

LSMS–L35, Miniature Crane for Payload Offloading and Manipulation: Development and Application

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The Lightweight Surface Manipulation System (LSMS) is a robotic agent for autonomous surface construction activities on planetary surfaces, that was designed at NASA Langley Research Center and has over a decade of research and development. The LSMS is a key component to achieving many goals of the NASA Artemis program. The LSMS is lightweight, structurally efficient system that can be easily packaged for launch and deployment on-surface, capable of a suite of surface activities enabled by modular end-effectors at the wrist. The focus of recent development work has been on using the LSMS for payload offloading and handling from lunar landers. Discussed in the paper is the development of the LSMS-L35 hardware (35 kg wrist lifting capacity on the lunar surface), designed to integrate with a Commercial Lunar Payload Services (CLPS) lander to offload payloads to the surface. The LSMS-L35 hardware development is part of a larger effort to enable autonomous payload handling and manipulation.

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I. Introduction

The Lightweight Surface Manipulation System (LSMS) is a family of robotically operated structurally efficient crane-like cable-driven manipulators designed to handle a wide range of payload offloading, and general coarse manipulation tasks on planetary surfaces such as the Moon or Mars [1-8]. The prototype LSMS-L35 (Figure 1) is a new addition to the LSMS family specifically targeting the smaller Commercial Lunar Payload Services (CLPS) class lunar landers [9-13] and has a 35 kg lifting capacity on the lunar surface at 2.25 m reach. Although at under 2.5 m reach and under 50 kg lifting capacity, there are capability overlaps with similarly sized conventional serial arms, the LSMS-L35 has several advantages over them, such as utilizing smaller motors, which consume less energy, and the ability to maneuver around obstacles to reach payload decks that would otherwise require a much longer arm. Most importantly, although the LSMS-L35 is currently the smallest LSMS in the family, the LSMS-L35 will share the same controls and operating architecture as the rest of the LSMS family, such as the LSMS-L1000 [1] that has a 1000 kg lifting capacity at 8 m reach on the lunar surface, or larger variants with several ton lifting capacity at 10 m+ reach. The shared control and operation architecture allows operators and integrators to adopt a wide range of lifting and reach capabilities without significant changes in operation concept and software architecture. The lift and reach capacity of the LSMS-L35 is right at the transition point where conventional serial arms start to reach their limit for lift capacity and reach potential, mainly due to the motors they must carry along the arm, a significant drawback as such structural architecture is scaled up. At reaches beyond 3 m, the structural efficiency provided by the LSMS architecture starts to benefit the system mass and power required.

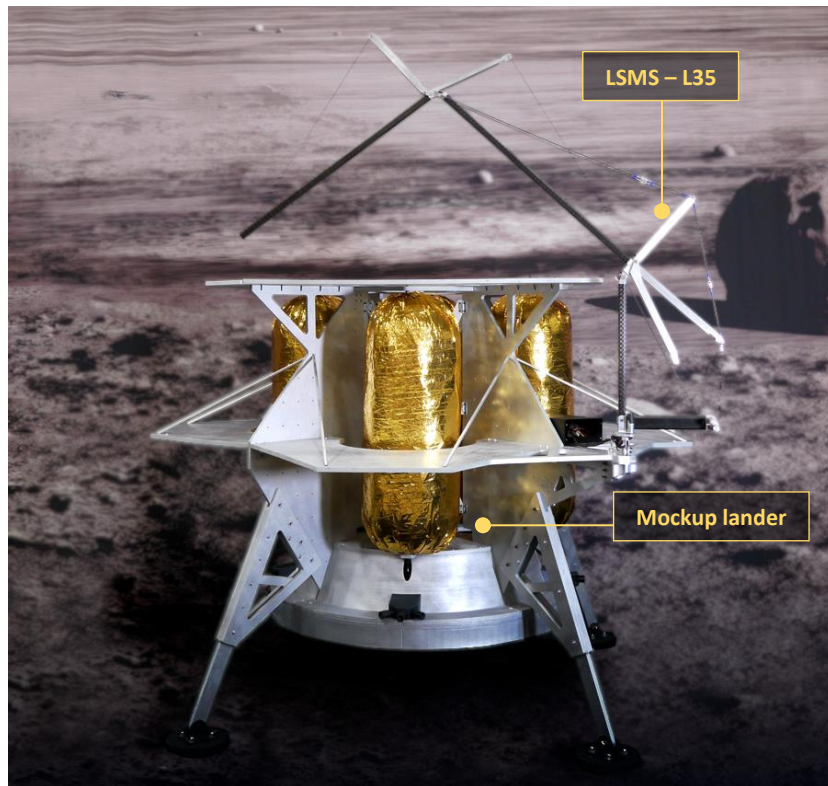


Figure 1: LSMS-L35 Prototype on a 1.9 m tall mockup lander.

Another feature of the LSMS architecture is that the LSMS can be utilized in different configurations to further reduce mass, improve dexterity, etc. to make it better suit the mission needs. The LSMS design has

lower mass and simpler electronics than comparable traditional serial arms, like the one on the Mars 2020 Perseverance Rover [15], because all major LSMS actuators are located near the base which eliminates the need for carrying the mass of the actuators along the arm links. The collocation of bulky actuators near the bottom also allows greater flexibility regarding packaging the links and spreaders for different landers and launch scenarios, especially for large-scale LSMSs.

Like serial arms, different end-effectors can be pre-attached or hot-swapped at the wrist to execute various tasks. Such end-effectors may include, but are not limited to, grippers, rotary tools, shovels, and lifting links. Herein, end-effectors will be referred to as tools. Unlike typical serial arms, tools such as lifting links can also be attached at the elbow joint between the upper arm and forearm, or even be configured to run along the arm in some cases. When lifting a heavy object, putting the lifting link closer to the elbow would increase the lifting capability and stability at a reduced reach. The wide range of lifting and end effector attaching options makes the LSMS a versatile tool for planetary surface operations.

The LSMS can be designed, using a plug-and-play architecture, to self-offload by including the ability to anchor itself to the lander at the wrist, detach the base, and relocate to a mobile platform. While self-offloading may be a desirable feature in some instances, self-offloading may not be feasible in some scenarios such as from a lander deck that is much taller than the LSMS reach. The LSMS, however, is the ideal candidate to offload a larger-scale LSMS. Estimates show that an LSMS can pick up objects that are four to five times its own mass and thus, each LSMS should be capable of offloading another LSMS that is at least two or three times the reach and lifting capability. The self-mass per lifting capability of the LSMS is a favorable feature to build up surface operational capabilities, by bringing high-capacity tools to other planetary surfaces and expanding reach and lifting capabilities significantly. Combined with its tightly packaged form factor, several LSMSs could fit on a single launch.

Currently, the LSMS-L35 can be tele- or script-operated, whereby a human is in the loop controlling all operations. Although tele- and script-operations are viable control schemes for flight missions, adding autonomous control to the LSMS would improve and expand existing capabilities. Given the simple crane-like architecture, the LSMS is relatively easy to manually operate with some practice by controlling each motor directly. The operator can also switch to wrist-control mode, where the operator controls the relative position of the wrist from its current position. In wrist-control mode the motors will coordinate automatically to move each joint to achieve the decided wrist position using inverse kinematics. Controlling the LSMS on its own is straightforward, but when payload is attached, or when operating in a rapidly changing environment, the system dynamics become less predictable. It can take a lot of practice to develop the right “feel” to operate the LSMS in these scenarios. And it will only become more challenging as communication delays increase, and operations become more complex with a higher chance of anomalies. At some point, a teleoperator can no longer be responsive enough to handle the situation properly and locally executed autonomy would have to step into and take control.

While teleoperation is feasible for lunar surface operations, significantly increased latency at Mars will require validated supervised autonomous technologies capable of operating with minimal human involvement (human-on-the-loop) unless an unexpected high-level event occurs requiring human intervention. Meanwhile, an autonomous agent can react much faster to time-sensitive events than a human operator with delayed information. NASA Langley Research Center (LaRC) is addressing autonomous control of the LSMS-L35 by researching and developing an autonomy framework to achieve supervised autonomous operations that can be expanded based on future desired operations. 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.

There is significant interest from CLPS lander partners (and others) in using LSMS technology on their landers and in support of expanded surface operations. The LSMS AutoNomy capabilities Development for surface Operations and construction (LANDO) project is accessing the interface and autonomy software for the LSMS. A goal of the LANDO project and LSMS teams is for the LSMS to be a “commodity device” whereby it can integrate easily with a variety of landers and surface agents with minimal additional development. Working together with customers is key to understanding their needs, including interfacing, desired capabilities, mass constraints, etc. Collaboration with industry ensure the LSMS design is applicable and that the LSMS can serve an important role in achieving a sustainable lunar presence. The LANDO project focuses on developing laboratory hardware and software for the LSMS-L35 and tackling the technical challenges associated with developing the autonomy software and selecting appropriate hardware. Future development of the system will need to include development of a flight engineering model with flight certified electronics, hardware, and software.

The LSMS-L35 hardware architecture and configuration are discussed in section II, and a leveling base and an end-effector are discussed in section III. Key aspects of the LSMS electronic system and the software architecture are provided in sections III and IV, respectively. System adaptability is discussed in section VI. Current and near-term developments are discussed in section VII, and the longer-term future developments are discussed in section VIII. Finally, concluding remarks are given in section IX.

II. Hardware Architecture and Configuration

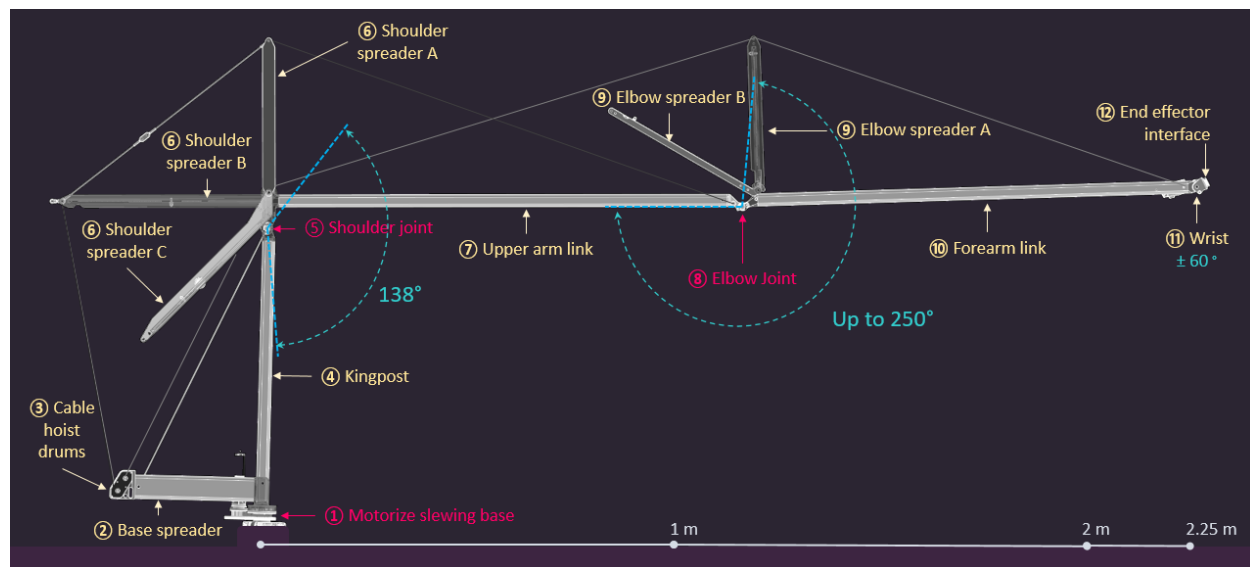


Figure 2: LSMS – L35 Prototype Key Mechanical Component Diagram.

A. The core system:

The LSMS-L35 is a cable-actuated robotic system with similar controls and basic operations to a crane. The primary structural elements operate in a vertical plane, while a slew bearing at the base is used to rotate the whole system. In its fully equipped configuration shown in Figure 2, the LSMS-L35 would have (1) a motorized slewing base; (2) a base spreader bar where (3) two motorized cable hoist drums are attached at the end and (4) a kingpost elevates the lifting arms; (5) a shoulder joint with (6) two main spreaders and a third ancillary spreader to manage the cable geometry to better spread out the load; (7) an upper arm; (8) an elbow joint connecting the upper arm and forearm with (9) one main spreaders and a second ancillary

spreader, (10) a forearm; (11) a wrist connecting the forearm and the end-effector interface; and (12) the end-effector interface. All joints would be equipped with absolute rotary encoders to ensure system accuracy and provide feedback to the kinematic control system for motion planning.

B. Core System Configuration Alternatives:

Not all tasks and operations need the full range of motion and capabilities that the LSMS–L35 can provide, therefore, reducing unnecessary elements can help the LSMS–L35 achieve its mission goal more effectively, with lower operational overhead. The following are some examples on how the LSMS–L35 can be configured, and a fully configured LSMS–35 is illustrated in Figure 3, spreader-reduced LSMS–L35, forearm-removed LSMS–L35, and the LSMS–L35 tip without the wrist joint and end-effector interface.

Shorten or lengthen Kingpost:

Shortening the kingpost allows the lifting arm to get closer to the payload and can reduce mass and potential lateral moments while increasing the stability of the system. But in some cases, the kingpost can be lengthened within structural allowances to extend reach with some reduction in load capacity.

Shorten or lengthen the Arm Links:

Each arm link can be shortened, which reduces the reach, but increases the payload lifting capability, without upgrading the motors or sacrificing dexterity. Like the kingpost, the arm links can also be lengthened to extend reach, but at the cost of stability. In general, the upper-arm link should not be shorter than the forearm, to allow the arm to fold up properly with the standard packaging scheme.

Removing Ancillary Spreader:

Ancillary spreaders can be removed to save mass when certain motions and arm positions are not required by the mission. Removing the ancillary spreaders will reduce mass, overall complexity, and some dexterity.

Removing Forearm:

The forearm might not be necessary for some simple point-to-point payload lifting and offloading operations that do not require long reach or dexterity. Removing the forearm can greatly reduce the mass and complexity of the system.

Removing Wrist and End-effector Quick Release Interface:

Having the wrist and end-effector interface greatly increases the dexterity and versatility of the LSMS–L35. However, in some cases, the wrist and additional hardware interfaces can also limit the lifting capability of the system dependent on how the wrist is being implemented, since all loads will go through the wrist. Also, the end-effector quick release interface is only needed when different end-effectors need to be swapped out during the mission. If there is only one end-effector needed, it is better to just integrate that end-effector directly to the forearm wrist.

Besides different structural configurations, each class of the LSMS can also be equipped with a range of motors that are better suited for a particular mission. LSMS–L35 for instance, can utilize 22 mm or 32 mm diameter brushless direct current (DC) motors to address different lifting needs. Motors are one of the main cost drivers for the system, so having the option of utilizing a wider range of motors allows better budgeting flexibility and makes it more viable for commercial adoption of each class of LSMS.

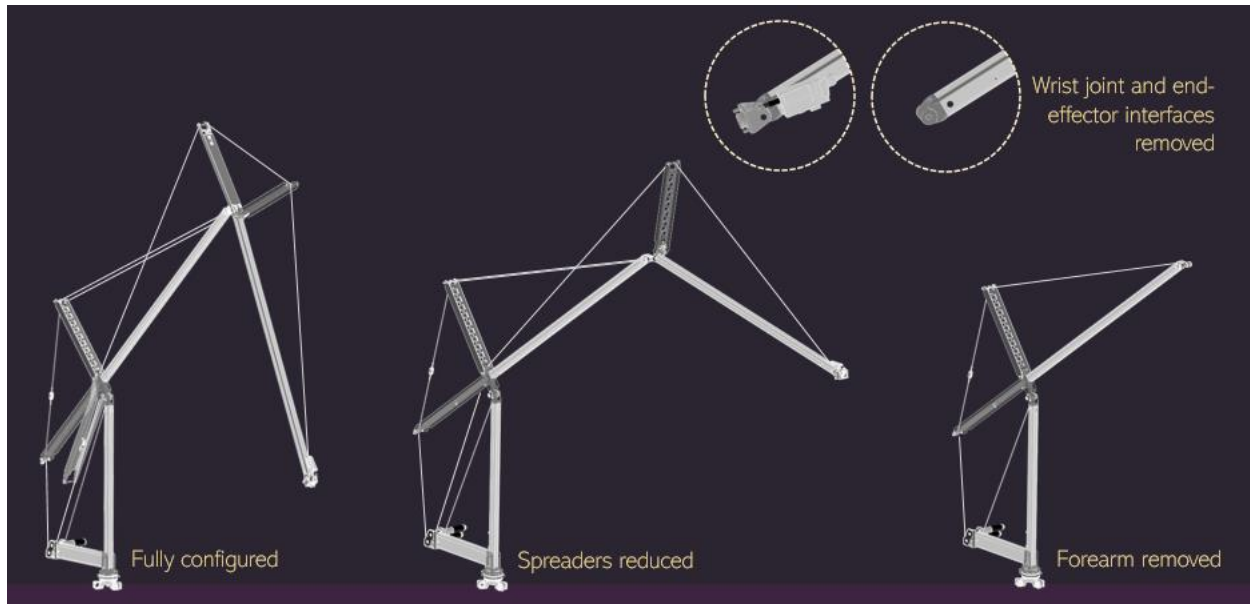


Figure 3: Various configurations of LMS-L35: left, fully configured; middle, with ancillary spreader removed; right, with forearm removed; top right, with and without the wrist joint and end-effector interface.

C. Stowing the LSMS-L35 for launch, and self-deployment:

LSMS-L35 can be stowed in a very compact configuration. The forearm folds underneath the upper-arm, and both arm-links pack against the kingpost. (Figure 4). The LSMS stowed configuration allows the system to be tightly packed and integrated with a wide range of lander configurations. For missions where the LSMS-L35 will be integrated on the lander, it is best if the system can be stowed vertically to keep deployment requirements to a minimum. However, the LSMS-L35 can be packaged horizontally as well, but it would need an additional up-righting deployment mechanism to get it in the vertical position. The up-righting deployment mechanism could later be used as part of a leveling system.

During deployment, once the launch lock is released, the cable controlling the shoulder joint winds up, pulling shoulder spreader B to deploy the other shoulder spreaders and upper arm. Then, the cable controlling the elbow joint will loosen, to release the forearm from underneath the upper arm, while giving enough slack for elbow spreader A to self-deploy by its spring-loaded mechanism and gravity. Once in place, a pin will pop out, and lock the elbow spreader A in place. Once all the spreaders are deployed, the motors would have full control authority over the joints. Then finally, the LSMS-L35 can move all its joints to the standby position, ready for operation.

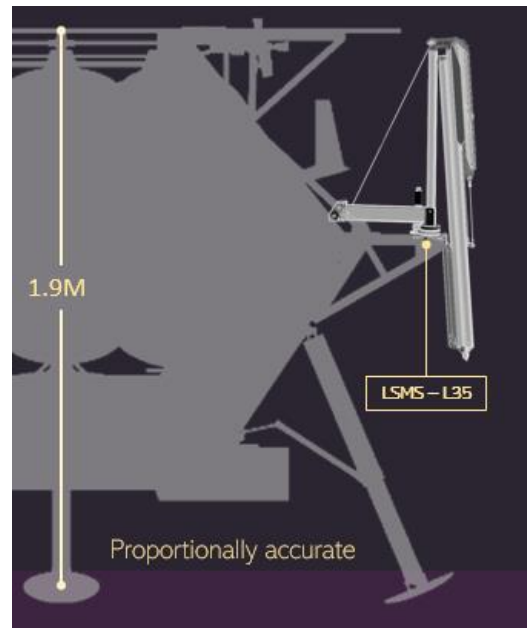


Figure 4: Example stowed configurations of the LSMS-L35 on the side edge of a CLPS lander.

III. Leveling Base and Orientation Adjustable Lifting End-effector

The terrain at the landing location on planetary bodies such as the Moon or Mars can be unpredictable. Even with surface scanning technologies used prior to landing, the exact terrain at the touchdown location will remain uncertain and could include features such as rocks which may ultimately lead to an inclined landing position for the Lander. If the lander lands on a slope or on something that causes it to tilt, the lander deck, the LSMS, and all payloads, will then be at an angle to the surface, and the gravity vector. The mission concept of operations anticipates that inclined surfaces could be up to approximately ± 15 degrees. If the lander cannot provide enough post landing leveling, a leveling base on the LSMS and an orientation-adjustable lifting end-effector might be needed to operate the system and offload the payload(s) safely. The LSMS can handle some amount of lateral tilt structurally, however, significant out-of-plane loading will compromise the LSMS and cause the kingpost to deform or buckle under heavy load. Thus, a self-leveling device has been designed, called the High-Stiffness Self-Leveling Platform (HSSLP), that can help address the leveling issue by providing two degrees of rotational freedom, roll and pitch, to align the LSMS kingpost in the vertical position and aligned with the gravity vector. The self-leveling capability can also react to some amount of unexpected lander sagging caused by the change of center of gravity or surface subsidence during a lifting operation. If the lander deck is tilted with respect to the surface, payloads may also need some orientation adjustment while being lifted to keep the payloads balanced, oriented correctly to the destination surface, and to prevent swinging caused by sudden shift of the center of gravity on the payload. The Auto Rigging and Orientation - Adjustable Lifting End-effector (ARO-ALEE) is designed to automatically attach to the payload with the appropriate rigging interfaces, while providing two degrees of rotational freedom, roll and pitch, to help orient the payload correctly up to 90 degrees during lifting (operational concept shown in Figure 5).

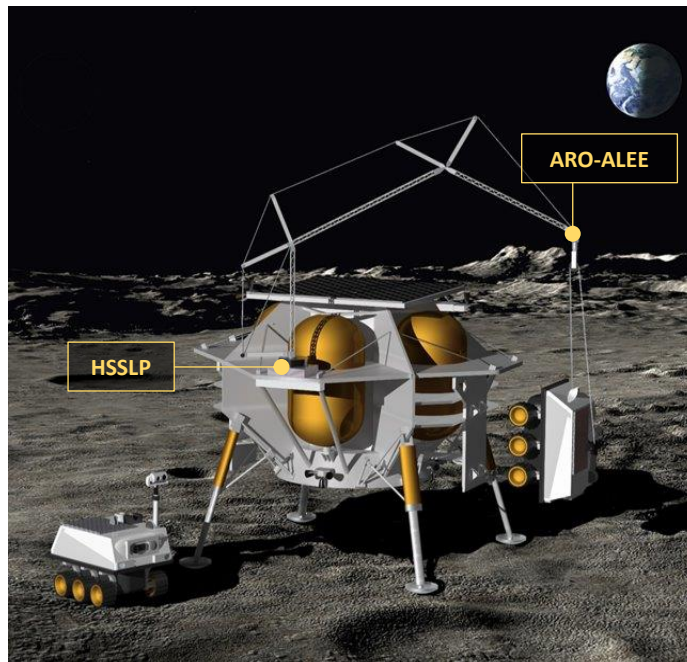


Figure 5: LSMS-L35 being used to offload a rover that needs to be reoriented to land on the wheels.

The Auto Rigging and Orientation - Adjustable Lifting End-Effector technologies is currently under internal review for new technologies to be considered for a patent, and the High Stiffness Self Leveling Platform has been filed for a patent.

IV. Electronic System

The LSMS–L35 prototype has a relatively simple electronic system. For the core system, there are three brushless DC motors equipped with Hall effect sensors and incremental encoders for closed-loop speed control, and one absolute rotary encoder for each joint for closed-loop position control. The base rotary encoder is a ring encoder that allows cables to pass through its center, while the elbow and shoulder joint encoders are axial rotary encoders. The motors selected for the prototype were selected to be as flight-like as are available commercially, without the heating element, which is only needed for flight or testing done in a similar environment with temperature as low as -200°C to keep the motor warm enough to stay within its safe operating temperature. A high-level diagram of the electronics and functions that are needed to run the system is shown in Figure 6. There is a data acquisition system that takes readings from the rotary sensors in the joints, and a microcontroller that sends control signals to the motor controller that drives the brushless DC motors of the LSMS–L35. Depending on the exact electronic hardware selected, the data acquisition system and the microcontroller for sending the control signal can utilize the same device.

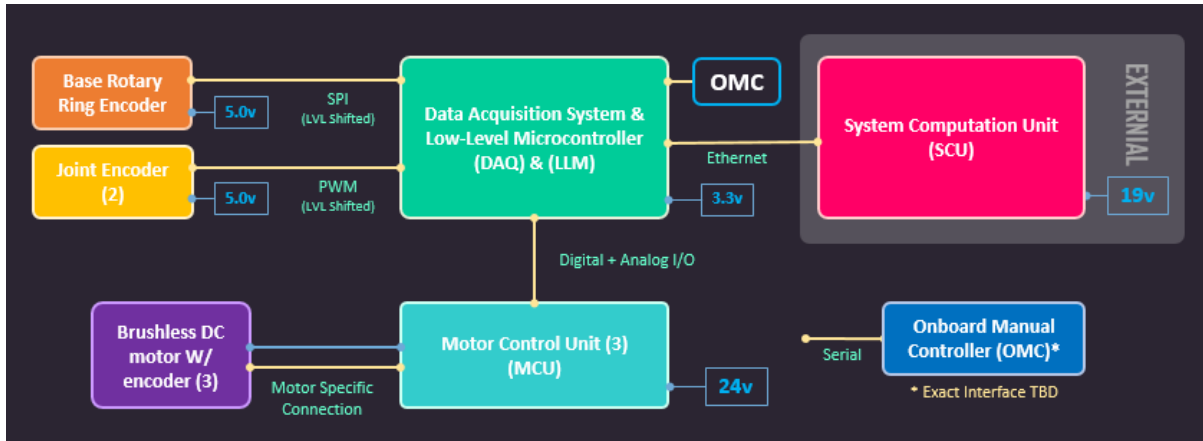


Figure 6: High-level electronic diagram showing key electronics for the LSMS–L35 prototype.

There are three required and two optional components in the *LSMS Control System (LCS)*:

[Required] *Data Acquisition unit (DAQ)* reads data streams from all the low-level feedback sensors including the base rotation encoder, both elbow and shoulder joints, as well as other sensors like an inertial measurement unit (IMU), proximity sensor, etc. Certain experimental sensors may have their own DAQ.

[Required] *Low-Level Microcontroller (LLM)* handles data packaging and translates high-level commands to electronic signals for the DAQ and MCU. The LLM is a standard component of the LCS and may be combined with the SCU as a single unit.

[Required] *Motor Control Unit (MCU)* reads the data stream from the motor's internal Hall effect sensor and encoder to control the motor. Depending on the configuration, each motor may have its own MCU, or several motors might share the same MCU.

[Optional] *System Computation Unit (SCU)* provides computational functions like data and command processing, artificial intelligence, and communication to external systems, such as the spacecraft. The SCU may couple with the Low-Level Microcontroller (LLM) to communicate with both the internal DAQ and MCU if necessary. In some configurations, both the MCU and DAQ may communicate with the SCU directly, if they come with their own interfaces to do so.

[Optional] *Onboard Manual Control (OMC)* provides low-level manual operation of the motors with basic direction and speed control. The OMC will be connected to the LLM to send user inputs and provide basic telemetry for the operator. The OMC is necessary when the LSMS needs to be put in a position where the actuating cables have no control authority on the joints, such as when stowing the LSMS. The OMC also provides a way to manually set the LSMS position without the SCU or use it to generate teaching data for the autonomy system. A display will provide basic sensor readings, and other system indicators. The OMC would not be required for the flight unit, but it is a useful optional component for the ground development unit.

The electronic components selected for the LSMS–L35 prototypes can be replaced by higher-fidelity counterparts as developments advance. For example, the absolute joint encoders used in the prototype were chosen to be functionally equivalent to flight proven counterparts. An incremental encoder is used for the closed-loop speed control on the motors, whereas a resolver would be used for the flight units. High-quality, off-the-shelf solutions for motors and encoders were chosen during early-stage development to keep the cost down and shorten lead time to speed up the development of the project.

The electronic architecture may be configured differently to suit specific mission or development needs, including highly experimental control architecture. For example, a different MCU may require different interfaces to be operated. Certain perception systems may need to be coupled with a specialized data processing unit to function properly. The goal is to have an open and standardized electronic architecture that enables the electronic interfaces and protocols to be customizable to communicate with a variety of external systems dependent on the customer’s needs.

The LSMS can be outfitted with other sensors such as IMU, light detection and ranging (LIDAR), and a camera to enable autonomous operations. These sensors give feedback to the system to make decisions to complete assigned objectives, avoid obstacles, and monitor the health of the system. These sensors are parts of the perception system are planned to be part of the autonomous outfitting package for the LSMS–L35 currently under development through the LANDO project and discussed in subsequent sections.

V. Software architecture

The LANDO project is currently focused on developing the autonomous capabilities for the LSMS–L35 prototype to safely handle payloads. To achieve the level of autonomy LANDO is after 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 laboratory using the LSMS–L35. Once the development version of the software framework is written, tested, with all critical functions are defined, the flight software can then be developed based on the LANDO LSMS-L35 development software framework. But the LANDO project would not be responsible for writing the flight software.

To maximize performance of the LSMS hardware, the motion control subsystem must consider the dynamic motion of the cable (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 kingpost. 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 items 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).

The modular autonomy software framework, as shown in Figure 7, shows the high-level capabilities needed to achieve supervised context aware autonomous operations for the LSMS, project LANDO is currently focusing on, and the future work needed to achieve full autonomy based on given task with capabilities to be able to work with other autonomous surface agents. The system complexity builds from left to right in Figure 7 with the low-level drivers, sensor system, and control system being required for higher order tasks such as motion planning, sensor fusion, and task level planning. Each hexagonal element outlined in orange or red represents a standalone software module that integrates with the framework and performs a system function. As the modules are developed, module stand-ins (called stubs) that initially make simplifying assumptions can be used to rapidly prototype the software. The stubs are iteratively updated during development to approach the requirements of the real-world system.

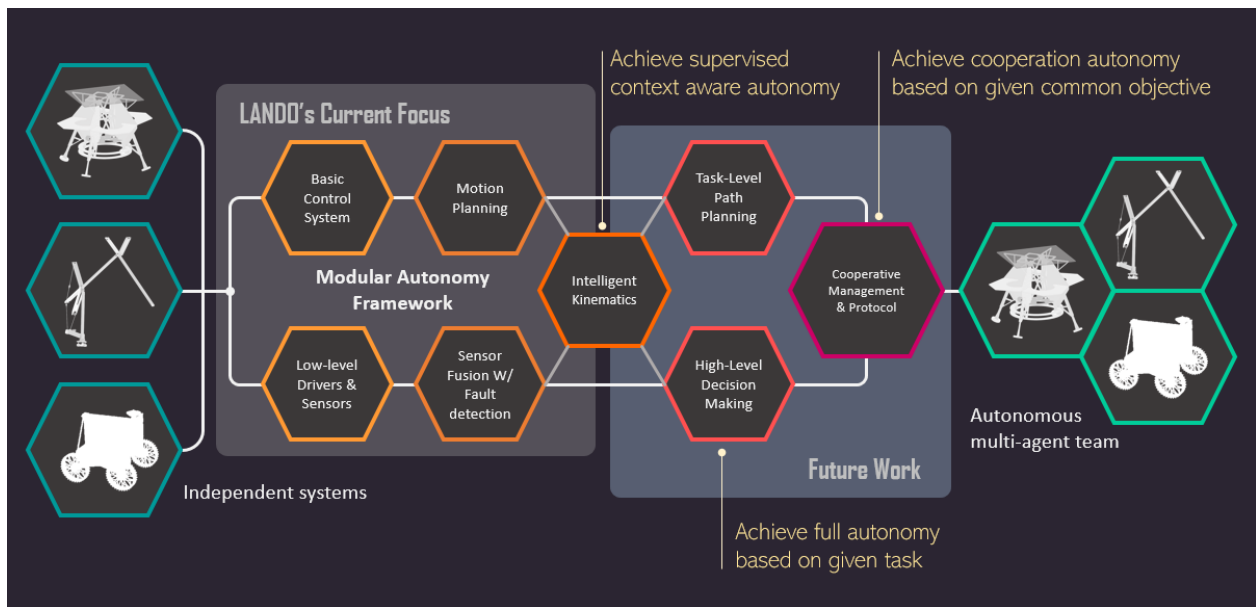


Figure 7. The modular autonomy software framework for LANDO is generic and applies to a variety of articulated agents.

Stub examples include using external motion capture 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. 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. One such package that is under consideration for use is the open-source Robot Operating System 2 (ROS2) [16]. ROS2 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. Common libraries for kinematic, computer vision, occupancy grid processing, and path planning will be incorporated as needed in the various components.

A robust sensing system is crucial for autonomy development and subsequential testing. To be able to select or develop the right sensing systems for the LSMS, a set of digital or physical “stubs” was created to help examine and experiment with different sensing approaches by feeding simulated information into the rest of the system. For instance, initially a motion capture system will be used to capture pose information to

simulate onboard sensors (encoders, IMUs) before the exact hardware is finalized and outfitted to the system. LANDO is developing a robust sensor fusion system that will only use the motion capture system to provide ground truth for validation purposes upon completion. The autonomy development will include low-level behavior control, such as moving to a goal position or actuating the tool before implementing behavior trees and decision-making structures. 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.

VI. System Adaptability

Given the current industry landscape with the Artemis program, and the availability of CLPS, one of the goals for the LSMS development is to better match the needs from industry and move forward with commercialization in mind. The first step is to scale each class of the LSMS to match their payload offloading capacity with different classes of landers, ranging from small CLPS landers, all the way up to Human Landing System (HLS) class landers. Once the sizing is selected based on projected need, then the development would shift focus to enabling technologies that allow the LSMS to handle a wider range of surface operations including, but not limited to, components assembly, on site construction, and other payload handling operations. The development of a wide range of operation concepts and associate tools is critical to establishing the LSMS as a standard payload offloading and manipulation service that can evolve with the lunar and Mars exploration campaign over time.

Lander payload decks typically range in height from 1 m to 10 m off the ground, with payload capacities from 1 kg to 15,000 kg. Conventional space-proven solutions such as serial robotic arms, are unlikely to be able to cover the full range of potential offloading and manipulation needs. Other single purpose systems such as davits, can be quite limited in terms of where, and how they can be implemented as each davit is lander specific to avoid tip-over, to match lander deck geometry, etc. To overcome these challenges, the LSMS architecture holds much potential in providing a long-reach and high mass-lifting capability, as well as providing the dexterity necessary to provide the versatility to cover a wide range of potential operations and tasks. But more importantly, the relatively high dexterity and lifting budget gives the system more options to handle unexpected events that might jeopardize a mission. These design principles also make the LSMS relatively easy and practical to be integrated into a wide range of different sized landers and configurations without significant system architecture changes. A range of potential LSMS variants is shown in Figure 8 along with landers currently under development [9-13].

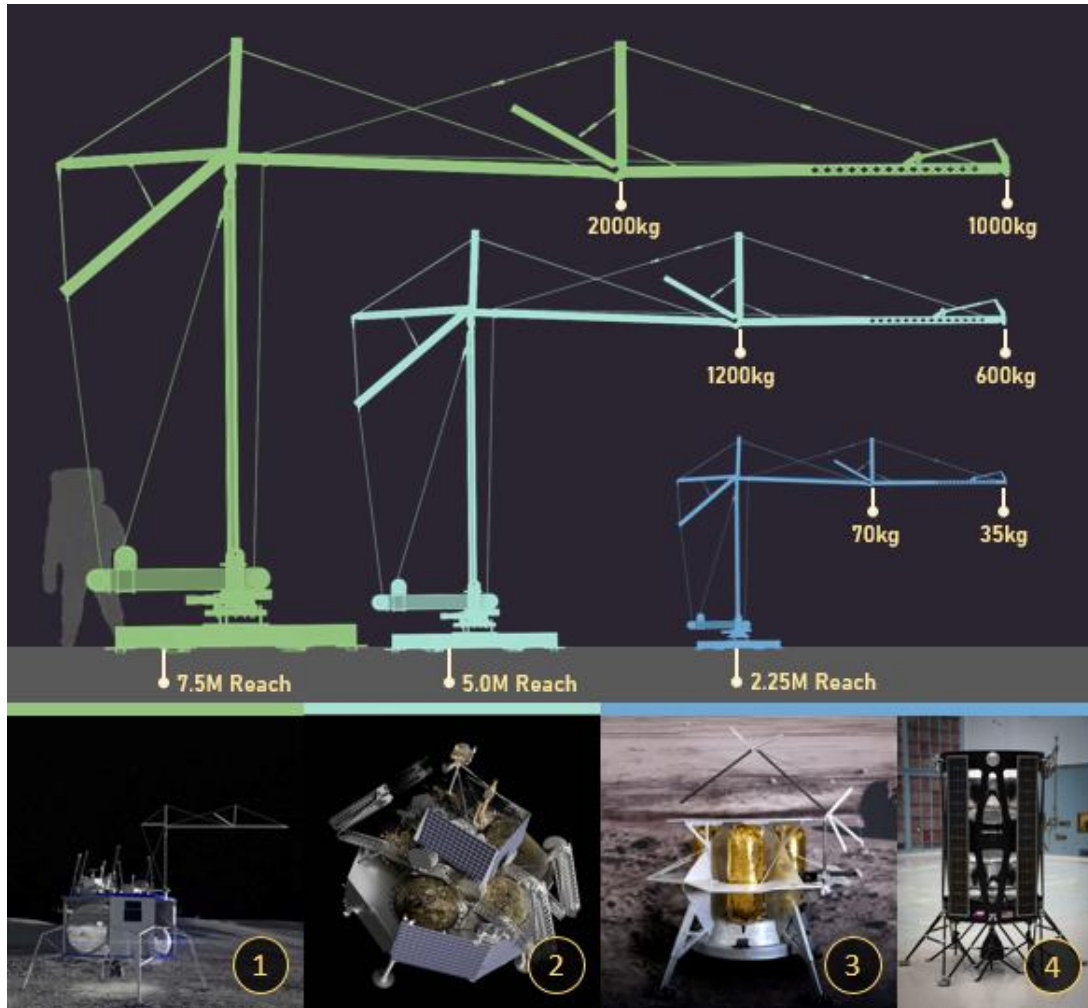


Figure 8. Potential LSMSs and their targeted lander(s). 1. Blue Origin - Blue Moon Lander matched with a 1000 kg class LSMS, 2. Astrobotic – Griffin matched with a 600 kg class LSMS, 3. Astrobotic – Peregrine, and 4. Intuitive Machines – Nova-C matched with a 35 kg class LSMS. Payload lifting capacity and reach are notional estimates based on currently available information.

The LSMS provides basic lifting and manipulation capabilities to accomplish most simple lifting and offloading tasks. The LSMS can also be used with special end-effector tools to perform more complicated tasks, which significantly increases the versatility of the system. The high tip-mass handling capability of the LSMS, allows these end-effectors to have a high mass budget to make them more robust to withstand impacts and heavy-duty use, which makes them ideal for construction tasks such as high-capacity regolith manipulation or large-component orientation maneuvers. The following are some examples of what large-scale LSMSs can enable with certain specialized end-effector tools:

- Manipulation of construction-grade tools, such as large-scale three-dimensional printing extruders, to be operated without the need for a massive serial arm or 3-axis gantry.
- High-capacity regolith shoveling and displacement to elevated locations.
- Orientation of construction components as they are being lifted to match their final assembly orientation.

- Deployment of a tall mast for communication or solar power utilizing the LSMS long reach capability.
- Deployment of anchors or other anti-tipping systems prior to offloading high-mass payloads that have potential to tip over a lander while being offloaded, without the need for an additional single-use deployment system.

A smaller-scale LSMS may not perform some of the above tasks, but the same operational principles behind these tasks can be applied to tasks other LSMS variants will perform, such as sample collection, reaching to payloads behind obstacles and deploying tall solar panels on a CLPS lander. But more importantly, early adoption of these operational capabilities can help build heritage to better prepare and lower the risk for the larger, more expensive LSMS systems and their associated missions. Scalability also ensures that development work can be investigated at a smaller scale and lower cost and still inform larger scale LSMS operations.

VII. Current and Near-Term Development

Currently, the LSMS–L35 prototype is being upgraded with high-fidelity components to have a more robust and developer-friendly prototype for laboratory hardware tests. In addition, the LaRC Space Technology and Exploration Directorate (STED) and Center Operations Directorate (COD) have funded an effort to build additional baseline LSMS–L35 units to support LSMS-related projects at LaRC, including the LANDO project. Collaboration with industry is ongoing to determine the best flight opportunity to demonstrate the LSMS and related technologies in upcoming missions to the Moon. On the research front, these platforms provide great test beds for tool and operational-control development to prototype the next generation of integrated tools, and robotic operating systems for the LSMS. These technologies are aimed to have the same scalability as the LSMS, so they can be applied across the entire LSMS family.

As several LSMS–L35 are being completed, the next step is to explore different use-case scenarios. A full-scale mockup lander has been created to test the LSMS–L35. New end-effectors, operating algorithms, and autonomy concepts will be tested in a concept-development lab environment with mockup features after validation in the simulation environment. The concept-development lab space can also be used for mission planning and investigation of unexpected events to better understand potential issues in real missions, where test data and results can be shared with industry partners to further reduce risk in adopting or commercializing these technologies.

LANDO will ground-demonstrate autonomous payload handling capabilities intended for lunar and other planetary surfaces, directly addressing Space Technology Mission Directorate (STMD) capability gaps in advanced robotics and spacecraft autonomy technologies, and technologies supporting emerging space industries including the In-Space Servicing, Assembly and Manufacturing (ISAM) National Initiative [17]. Specifically, LANDO will develop the capability to offload (and upload) structured and unstructured payloads onto and from the lunar surface using an integrated autonomy system linking object recognition, path planning, and fault detection and recovery. An autonomous LSMS supports future capabilities in autonomous surface construction.

Furthermore, LANDO will address the gap and lack of common frameworks available to implement autonomous operations and will interface with infrastructure to promote interoperability in space, including the standardization of interfaces and technologies that have low barriers to entry. The LANDO project is bridging the gap by focusing on a general-purpose autonomy framework that is applicable to a host of in-space assembly applications being pursued by LaRC, including the Precision Assembled Space Structures (PASS) project, Tall Lunar Tower (TLT) project, and leveraging nearly a decade of work at LaRC. The

nominal LANDO Design Reference Mission is shown in Figure 9 to demonstrate the capability of the LSMS–L35 to self-deploy, handle a structured payload, and handle an unstructured payload, such as picking a rock for sample return.

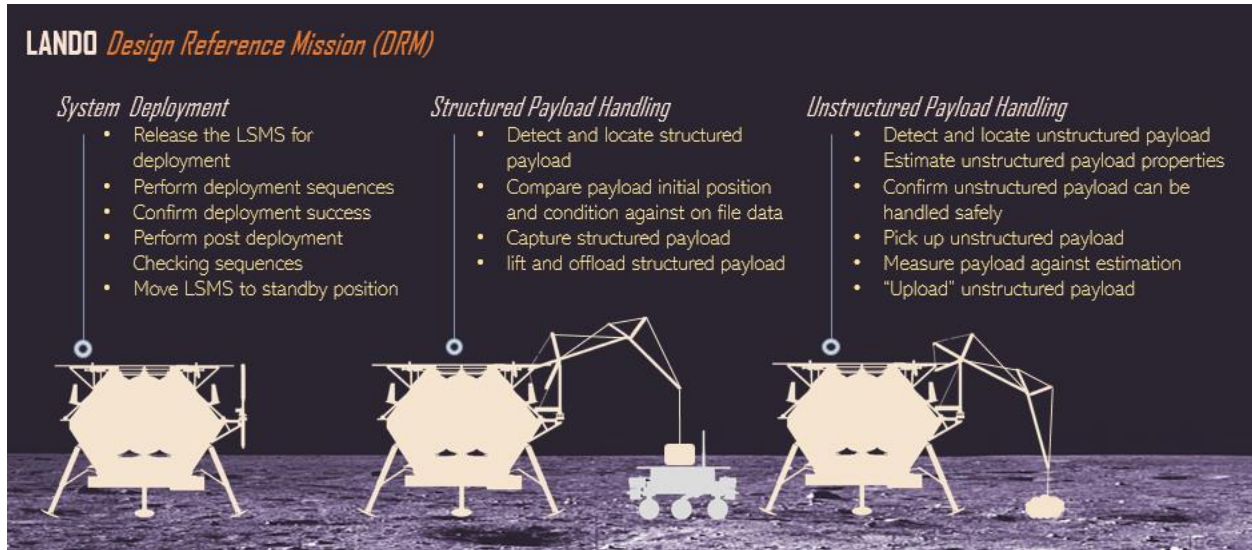


Figure 9. The Design Reference Mission, which will be performed during the final ground demonstration of the LANDO Project.

VIII. Future Development

End-effectors are the key to expanding the capabilities of the LSMS. There are several end-effectors developed at LaRC that demonstrated shoveling, fork lifting, welding, etc. using the LSMS [4]. Some of these tools can be miniaturized for the LSMS–L35, while new tools are being created for other tasks such as a dust tolerant charging port for rover recharging, an unstructured payload capture and handling tool for large irregular solid sample collection, and an automated payload rigging system to provide an advanced lifting option. These seemingly simple tasks, when manual labor is available, can be extremely demanding for robotic agents to emulate. Therefore, it is critical to streamline and simplify the processes required to accomplish these tasks so that a robotic agent can perform them.

Conventional rigging, for example, has a lot of small highly dexterous tasks, such as, hooking up a buckle, wrapping a webbing around, tying a knot, etc. Without simplifying these processes and making them robot-friendly, the cost, complexity, and risk for the mission can increase. One of the main focuses for the development of the LSMS on the application front, is to identify these rigging-like processes, and develop robotic equivalents to achieve the same goal. The robotic oriented reimplementation of tools and workflow would augment and simplify operations of the LSMS but would also benefit other robotic systems that need to deal with similar problems. More importantly, such simplification for robotic system is a critical step toward autonomous operation.

Autonomy also will play a very important role on planetary surface operations in the future. Especially, for systems needed to prepare essential facilities prior to human arrival or to support continuing operation after astronauts leave. As robotics advance, the missions they are used for can also get more complex, such as with robotic agents working together to achieve a single objective. In addition, these autonomous robotic agents may have to complete tasks by working with astronauts. Robotic collaboration is an important research area for the LSMS because of these future applications. Machine-to-machine collaboration

interfaces and Machine-to-human collaboration interfaces are research topics for autonomous robotics that need to be a part of the LSMS development. Meanwhile, specialized tools like the LSMS also have collaboration requirements and other cooperation aspects unique to itself, such as end-effector use. While many of these requirements and considerations are known, others may not be as obvious and are something only experience working with the system will identify.

To apply LSMS technologies effectively, and guide future development that is aligned with the interests of industry and NASA, it is important to understand the applications for the LSMS in the lunar and Mars exploration business. Furthermore, identifying applications for terrestrial use will help expand the adoptability of the systems and provide further interest and resources to support the research and advancement of the LSMS. One of the goals for the development of the LSMS is to make the LSMS a commodity device. The system is designed to be as near to a plug-and-play user experience as possible so that academic and industry partners can utilize it and further develop the technology.

Availability and easy integration play a critical role in adoption of technology. Refinement specifically toward productization is required to make the LSMS a valuable and applicable product. Better production processes and smart component selections reduce lead times and production costs, which simplifies commercialization and mass production. Traditionally, productization research is performed by industry partners who are interested in mass production and providing service for the system. But given the rapid schedule of the Artemis program and other driving factors, it is beneficial for NASA to address some of these technical challenges to encourage industry partners to adopt the technology without major reinvestment of time and development. Aligning the work with interest from both public and private sector is key to the success of these public-private partnerships, and it enables space technologies to be made commercially available more quickly [13].

IX. Concluding Remarks

The LSMS is a versatile crane-like manipulator with high tip-mass lift and long reach capabilities. The LSMS-L35 can bring these capabilities to smaller CLPS landers. Designed with a highly configurable architecture, the LSMS-L35 can be integrated with a wide range of landers and surface vehicles that come in various sizes and form factors. The LSMS-L35 can also be simplified to minimize operational overhead for certain point-to-point offloading missions. Capable of being equipped with a wide range of end-effectors, the LSMS-L35 can perform many small local tasks, while larger-scale LSMS versions can be utilized for large scale assembly and construction tasks using the same operating software for the entire LSMS family.

Operational concepts, end-effectors, and autonomy are the main development focus areas for the LSMS with productization in mind. The LSMS development team is continuing to work with industry to commercialize the LSMS, while also working with academic partners to further develop and bring innovation to the systems. Availability and adoptability are the keys to bringing the LSMS technologies to the public and to supporting the rapid schedule of the Artemis program. The hardware and software developed for the LSMS could also greatly benefit terrestrial robotic and autonomous construction, by bringing large production automation from the well-defined factory floor to less predictable and remote construction sites. Interest in autonomous construction for terrestrial applications could also provide advocacy and collaboration opportunities for the development of the LSMS for space applications.

As important as the hardware is, the software is also extremely critical to the LSMS family, making the software scalable is one of the most critical requirements; the software that controls the larger LSMSs can first be tested with smaller variants, and provide common control and integration interfaces across the entire

LSMS family. Such cross-scale software architecture allows the technology developed under the LANDO project to be leveraged for other scales of the LSMS, instead of requiring additional separate development. In the future, cooperation with external systems will become the norm for these remote autonomous systems. To allow such cooperation, an agreement on protocols between all involved partners will be required. The LSMS cannot do that alone and will require all partners to come together. Whether these protocols are based on existing ones or require something completely different is still in question.

The capabilities that the LSMS–L35 and the rest of the LSMS family provide will be an essential part of our future sustainable presence on the Moon and Mars. Beyond internal development, the LSMS also needs to evolve along with the rest of the technologies and systems that make a sustainable presence on other planetary surfaces possible. Keeping the LSMSs concurrent with technologies within the planetary surfaces operation ecosystem is an ongoing process only made possible if the LSMS is available and open to other partners from both academia and industry. Once such an open platform has been made, services can be provided through commercial partners, while innovative experimental research with academia can take place at a rapid rate to better prepare for and serve future exploration needs. The initial idea for the LSMS is simple, to provide a long reach, high mass-lifting capability for payload offloading and manipulation. While addressing these initial challenges, many operation concepts and application opportunities were developed and discovered. The LSMS team will continue to investigate these new ideas, addressing challenges that come along, and make these technologies available to external partners for upcoming missions.

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