LANDO: Developing Autonomous Surface Operations for Planetary Surfaces

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The Lightweight Surface Manipulation System (LSMS) AutoNomy capabilities Development for surface Operations and construction (LANDO) project is an Early Career Initiative (ECI) selected for funding by the Space Technology Mission Directorate (STMD) beginning in fiscal year 2022. Over the two-year project duration, the LANDO project will deliver a general-purpose autonomy framework applicable to serial and tension-actuated manipulation agents, that has been validated using an existing prototype of the LSMS-L35 (35-kg wrist lift capacity on the lunar surface, sized for a Commercial Lunar Payload Services (CLPS) mission). Specific to the LANDO project, the autonomous LSMS-L35 will be used to demonstrate autonomous payload handling capabilities for Lunar and other planetary surfaces, directly addressing STMD capability gaps in autonomous surface construction (ASC) operations, advanced robotics and spacecraft autonomy technologies, and technologies supporting emerging space industries including the On-orbit Servicing, Assembly and Manufacturing (OSAM) National Initiative. In this paper, an overview of the LANDO ECI project is presented.

I. Introduction

The Lightweight Surface Manipulation System (LSMS) AutoNomy capabilities Development for surface Operations and construction (LANDO) project is a NASA Early Career Initiative (ECI) selected for funding by the Space Technology Mission Directorate (STMD) in fiscal years 2022 and 2023. The LANDO project will deliver a general-purpose autonomy framework applicable to serial and tension-actuated manipulation agents, that has been validated using an existing prototype of the LSMS-L35 (35-kg wrist lift capacity on the lunar surface, sized for a Commercial Lunar Payload Services (CLPS) mission[1], Fig. 1). Specific to the LANDO project, henceforth called LANDO, the autonomous LSMS-L35 will be used to demonstrate autonomous payload handling capabilities for Lunar and other planetary surfaces, directly addressing STMD capability gaps in; advanced robotics and spacecraft autonomy technologies, and technologies supporting emerging space industries including the On-orbit Servicing, Assembly and Manufacturing (OSAM) National Initiative. An autonomous LSMS supports future capabilities in autonomous surface construction (ASC) because the LSMS is a versatile, reusable robotic agent.

A common and critical technology gap recognized across NASA, as identified by STMD and the Human Exploration and Operations Mission Directorate (HEOMD)[2], is the capability to autonomously handle payloads, including payloads arriving at the surface aboard a lander and unstructured payloads on the surface (boulders, regolith, etc.). Autonomous payload handling is required to: remove payloads from a lander; transport payloads from a lander to construction site/assembly point; emplace payloads in their operational configuration, and aggregate components to create an asset. As an example of this critical gap, manifested CLPS missions do not currently have a ubiquitous payload offloading capability; payloads (excluding rovers) are designed to remain on the lander. Rovers are designed to either drop from the belly of the lander or drive off using a deployed ramp; which is a heavy, single-purpose system with built in redundancy (strategy used for offloading the Volatiles Investigating Polar Exploration Rover (VIPER) and egress of Mars Exploration Rovers[3]).

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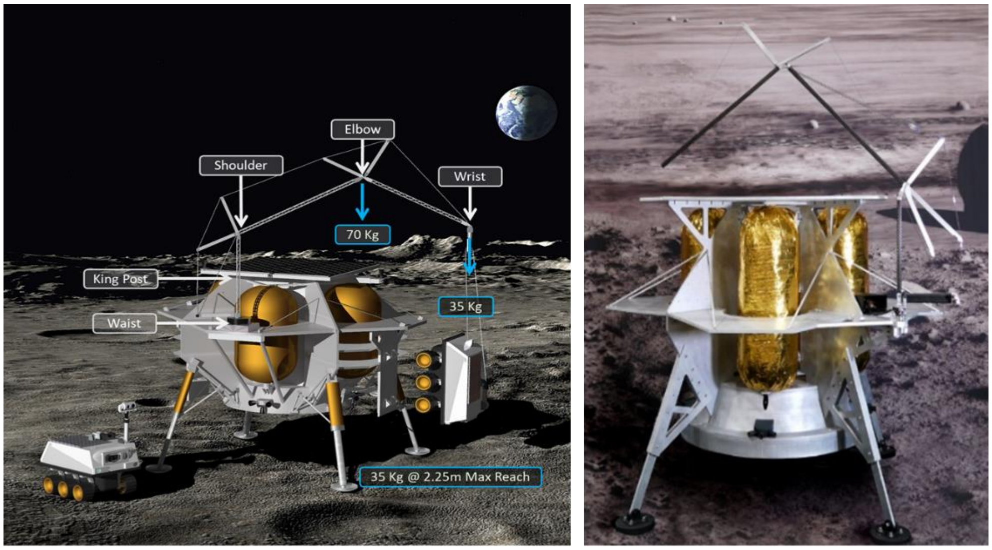


(a) (b)

Fig. 1. (a) A labelled diagram of the LSMS-L35 system identifying key features, and (b) the existing LSMS-L35 prototype in the in-space assembly laboratory at NASA Langley Research Center (LaRC).

STMD and HEOMD recognize a gap and lack of common frameworks available to implement autonomous operations and interface with infrastructure to promote interoperability in space, including the standardization of interfaces and technologies that have low barriers to entry. NASA is tasked with the key challenge of performing all the ASC operations necessary to establish a permanent settlement on the moon in a cost and time efficient manner[4]. Off-the-shelf "commodity" devices that are designed to integrate easily with a variety of landers and surface agents can: promote the standardization of space technologies; reduce the cost and time of technology insertion; as well as significantly reduce risk associated with surface operations. Additionally, general-purpose autonomy frameworks that apply to serial and tension-actuated manipulation agents are needed to overcome the current customized, single-use paradigm.

Autonomous robotic systems capable of carrying out ASC operations with supervised autonomy are a fundamental and critical capability required for realizing the NASA Artemis program vision to "emplace and build the infrastructure, systems, and robotic missions that can enable a sustained lunar surface presence[5]." While teleoperation is still feasible for lunar surface operations, increased latency at Mars will require validated supervised autonomous technologies capable of operating with minimal human involvement (human-on-the-loop) unless an unexpected event occurs requiring human intervention. Autonomy reduces operator burden, allows operations to continue during uncrewed periods, increases the safety of operations by automatically detecting and handling faults, and allows operating in high latency environments. In order to ensure infrastructure that would be in place when the first astronauts reach Mars in the late 2030s, a goal of NASA is to test and validate autonomous systems first on the lunar surface. LANDO will demonstrate and validate autonomous payload handling capabilities for Lunar and other planetary surfaces. An overview and project plans of LANDO will be presented in this paper.

II. State-of-the-Art Autonomous Payload Handling

State-of-the-art for in-space robotic manipulators are exclusively represented by serial arms (Fig. 2): e.g., Canadarm2[ϕ] and Special Purpose Dexterous Manipulator (SPDM) or Dextre on the International Space Station (ISS), and robotic arms deployed on Mars (Mars Insight Lander Arm[6] and Mars Exploration Rover Arms[7]). The arms on the ISS do not have autonomous capabilities and are currently exclusively teleoperated[8]; though, adding automation is part of ongoing upgrades[9]. The high latency with Mars communications prevents direct teleoperation, so the arms currently deployed there are commanded by a team that constructs, simulates, and sends a set of low-level instructions to be executed unsupervised with fault detection and recovery[10]. The upcoming OSAM-1 (formerly Restore-L)

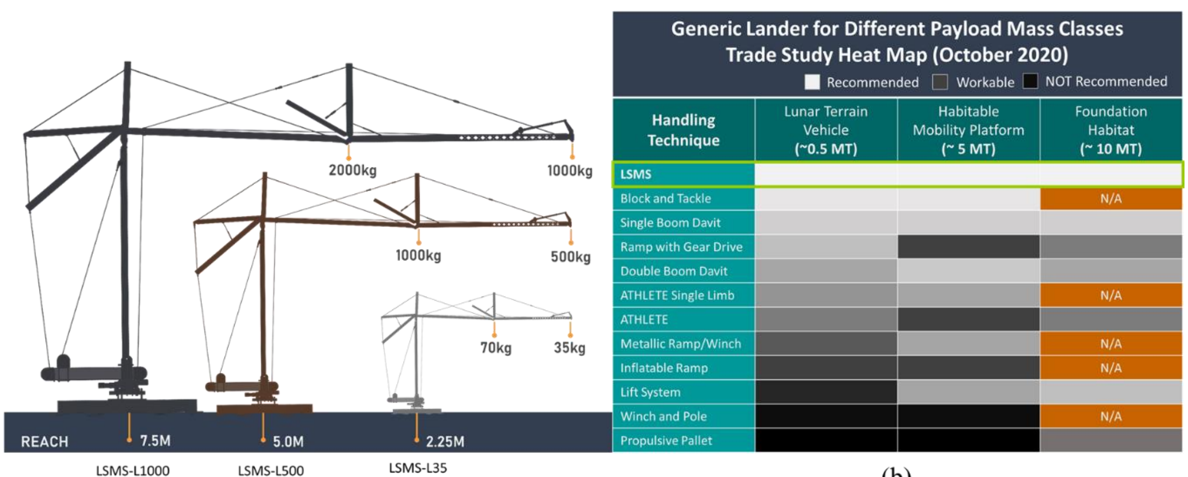
[ϕ] The mention of a company or product is not an endorsement by the National Aeronautics and Space Administration (NASA).

mission will employ autonomous grappling of a standard connector during its time-critical rendezvous with the target satellite, reverting to teleoperation for the remainder of the mission[11]. The Robotic Servicing of Geosynchronous Satellites (RSGS) project will perform an autonomous berthing procedure similar to that performed for OSAM-1 and will provide software interfaces for both teleoperated and scripted operations after attaching to the client[12]. A limitation for the current serial space arms is that each system uses a uniquely developed control system for operation that does not readily support autonomy nor extend to other systems.

(a) (b) (c) (d)

Fig. 2. Serial robotic manipulators in-space include (a) the CanadaArm2; (b) the Dextre two-armed robot; (c) the Mars Insight Lander Arm; and (d) the Mars Exploration Rover Arm.

Another severe limitation of traditional in-space serial arms is that they do not efficiently scale in either reach or payload handling mass for use in a gravity environment. The LSMS[13,14,15,16,17] (Fig. 3) is a scalable, versatile, reusable robotic crane developed specifically to overcome this limitation and efficiently execute planetary surface operations. Because of its recognized capabilities and efficiency, proto-flight LSMS hardware development is currently being funded by STMD Game Changing Development (GCD) program[18]. LSMS architectural and operational advantages were confirmed in a recently completed NASA inter-agency cargo offloading trade study[19], which ranked the LSMS as the "most recommended" handling technique (Fig. 3). The structural architecture, using tension-compression structures and non-collocated joint actuation, efficiently scales its reach and payload mass capability in varying gravity environments. Compared to serial arms, the LSMS provides significantly higher structural efficiency and mechanical advantage, thus, enabling a greater payload mass for a lower system mass[10]. Although, the LSMS mechanical system is mature and being developed for flight (GCD project), the LSMS is currently teleoperated or commanded by low-level scripted commands.



(a) (b)

Fig. 3. The LSMS (a) scalable architecture spans desirable lifting capacities and reach. The LSMS is recognized as the "most recommended" handling technique across different payload mass classes in a (b) payload offloading trade study "Heat Map" results.

III. LANDO will Advance LSMS Technology Resulting in a Commodity Device

In order for the LSMS to be a truly versatile and ubiquitous "commodity device" supporting many ASC capabilities, the LSMS must be enhanced to operate autonomously (driven by Mars communication latency) and integrate rapidly (with minimum effort) to lander and rover customers through a standardized, plug-and-play modular electrical/software and communications interface. LANDO will develop the complementary and necessary autonomy system package (software and accompanying sensor system), applicable to the GCD LSMS proto-flight hardware, that will enable autonomous LSMS operations and validate key payload handling operations needed by NASA and commercial partners.

LANDO is the first project to focus on a modular, plug-and-play interface and autonomous operations for serial or tension actuated manipulators (like the LSMS), and LANDO technologies will be directly applicable to the GCD-developed LSMS, Cold Operable Lunar Deployable Arm (COLDArm)[20], and other future manipulators. LANDO will exploit the existing low-cost LSMS-L35 hardware as a pathfinder to validate the autonomy framework which can later be extended to support other agents. LANDO will extend critical autonomous operations to the manipulation domain and create an integrated system, based on reusable software modules, that is capable of planning and executing payload handling and ASC operations without requiring human intervention beyond a supervisory role. Just as important, the autonomy package will be designed to monitor operational conditions and ensure that those operations are conducted in a safe manner. Using the LSMS-L35 as a pathfinder, LANDO will deliver a system that can:

- Autonomously offload payloads from a tilted lander deck, while maintaining safe operations by sensing the misalignment of the LSMS king post with the gravity vector and self-leveling to ensure they are aligned. This capability is a critical use case for the likely scenario when a lander lands on a sloped surface and the deck is tilted
- Autonomously determine if a payload is safe to lift and handle by sensing the force required to lift from the surface using a force/torque sensor at the wrist and comparing the measured force with the known safe operation envelope. Sensing is a critical use case for future ASC operations involving relocating rocks and regolith (i.e. unstructured payloads) on the surface
- Integrate with the Astrobotic Technologies, Inc. (Astrobotic) CLPS lander in a modular plug-and-play architecture that can be easily extended to other landers/surface agents. Working with Astrobotic provides a use case to demonstrate and validate that the modular plug-and-play interface can serve as a standard that provides efficient integration and is extensible to other landers and surface agents.

IV. Developing Autonomous Plug-and-Play Interface enables efficient Surface Operations

By developing a modular, plug-and-play software/hardware/communications interface, LANDO ensures that ASC agents, such as the LSMS, can be easily integrated with a variety of landers or mobility agents. The LSMS then becomes a ubiquitous device for payload handling and ASC that payload/instrument developers can confidently depend on as being available for use. This capability can significantly expand the science, exploration, and ASC operations that can be accomplished on the lunar and other planetary surfaces. For example, instead of having to integrate a heavy and complex science payload with a rover and offload that system (and risk mission loss if the rover fails), the science payload could remain on the lander and a simpler, less costly rover (or multiple rovers) could traverse the terrain, obtain samples, and return them to the payload for analysis.

By incorporating a LSMS on their landers for payload operations, CLPS partners will be able to expand their offered services beyond just payload delivery to also include offloading to the surface and other support operations such as rover recharging. The ability to handle payloads allows CLPS/Human Lander System (HLS) partners to modify how they pack their lander for launch, leading to greater packaging efficiency, increased payload capacity on each lander and potentially, reduced schedule risk and lower cost of launch per payload.

Successfully validating a safe and efficient strategy for autonomously unloading payloads from landers will allow LANDO to extend LSMS operational versatility to include the multitude of ASC and payload handling operations enabled by easily exchanging modular tools[10,11] at the LSMS wrist. When a new operation is required, rather than designing an entirely new device, a new tool attachment with accompanying software module will be developed to integrate with the standardized LSMS wrist interface and software architecture and launched to the surface with the payload. As the LSMS scales in size (Fig. 3), the degrees-of-freedom and forward/inverse kinematic relationships remain identical[12] (other than a scaling factor), which means the autonomy system developed under LANDO is directly applicable to any size of LSMS. By accelerating the development of flight-ready LSMS autonomy software, which is not currently planned under existing funding (i.e., GCD), LANDO will not only complement the current GCD LSMS hardware development program, but will also accelerate the development of the first LSMS flight unit, allowing it to serve as a pathfinder for a variety of robotic agents. Of strategic value to HEOMD, the autonomy framework will be applicable to a variety of agents and is directly extensible to future Mars surface missions without modification.

The physical features of an intelligent LSMS (autonomous, lightweight and efficient packaging for launch), coupled with operational versatility, will enable future cost-efficient ASC operations. The autonomous payload handling capabilities developed in LANDO are a first step toward using the LSMS for ASC operations. Autonomous technologies make infrastructure emplacement not only more affordable by reducing the operator workload, but also increase the safety of operations due to on-board fault detection. The LSMS will be an integral participant in the ASC ecosystem and is of interest for infusion into programs like the Moon to Mars Autonomous Construction Technology (MMPACT) project that will focus on in-situ resource utilization for ASC.

V. Technological Challenges and Strategy

Providing the LSMS with the autonomous capabilities needed to perform payload handling safely requires solving several technical challenges. LANDO must establish a robust framework consisting of motion control, environmental sensing, fault detection and recovery, and payload manipulation. The framework will be validated by testing in the existing laboratory using the low-cost LSMS-L35. To maximize performance of the LSMS hardware, the motion control subsystem must consider the dynamic motion of the crane system (e.g., cable winch speeds). Developing the environmental sensing subsystem will be informed by results of a trade study that considers sensor types, numbers, and positions as well as the implementation of state estimation and sensor fusion algorithms. The fault detection subsystem must be capable of detecting and mitigating critical fault modalities like excessive loading or misalignment of the king post, shown in Fig. 1. Payload manipulation challenges will vary depending on the type of tool (e.g., a rigid-mounted gripping mechanism versus a hanging cable-driven drag line bucket) as well as the type of payload (e.g., structured versus unstructured [such as rocks and regolith]). Common design elements include tool hardware interfacing and control, payload identification, and grasp planning (with the unstructured payload case adding more uncertainty and complexity).

Using the established framework, LANDO can then address technical challenges associated with creating a commodity payload handling device including surface agent interoperability, the scale of autonomy and role of the human operator, and path-to-flight. The autonomy package must maximize the amount of reusable software and hardware that will enable plug-and-play integration across other lander and surface agent customers. Even with the goal of task-level autonomy and a supervisory role for the human operator, LANDO must allow the operator to change the level of autonomy as needed (e.g., take direct control to resolve an unforeseen fault through a software hook). Finally, to inform the path-to-flight, the autonomy package should consider size, weight, power, and computation limitations of the host during sensor and algorithm selection.

LANDO will overcome these challenges through a test-driven process that builds up the layers of autonomy, as shown in the modular architecture in Fig. 4. Rapid prototyping of the integrated autonomy package will utilize component stand-ins (called stubs) that initially make simplifying assumptions which are iteratively relaxed to approach the requirements of the real-world system as module development progresses. Stub examples include using external motion captures in lieu of sensor fusion; executing scripted tasks instead of dynamically planned ones; and, moving the LSMS slowly enough for kinematic trajectories to be realizable.

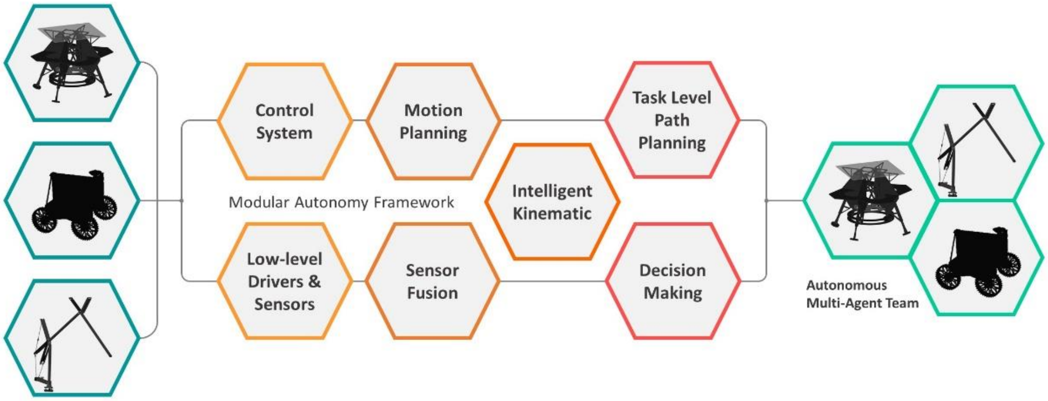


Fig. 4. The modular autonomy software framework for LANDO is generic and applies to a variety of articulated agents.

Component design and development will be informed by results from trade studies on algorithms, software, and sensors to identify available commercial-off-the-shelf solutions. When appropriate, the autonomy package will make use of third-party software to speed up development. For example, Robot Operating System (ROS2)[21] is a robotics software framework consisting of a decentralized message passing infrastructure and an ecosystem of algorithms, hardware drivers, and other utilities, that facilitate implementation of the proposed modular architecture. Space ROS, a space-rated version of ROS, is being developed through a NASA Announcement of Collaboration Opportunity (ACO) with an industry partner[22]. Common libraries for linear algebra[23], computer vision[24], occupancy grid processing[25], and path planning[26] will be incorporated as needed in the various components. The lander integration component will be designed with input from Astrobotic to inform both the plug-and-play surface agent-agnostic interface and the Astrobotic-specific implementation. Testing using equipment from Astrobotic will replicate the flight environment and validate integration.

VI. Technology Development Work Plan

The Agile Development Cycle[27] emphasizes iterations of increasingly advanced capability tests throughout the project. LANDO will target a series of milestones using the modular, layered framework as both a roadmap and a scaffold for the final autonomy package, and the final tests of picking and placing structured and unstructured payloads. Initially, the team will leverage existing work on hardware interfaces and low-level controllers to create the first components, demonstrating basic motion control upon completion. An initial lander integration module will be written to bridge autonomy framework of LANDO with the Core Flight System (cFS)[28] used by Astrobotic (developed by Goddard Space Flight Center [GSFC]). Work on a ROS to cFS bridge[29], being developed to integrate VIPER with Astrobotic's Griffin lunar lander, will also be leveraged. Data integration between the systems can be demonstrated by ingesting sensor data from a lander analog into the framework and creating live visualizations.

Because a robust sensing subsystem is crucial for developing and testing all other modules, sensor module development will begin by creating component stand-in "stubs" that can feed information into the rest of the system. The first iteration will utilize a Vicon motion capture system to provide pose information for the LSMS and relevant objects in the environment. Next, the Vicon-based LSMS pose estimate will be replaced with a nonlinear Kalman filter-based approach[30] that integrates onboard sensors such as encoders and inertial measurement units. Simulation[31] will be used to identify types, quantities, and mounting positions of environmental sensors such as light detection and ranging and cameras. Once the sensors are installed on the LSMS, more sophisticated environmental modeling using fiducials, occupancy grids[32], or mesh reconstruction[33] will replace the Vicon system, which will then be relegated to providing ground truth for validation purposes.

The motion planning modules will be developed in a similar fashion, starting with strong assumptions that are gradually relaxed. The autonomy package will initially use off-the-shelf, sampling-based kinematic motion planning algorithms such as optimized, rapidly-exploring random trees (RRT*) and variants[34], which assumes that the LSMS has a robust trajectory-following controller and motion is slow enough to not induce dynamic modes. Dynamics-aware planners[35] will later be swapped in to improve performance and robustness. At each stage, testing will consist of trajectory planning and execution with obstacle information and state feedback provided by the sensing module.

The next layer of autonomy consists of modules implementing a small set of low-level behaviors, such as moving to a goal pose or actuating the tool. Higher level behaviors, such as scanning the environment or picking and placing an object, will then be implemented by composing lower level behaviors into behavior trees[36] that can represent several common decision-making data structures. Behavior planning will start by scripting simple chains of behaviors, followed by evaluation of search-based and optimization-based planning approaches to generate the behavior trees[37].

While the nominal functionality of each module is being developed and tested, fault detection and handling components will be created in parallel to incorporate relevant fault modalities. At the lowest level, sensor metadata such as expected data rates, bounds, and noise will be monitored, and handling can vary from removing a bad sensor from the estimation pipeline to stopping the system if the maximum load or king post tilt thresholds are reached. The output of other modules, including the sensor fusion and control components, can also be monitored for data rates and thresholds. At the task level, fault detection will include validating pre- and post-conditions of behaviors, and handling will require additional contingency behaviors to safely disengage the system. Fault handling demonstrations will vary from injecting simulated faults into the system to staging situations that the autonomy package must respond to (e.g., tilted LSMS or overweight payload).

VII. Key Performance Parameters

Key performance parameters (KPPs) are defined to evaluate the performance attributes considered critical to the development of the LANDO technology. Throughout the project, laboratory tests will be executed to determine the degree to which the driving requirements are satisfied. The minimum and desired KPPs are summarized in Table 1.

Table 1. The KPPs ensure the autonomy system meets the necessary performance goals.

	KPP	Minimum Performance	Desired Performance
1	Payloads Autonomously Unloaded	50% (of 28 diverse payloads)	100% (of 28 diverse payloads)
2	King Post Self-Leveling Accuracy	Level to 1 degree	Level to 0.5 degree
3	Level of Autonomy	Manage by Consent	Manage by Exception
4	Number of Safe Modes Handled Autonomously	2 (critical modes required for safe operations)	6 (critical modes plus optimal performance)
5	Interoperability (ROS2 to cFS)	Reading critical data	Bidirectional communication

Percent of Payloads Autonomously Unloaded (Autonomy) evaluates the autonomous offloading capabilities developed for the LSMS based on the anticipated number of payloads for the first Astrobotic CLPS mission[38]. The desired performance is to unload all payloads (having varying sizes and masses).

King Post Self-Leveling Accuracy (Safety) minimizes out-of-plane loading on the LSMS structure which can result in reduced payload handling capability, structural degradation, or failure (buckling)[10]. The minimum represents the amount of misalignment the LSMS system can tolerate before damage occurs; the desired performance is a higher degree of alignment accuracy.

Level of Autonomy (Autonomy) indicates the level of human involvement required during autonomous operation (supervisory role). The minimum requires the operator to review and approve all actions (management by consent); acceptable for latency to the lunar surface. The desired requires the system to act independently until an unresolvable problem arises (management by exception); necessary for autonomous martian operations with minutes of latency.

Number of Safe Modes Handled Autonomously (Safety) refers to the ability of the system to monitor potential failure modes and react in order to maintain safe operations. The minimum requires the LSMS system to: 1) monitor king post alignment and self-level (if misaligned), and 2) monitor force/torque at the wrist to ensure structural capabilities are not exceeded and determine if a payload can be safely lifted. The desired includes the minimum plus modes to optimize performance, including handling out-of-plane loading, identifying bad sensor data, operations during extended communication outages, and issues with the lander or surface agent.

Interoperability (Plug-and-Play) evaluates the level of implementation and integration achieved with the lander. The minimum is required for safety critical operations, allowing the lander to pass information the LSMS needs (e.g., lander orientation to the surface) to safely operate using a ROS2 to cFS bridge. The desired performance is bidirectional communication (ROS2 to cFS) between the lander and LSMS with the sharing of health information, visual data, and command structure.

VIII. Concluding Remarks

In this paper, an overview and the project plans for LANDO, an STMD ECI project led by NASA Langley Research Center (LaRC) personnel, was presented. LANDO will focus on developing the autonomy framework for articulated agents using the LSMS-L35 as a pathfinder robot. Specifically, LANDO will develop the capability to offload (and upload) structured and unstructured payloads on the lunar surface using an integrated autonomy system linking object recognition, path planning, and fault detection and recovery. Further, LANDO will work with Astrobotic Technologies, Inc. to integrate the LSMS-L35 system with their CLPS lander to develop the modular plug-and-play interface for landers and surface agents to close the recognized interoperability of space systems gap. KPPs targeting desired attributes will be evaluated throughout the project duration. Following the ECI project, LANDO will pursue a CLPS technology demonstration mission to validate the technology in a relevant space environment.

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