meal including compressing food packages, wiping clean trays, utensils, and food preparation areas used, and storing all equipment and wastes. The crew will also be responsible for disposing of their personal hygiene products and keeping their personal areas clean. The recycling of human wastes, on the other hand, must be an automated process. The crew may perform periodic checks of these systems when present, but the systems should be capable of operating with minimal human intervention. Other waste management tasks that could be automated and performed without the crew include collecting, compacting, sealing, transporting, and storing trash and waste until disposal. Depending on the methods of disposal pursued, they too could be automated. In any case, the managing and disposing of waste in an environmentally friendly manner is critical on the Moon.

VIII. Extreme Lunar Environment Impacts on Integrated Surface Operations Planning

When planning surface operations on the Moon, there are distinct environmental factors that set it apart from Earth: its lower gravity (1/6g), its virtual lack of an atmosphere, its soil characteristics, its extreme surface temperature fluctuations, its illumination conditions and permanently shadowed regions, and its exposure to space radiation. Another factor is the induced environmental effects of plume surface interactions and ejecta impacts on nearby surface assets.

To aid in surface planning activities, a team supporting the formulation of uncrewed lunar surface operations is in the early stages of developing an integrated lunar operational environment simulation tool that is accessible to various users with existing computing hardware. It will be a capability that addresses a gap and does not compete with other existing agency simulation/visualization tools. The tool integrates preprocessed data sets from known and trusted sources and visualizes the information in an interactive, user-friendly manner. It is referred to in this paper as Lunar Uncrewed Exploration Tool (LUNEXT).

A few of these major environmental factors will be further described along with visualizations from LUNEXT.

A. Dust

Lunar dust is a serious issue to crew health, performing EVAs, and operating and maintaining surface systems. Regolith particles are very rough, jagged, and irregular. Because of their shape, they tend to pack together along the long axes [15]. Based on Apollo samples, lunar regolith is composed of grains ranging in size from medium sand to fine silt. The median particle size is 40 to 130 μm, with an average of 70 μm [15]. Nearly half of the regolith is finer than the human eye can resolve, and roughly 10% to 20% of the dust is smaller than 20 μm [15]. Particles also adhere to surfaces due to gravitational, Van der Waals, capillary, mechanical, and electrostatic forces. The Van der Waals force is the strongest, but only for extremely small particles of 10 μm or less. Increasing the surface roughness can significantly reduce the effects of this force [16].

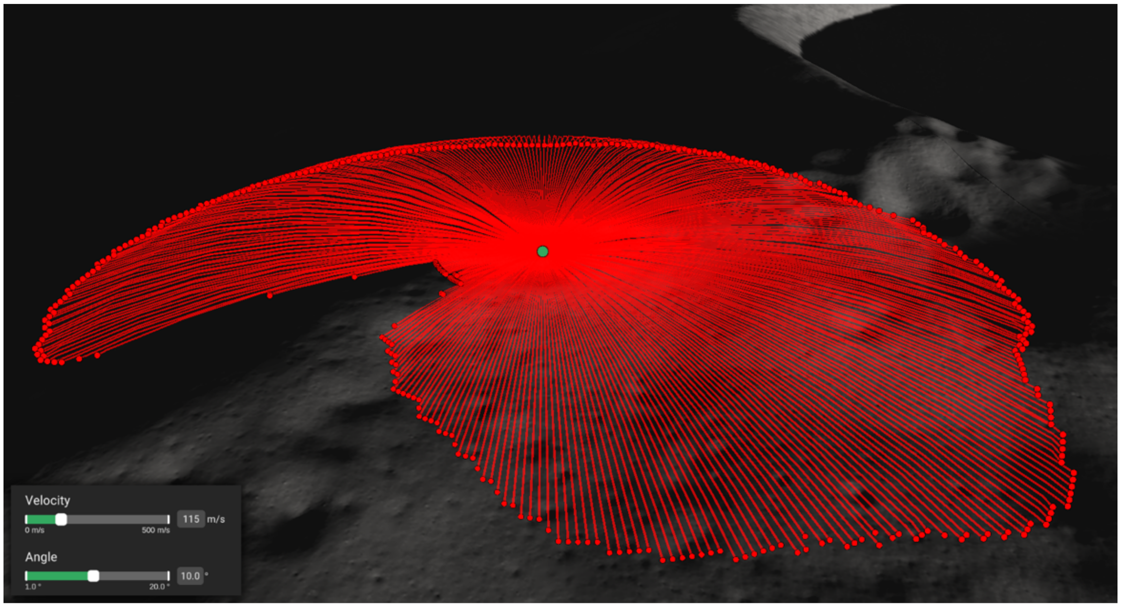
Managing the effects of dust is vital for safe and effective surface operations and may be accomplished through operational mitigation methods with the aid of robotic systems. Post-EVA dust mitigation activities might include aiding in bagging, brushing, and cleaning, or using an airlock/air shower to remove dust and limit the crew's exposure before entering a habitable area. Another robotic use case includes surface preparation, such as compacting the regolith or using vacuum-stable spray-on thermoset polymers that create dust-reduced zones around operational areas that receive human-machine traffic. Maintenance activities, including removal, repair, and replacement, must consider dust intrusion during these operations. Operating and maintaining surface systems may require dislodging and cleaning dust from equipment to ensure optimum performance (e.g., solar panels) and minimize wear (e.g., dust in motors, gearboxes, rotary mechanisms, abrasion in seals, electrical connectors). These are a few examples that could be performed robotically.

B. Plume Ejecta

Surface plume mitigation minimizes plume-surface interactions (PSI), surface erosion, and high-speed ejecta produced by planetary landers during landing and ascent. Generally, the top few centimeters of lunar regolith are very loose, and it becomes more compacted as the depth increases. During the Apollo program, the optical mirror on the Surveyor III spacecraft was damaged by debris and pitting due to landing [15]. In addition, two coupons from the Surveyor III spacecraft facing the Apollo 12 landing site were analyzed, showing an average of 103 pits/cm^2 [17]. The data indicated that the spacecraft was not exposed to the direct spray of the landing Lunar Module but was exposed to the fringes of the ejecta plume [17]. If it had been exposed to ejecta, the damage would have been orders of magnitude higher [17]. While Apollo landers demonstrated that it is possible to land on an unprepared surface, landing multiple, proximal assets will pose an unacceptable risk to nearby surface equipment.

Mitigating the dangers of plume ejecta on nearby surface equipment may be achieved by surface preparation, using physical barriers (e.g., berms), or the natural surface topography. Launch and landing area surface preparations may be performed robotically, and involve soil compaction, additive manufacturing, placement of premade pavers or fabrics, regolith sintering, polymer coating, or some combination of these techniques. Berms and blast protection can be constructed robotically with locally sourced materials to shield sensitive fixed equipment from the ejecta. Operational planning aids in robotically deploying other fixed assets at a distance to prevent damage from the ejecta. Mobile equipment, however, is prepositioned at a safe distance before launch and landing events. These examples rely on uncrewed operations performed by robotic equipment.

LUNEXT allows users to select an impingement point and simulate plume ejecta on the lunar surface environment, adapted from a process designed by NASA Kennedy Space Center (KSC) scientists [18, 19]. The 80 meter/pixel Lunar Reconnaissance Orbiter (LRO) Digital Elevation Model (DEM) is sampled outwardly at various azimuthal angles, and impact points are calculated at these azimuths by the orbital physics and trajectories equations. After selecting an impingement, users can vary the range of velocities (0 – 500 m/s) and angles (0 – 20 degrees) using two sliders for rapid changes to the visual representation of the simulated ejecta. As shown in Fig. 7, the natural surface topography affects the travel distance of the ejecta.



Velocity 115 m/s

Angle 10.0 °

Fig. 7 LUNEXT Simulated Plume Ejecta

C. Surface Illumination & Localized Shadows

The polar regions have the most extreme range of illumination. The Sun is constantly low on the horizon; thus, the insides of polar impact craters receive no direct sunlight and have become permanently shadowed regions (PSRs). Other locations, however, receive sunlight up to 72% of the year [20]. Illumination conditions improve with elevation above the surface (e.g., 2m above can have solar illumination up to 86% of the year [20]). Since the Sun never rises much beyond a degree above the horizon, long shadows are cast from topographically elevated areas, affecting illumination conditions and surface temperatures.

Surface illumination and localized shadows pose distinct challenges. Supplemental lighting is needed to perform tasks and for imagery to be acceptable. Surface mapping operations to chart the local illumination conditions are time-consuming and could be performed robotically. These operations can inform optimal surface asset emplacements, navigational paths, night-survival locations, and possible EVA durations in PSRs.

Night-survival operations may include thermal management, battery pre-charging, and load shedding. Some surface systems may hibernate through the night, and then awaken and continue nominal operations. Mobile assets may use a more adaptive approach to optimize their power and operations; one method is to follow the sunlight. For example, in the lunar polar regions, a rover could be designed to follow the light, and remain illuminated for up to 94% of the year [20]. In this example, the average traverse speed would need to be 2.5 meters per hour, with a maximum speed of 30 meters per hour [20]. Even with those mitigating operations, there would still be about 100 hours of eclipse during a year [20]. These operations may be initiated remotely, automated, or accomplished by supervised autonomous operation.

The two images in Fig. 8 are average illumination maps of the connecting ridge near the Shackleton crater. The data source is LRO Lunar Orbiter Laser Altimeter (LOLA) with a resolution of 60 m/pixel. LUNEXT uses the LRO LOLA average illumination map [21] and displays the data using adjustable heatmap overlays that are color-coded, representing data ranges. Users can adjust the range and opacity of the overlays for improved visualization. For example, the first image shows the average illumination over the entire range (0-100%), while the second image shows only the areas with an average illumination of 50% and above.

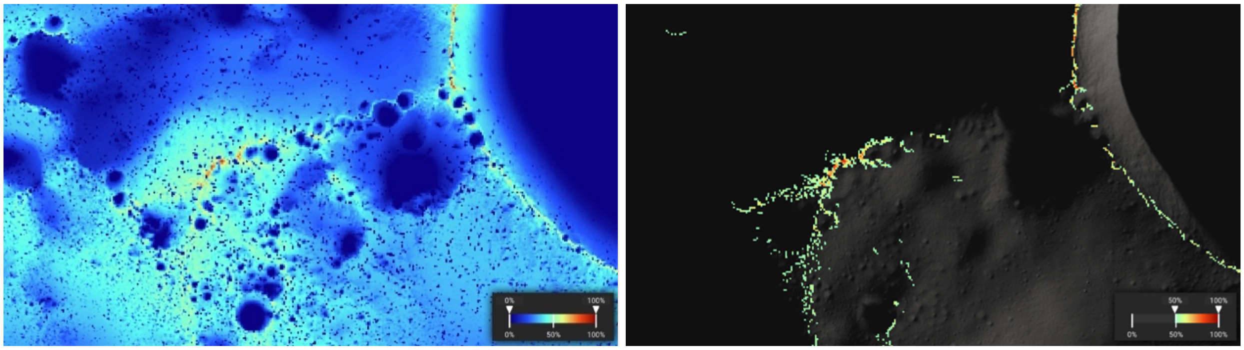


Fig. 8 LUNEXT Average Illumination (a) 0-100%, b) 50-100%) Heatmaps

D. Surface Temperature

The Moon’s surface thermal environment is extreme. Two main factors contribute to the extreme range of temperatures on the surface. First, the Moon has virtually no atmosphere to trap heat or insulate its surface. Second, it has an approximately 27 day/night cycle, meaning daytime on one side of the Moon lasts ~13.5 days, followed by ~13.5 nights of darkness.

NASA’s LRO spacecraft collected precise information about the South polar region, offering scientists details about its surface temperature. The LRO Diviner Lunar Radiometer Experiment (DIVINER) acquired the surface temperature data. LUNEXT integrates the preprocessed temperature maps from DIVINER [22] and displays them using adjustable overlays. The temperature maps from DIVINER have a resolution of 240 meters/pixel and change about every 30 hours. For example, the first image in Fig. 9 shows the surface temperature over the entire range (10K-420K) for July 5, 2030, while the second image shows only the areas with surface temperatures above 160K.

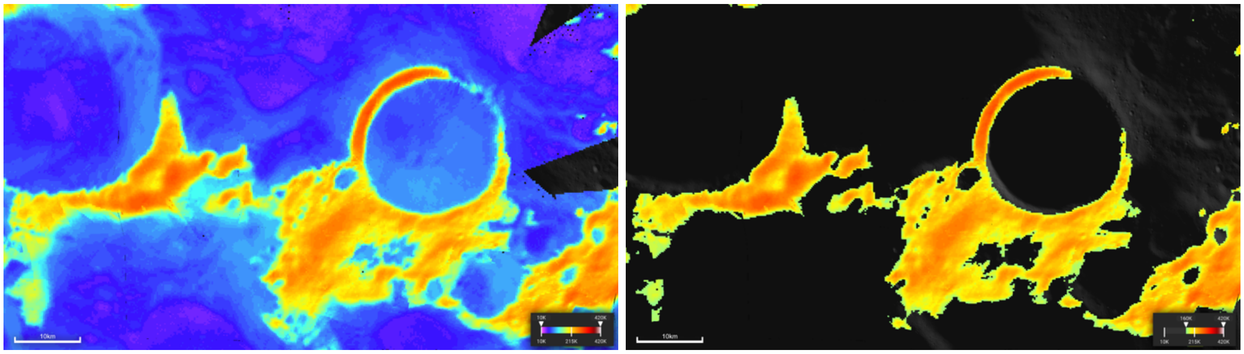


Fig. 9 LUNEXT Surface Temperature Map (a) full range, b) 160-420K) Heatmap

E. Terrain

The moonscape of the south polar region is rugged and features many craters and basins. As shown in Fig. 10 of the connecting ridge near the Shackleton crater, the topography features relatively flat regions with 0-15 degrees of slope (see image on the right), which is advantageous for surface traversals. LUNEXT uses 5 meter/pixel LRO LOLA slope maps [23] and displays the information using an adjustable color-coded heatmap overlay that is user-adjustable for improved visualization. This feature is practical for planning surface traversals that need to meet specific criteria, such as slope.

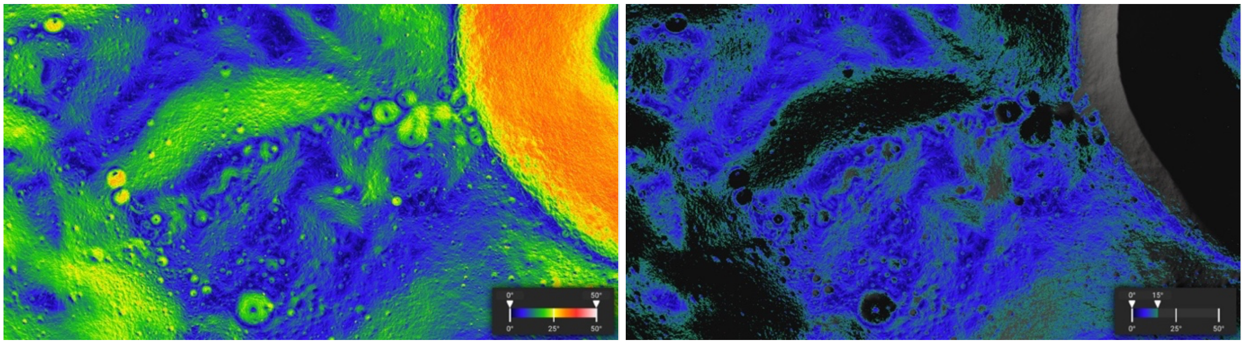


Fig. 10 LUNEXT Slope Map (a) full range, b) 0-15 degrees) Heatmap

F. Radiation

Without the protection of an atmosphere and with no intrinsic global magnetic field, the lunar surface is exposed to the full radiation spectrum in the form of high-energy radiation from solar flares and energetic Galactic Cosmic Radiation (GCR). Furthermore, when the heavy nuclei in GCR hit the lunar regolith, they produce secondary particles, including neutrons, which require shielding to protect humans and sensitive electronic equipment on the lunar surface [15]. Human exposure to all this radiation can damage DNA, increasing the risk of cancer and other diseases.

Radiation conditions pose serious risks to humans and deployed systems on the lunar surface. Continuous environmental monitoring of radiation levels on the surface will provide insight into conditions before and during surface operations. Knowledge of these conditions could inform the planning and scheduling of crewed and uncrewed operations, thus reducing exposure of the crew and surface systems to high levels of radiation.

Radiation shelters could be constructed using robotic systems (e.g., excavators) and local lunar materials. Other surface equipment (e.g., rovers) operated in uncrewed modes could reduce the direct exposure of the crew to radiation by allowing them to perform tasks (e.g., delivering small cargo, surveying, and exploring the surface) remotely from a shelter.

Additionally, limiting the use of some surface systems when radiation levels are high reduces the probability of Single Event Upsets (SEUs) caused by ionizing radiation. It may also reduce the need to use radiation-hardened semiconductor components in some non-critical surface systems.

IX. Technology and Development Challenges for Uncrewed Surface Operations and Support Activities

A. Enabling Technologies

For many years, NASA has identified robotic, autonomous, and sensing capabilities as enabling technologies for future exploration missions. Automation and autonomy technologies play a critical role in enabling sustained human and robotic operations starting on the Moon, and then on Mars. These technologies help minimize crew timeline activities dedicated to O&M and improve task efficiency. They also address operational performance, decrease mission and human safety risks, and improve surface systems availability and overall safety.

Some broad-spectrum enabling technologies for robotic and autonomous systems include sensing and perception, mobility, manipulation, human-robot interaction, situational and self-awareness, reasoning and acting, collaboration, integration, and verification and validation (V&V) [24]. These technology topics are organized and identified in the 2020 NASA Technology Taxonomy.

Other surface-related technologies and capabilities needed to perform effective uncrewed surface operations and support activities include surface architectures that support integration and enable interoperability for multi-user utilization; robotic surface equipment for site preparation; task planning, resource allocation, and scheduling tools to enable effective execution of automated and autonomous operations; system health determination and fault management tools; automated/autonomous cryogenic loading, transfer, servicing, and long-term storage of commodities; surface logistics management and reliability; and advanced umbilicals and dust tolerant interfaces [25].

Some deployed surface systems will need to operate independently, directing their motion, governing and managing their health, and performing maintenance and repairs as required with minimal or no human intervention. The advancement of robotics to self-sustainable and independent systems will reduce the need for human supervision.

To enable these surface systems to operate independently with minimal human supervision and to achieve a high degree of interoperability, an approach for the integration, verification, and validation of technologies, systems, and capabilities is needed. High-fidelity process simulations and visualizations are needed for surface analogs. For example, creating a capability to integrate new and existing ground analog test beds (physical and simulated) into a relevant multi-element lunar surface environment will uncover system incompatibilities and technology capability gaps, determine operational effectiveness, and verify/validate integrated operations for risk reduction [25]. Such a capability must be extensible to include the functional coverage of the surface architecture in Fig. 6. Additionally, it must validate separately developed systems, including their control continuum (i.e., human-robotic), to fully test lunar surface operations while simulating the resources needed. Such an environment will expedite the identification of standardized interfaces.

More precise positioning and tracking technologies will improve autonomous navigation, proximity operations, docking, robotic pre-positioning, assembly, and servicing. Actively tracking and correlating surface vehicles into a three-dimensional coordinate space is required to navigate, inspect, and repair system components autonomously. In support of cooperative and collaborative human-machine and multi-platform activities, position determination performance better than tens of meters on the surface will aid in accurately determining relative position, velocity, and pose with respect to the other agent.

Enhanced sensing and perception technologies impact robotic capabilities and enable autonomy. Sensors provide information about the physical environment to robotic systems. Robotic systems use onboard visual and non-visual sensors to reflect the conditions of the environment and artificial intelligence to integrate the information and build relationships that allow them to reason and react to the environment. Autonomous navigation with obstacle avoidance and tactile sensing for object manipulation are two broad areas that benefit from improvements in sensing technologies.

Fusion of information from various sensors like radar, video, and LIDAR can enhance a robotic system’s safety, efficiency, and effectiveness by improving data robustness and confidence for autonomous navigation and obstacle avoidance. Information fusion is not restricted to onboard sensors only. For example, propagating and fusing information with sensor data from other surface vehicles or from the surface infrastructure allows the rovers to perceive information, and represents the basis for cooperative autonomous navigation. Information sharing is critical for automated task planning, prioritizing, and scheduling, as well as resource allocation.

Information from disparate sensors typically differs in its characteristics (spatial resolution, temporal sampling, specific measurement property, and environmental sensitivities). When fused, there must be careful consideration to ensure that the resulting product carries the provenance of the constituent data sources. This is particularly important when there is divergence where concordance is expected. When humans consume fused data sources, presentation of these nuances is important to support diagnosis of discrepancies and flexibly reconsider what aspects of the data are to be used. This uncertainty management, with or without human involvement, supports robust decision-making.

Some tasks may require complex manipulation of objects. These tasks may be easily accomplished by humans, but with the use of robots, pose a major challenge. Common functions performed by a human arm, hand, and fingers add increased complexity to a robotic system. Robotic manipulators commonly consist of arms, fingers, scoops, and combinations of multiple limbs, whereas end-effectors are typically defined as a device at the end of a robotic arm that interacts with the environment. End-effectors may consist of a gripper, such as a claw and fingers, or a tool, such as a drill, cutting wheel, screwdriver, or pliers. Examples of manipulation include crew task positioning, moving and handling objects in the environment (for example, placing sensors and instruments on planetary bodies), assembling in space and on surfaces, excavating (digging, trenching, drilling), collecting and handling samples, grappling, and berthing [4]. To successfully achieve the transition from humans performing tasks to robotic systems accomplishing these tasks, robotic manipulators with a high degree of dexterity may be required.

As technological systems venture further from the presence of any human oversight, and our ability to predict the conditions they will encounter decreases, it becomes increasingly advantageous to imbue technology with the capability to learn and adapt. High-level goals would presumably be inculcated by designers, such as priority of self-preservation over data collection. However, more intelligent sensing would drive more intelligent behavior, and the collective consideration of these sensing systems and the degree of success of resulting behaviors will support increasingly flexible and robust in situ operations.

B. Human/Autonomous Systems Challenges

Uncrewed Surface Operations, as defined in this paper, include the case where technology is envisioned to operate in a self-sufficient (requiring no other entities for task completion) and self-directed (requiring no other entities for authorization) manner [26]. Additionally, Uncrewed Surface Operations include those cases where humans may collaborate with technology to complete a task, and those in which humans are remotely engaged at some degree of control. Trust has been defined as “the attitude that an agent will help achieve an individual’s goals in a situation characterized by uncertainty and vulnerability” [27]. Where autonomous systems or robotics are operating in a highly self-sufficient and/or self-directed manner, humans must assign a degree of trust to them. When humans’ trust in, or reliance on, an autonomous or robotic system exceeds its capability, that system is over-trusted and misused (see Fig. 11). Even when a system may be verified and validated to have competent performance, humans may still distrust it – when this occurs, the technology is not used where it is intended to be. Calibrated trust occurs when humans’ trust in a technology matches the trustworthiness of its capability, leading to appropriate use and surveillance.

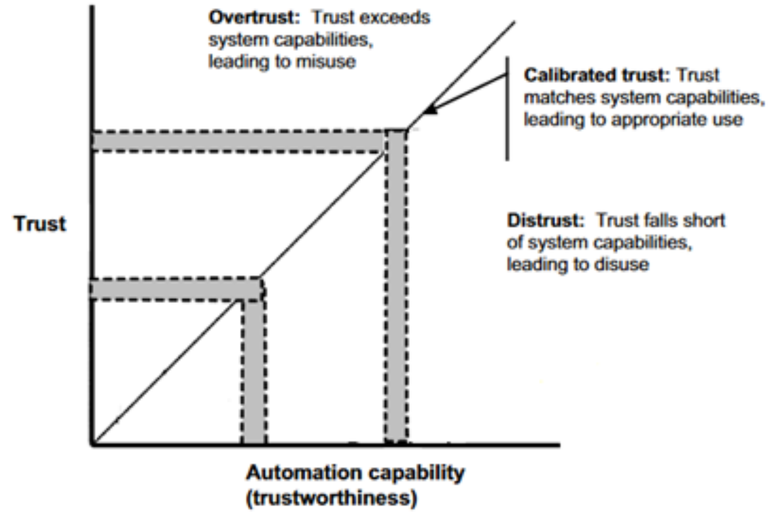


Fig. 11 Challenges of Autonomous Machine Capabilities [27]

As such, autonomous systems/robotics design must ensure that humans can appropriately calibrate trust [27] and maintain it as the dynamics of technology/task and technology/environment fit may affect performance [28]. Broadly, there are two challenges to Human/Automation design considerations: designing the nature of human/machine coordination and designing the interface between human/machine agents.

When human characteristics and roles are not explicitly considered in technology development, misuse or disuse of technology can result in unsafe operations, mission ineffectiveness, unnecessarily increased human burden, and wasted development resources [29]. For example, in cases of complex joint activity involving mixed teams of humans, software agents, and robots, increased autonomy can eventually lead to degraded performance when the conditions that enable effective management of interdependence among team members are neglected [30]. Such a scenario occurred with the early NASA Mars rovers, whose autonomous capabilities weren't fully utilized due to concerns about the high cost of failure [30]. Instead, consideration was given to when manual operations were preferred to more autonomous robotic capabilities, and how the rover and human operation needed to coordinate for some tasks [31].

The first challenge is to intentionally design human roles with respect to the type of tasking, as well as the degree of involvement and authority demanded. While automation is often referred to as having levels inverse to those of human involvement, such levels of automation can be described for different aspects of task performance (e.g., directedness, sense-making, data integration, inferencing, logical reduction, decision-making, action selection, re/planning, reconfiguration, and learning). Human roles must be defined in consideration of human effectiveness and workload, and for anticipated off-nominals and 'unknown unknowns' [32], as well as nominal conditions. Who can reassign and when role assignments change must also be considered. It is important to recognize that where humans are affected (their safety, or perceived responsibility), they will likely assume control roles even when not assigned.

Automated systems that are fully self-directed provide little feedback, with interactions that are poorly timed and complex, such that the human/machine performance is degraded [29]. The second challenge is to ensure that human interfaces support their assigned roles. When the complexities of executing system operations are transparent to the user interface, then the operators perceive the operation as simple. This assertion is also supported by Chen et al. [28, 33], who itemized the benefits of simplicity and also noted another benefit associated with projecting future states. Controls must also be provided to support the form and timeliness of required actions where teleoperation introduces additional interface demands to ensure coordinated behavior with, for example, time delays [34]. Robotic controls require additional interface considerations, such as consistency of coordinate frames, naturalistic intention-level commanding language, and motion feedback to support coordinated movement.

Even when operating at the highest level of self-sufficiency and self-directedness, in the case that technology operates without human involvement or oversight, there are still humans who must assess the degree of and bounds on trustworthiness for system performance – designers, those who accept procured technology, and those who field it. Considerations of system trustworthiness, human trust, and the potential for system misuse and disuse are relevant throughout the system design and development process.

C. Integration, Verification, and Validation

System V&V must include humans in the system and the interfaces that allow coordinated behavior across the human-robotic continuum (see Section III). Requirements must ensure that roles are defined as intended to support effective and efficient work, including resilience to off-nominal and unknown conditions.

An approach is necessary to ensure that V&V occurs with operators immersed in relevant environments with the capabilities under test, ultimately in or with high-fidelity testbeds [35]. Training must convey bounds of operability, and appropriate use [27] and, where they plan an oversight role, methods for assessing operational performance. Metrics must reflect system performance and resilience, human trust, impact of use on human operators, and other effects [35]. The history of system performance across users should be evident to all users [27, 35].

X. Summary and Conclusion

This paper has provided a broad overview of the types of operations and support activities expected to emerge during the Artemis Era—a period that begins in this decade of the 2020s and extends to the emergence of long-term human presence and new markets on the surface of the Moon. The basic functions have been organized such that systems solutions can easily be identified, initial mission operations and support infrastructure can more easily be planned, and competitive commercial markets can be identified. These emerging markets, and the resulting commercial products and services provided, are envisioned to take over the burden of operating and supporting many of these functions in the future. We noted many of the nominal lunar surface functional needs for operations support and some of the off-nominal considerations and identified key interface types among these functions. Several challenges associated with implementing these functions and maturing the needed system solutions were enumerated. Also noted are the challenges associated with the lunar destination and its extreme local environment. This paper addressed the role of complementing crew time, which comes at a very high premium, with technological advancements capable of fulfilling many lunar surface functions. While not prescribing a hard definition, we nevertheless offered a structured approach to understanding the concepts behind loaded terms, such as uncrewed and operations and support, and the associated qualities that influence sustainable lunar activity.

Future work will be necessary to ensure that architectural foundations laid during the Artemis Era are designed to support effective and efficient functional performance and provide supportive interfaces to humans and coordinating elements. We conclude that to obtain sustainable lunar operations, it is vitally important to recognize that system designs must thoroughly account for and anticipate the interactions between humans and automation/robotics.

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