A Protoflight Lightweight Surface Manipulation System to Enable High-Load, Long-Reach Lunar Surface Operations

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There is a current critical need under the Artemis program for a versatile, high-load, long reach manipulation system that can provide payload offloading and handling for lunar landers. The Lightweight Surface Manipulation System (LSMS) is a highly structurally efficient, long-reach robotic arm that can be sized for a wide range of missions and payload ranges. The LSMS has more than a decade of heritage and testing at NASA Langley Research Center (LaRC), including laboratory and field testing of multiple end effector tools and operational scenarios. With the need for rapid development of a flight-proven offloading capability and the desire to have that device be reusable for future missions and services, a 4-year program was initiated this year under NASA's Space Technology Mission Directorate, to develop and build a protoflight unit of the LSMS, capable of lifting 1,000 kg on the Moon at an 8-m reach. The target mission is to fly on a large cargo lander as a technology demonstrator to validate self-leveling, deployment, and payload handling operations, with future flights adding additional tools and capabilities. This paper provides a summary of the prior decade of work on the LSMS, the current mission drivers and goals, and details the first year of development of the LSMS toward a protoflight unit.

Nomenclature

CAD	=	computer aided design
CG	=	center of gravity
CTE	=	coefficient of thermal expansion
DOF	=	degree of freedom
EM	=	engineering model
FEA	=	finite element analysis
LSMS	=	lightweight surface manipulation system
UV	=	ultraviolet

I. Introduction

NASA has been mandated, in collaboration with the commercial space industry, to establish an expanding and sustainable human and robotic presence in our solar system [1]. This vision includes the development of critical technologies and operational capabilities that will enable humans to build a foothold on the Moon and eventually Mars, to live, explore, and perform science over an extended and ongoing set of surface missions. To accomplish this, entirely new classes of equipment and tools are needed to perform the multitude of tasks necessary to maneuver, assemble and maintain the assets needed to support long term human habitation on another planetary body. The Artemis program is the first step toward this vision with the focus on using the Moon as a proving ground for these technologies. NASA and industry are pursuing several classes of landers to support the wide variety of payloads that are needed. These range in landed mass from a few hundred kilograms up to 15 metric tons. The Commercial Lunar Payload Services (CLPS) program will provide multiple commercial options for landing payloads initially up to 500 kg, with future expansion possible to one or two metric tons. Large cargo (1,000 to 5,000 kg) and Human Lander Systems (10,000 to 15,000 kg) are also being pursued by NASA in collaboration with space industry for larger systems and outpost elements such as habitats, rovers, and power systems. Many of these payloads need to be offloaded and placed on to the surface, yet even for CLPS missions, the payloads represent a mass class that is one to two orders of

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magnitude higher than current state-of-the-art planetary surface manipulators. A proven, high-load capacity offloading device for use on the Moon or Mars does not currently exist.

A. Planetary Surface Offloading: State-of-the-Art

All payload positioning on the Moon and Mars to date has been performed using small robotic manipulators. Table 1 lists all successfully landed and operated robotic arms that have been flown to the Moon and Mars. These arms have reaches between 0.75 m and 2.2 m, with payload lift capacities of up to 45 kg with the latest Mars 2020 Perseverance robotic arm. Only one arm has currently flown and operated on the Moon, as a part of the Surveyor 3 and 7 missions, with minimal lift capacity for sample collection. The other arms were all used on Mars and employed 4 DOF or 5 DOF serial manipulators to position attached instrument suites near the surface. The InSight IDA is the only surface robotic arm that has been used for offloading payloads. Its largest payload was the 29 kg Seismic Experiment for Interior Structure (SEIS) instrument which was maneuvered and lowered approximately one meter to the ground. Small robotic manipulators, where the motors are collocated at the joints, work well, and are of reasonable mass, for high precision placement of small tools and instrumentation in a gravity environment. However, as required reach increases to several meters, and payload mass increases into the 100's of kg or 1000's of kg, a more structurally efficient approach is needed to minimize the system mass of an offloader [2].

Table 1. – Prior Robotic Manipulators used on the Moon and Mars

Mission Name	Body	Year	Robotic Arm	DOF	Reach (m)	Payload (kg)	System Mass (Kg)
Surveyor 3 & 7	Moon	1967, 1968	Soil Mechanics Surface Scoop (SMSS)	3	1.5	0.15	3.9
Mars Exploration Rovers (MER)	Mars	2003, 2004	Instrument deployment device (IDD)	5	0.75	2	4.2
Mars Science Lab (MSL)	Mars	2011	MSL Robotic Arm (MRA)	5	2.2	34	67
InSight	Mars	2018	Instrument Deployment Arm (IDA)	4	1.8	29	3.4
Mars 2020	Mars	2020	Robotic Arm	5	2.1	45	~55

B. Design Features of Terrestrial versus Space Heavy-Lift Devices

On Earth, industrial lifting devices for maneuvering heavy payloads at long reaches utilize several structural features to increase their structural performance (Fig. 1a). They use tension-compression designs to avoid induced bending, and trussed structural members to efficiently maximize their stiffness and strength. They also actuate the joints via cables that run over standoffs (or spreaders) that provide significant mechanical advantage versus colocation of the motors and joints. The hoist actuators for the cables can be placed at the base of the device to allow for ease of access for maintenance or upgrade, reduction in mass carried at the joints, and lowering of the center of gravity. The Lightweight Surface Manipulation System (LSMS) incorporates these principles to provide a highly structurally efficient, 3 DOF, long-reach robotic arm (Fig. 1b). The LSMS has the added ability to articulate its shoulder and elbow joints through a large angular range to precisely position payloads and can support additional functional capabilities via custom end effectors. As landed mass will always be at a premium for planetary surface missions, thus versatility and re-use of a single device for several different applications is of high value for enabling efficient mission architectures.

A space crane will differ from a terrestrial crane in a number of additional areas that have to be considered in applying a similar architectural approach. Compact packaging and a small footprint is required for launch and operation. Maximizing the deck area of a lander for payloads, and minimizing the size, mass, and impact of the offloader is critical. Typically, a terrestrial crane will have a large available footprint and will carry counterweights at its base. This isn't feasible for a space crane given volume and mass constraints; therefore, the loads are reacted into the lander structure, or outriggers are used to counter tip over for a surface mount. In addition, the site where the crane

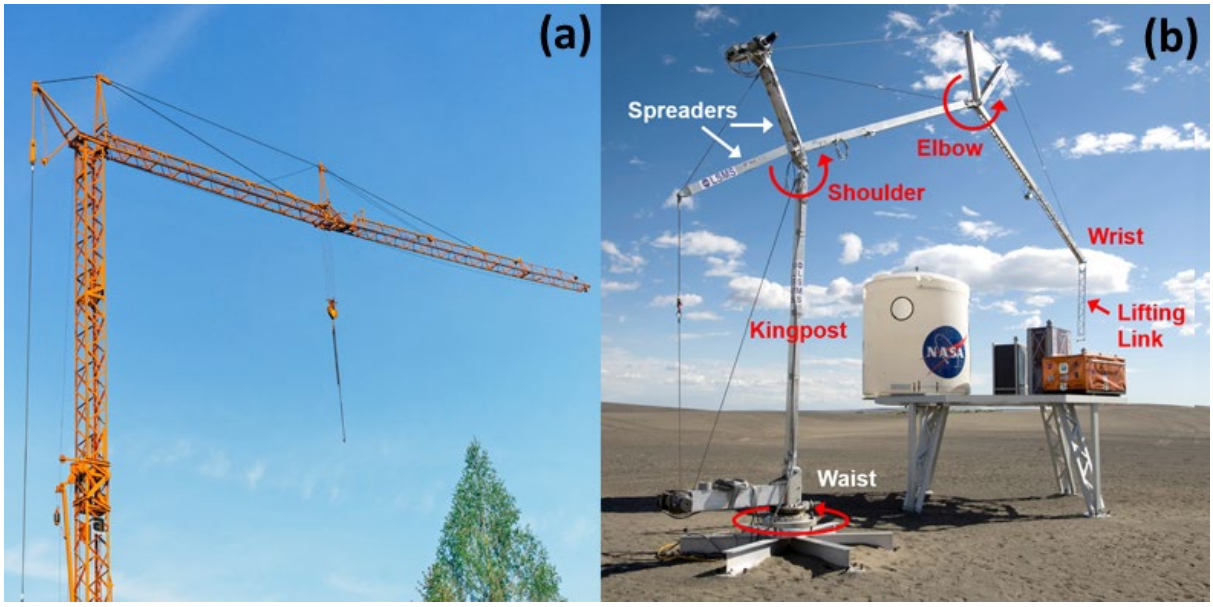


Figure 1. a) Structurally efficient industrial crane, b) prototype LSMS at Moses Lake, WA field test

is placed must be leveled and compacted prior to setup. Leveling of a space crane has to be incorporated into the design of the base or the attachment structure. There is greater reliance on robustness, and operation without local human intervention, i.e., teleoperation from Earth or a remote mission site. Maintenance and repairs are likely not possible for initial missions, and the desire is to minimize required astronaut interaction for risk mitigation. Operational speed of a space crane can be significantly slower than a terrestrial crane where speed of operations is a driver. Slow speed surface operations enable stepwise teleoperation or automation and again mitigates risk, by increasing the time to address an anomaly. Operations can be performed quasi-statically to reduce dynamic loads on the structure and allow for higher gear ratios in the actuators that both saves mass and reduces required power. Operations will involve various tasks that would likely be performed sporadically, with periods of dormancy possibly lasting weeks or months between uses, depending on the cadence of missions. This puts different requirements on the system versus continuous operation on a specific task performed quickly and repeatedly. Finally, the operational environment includes: extreme cold and hot temperatures, extremely low pressure or vacuum, powerful ionizing and ultraviolet (UV) radiation, and ultra-fine dust, where all have significant impact on the design and choice of materials.

C. LSMS Prototype Design and Demonstrations

The LSMS was originally designed during the NASA Constellation program in 2007, and a prototype LSMS has gone through more than a decade of laboratory and field testing [3–8], (Fig. 2). The prototype was designed to lift 1000 kg on the Moon at a reach of 7.5 m. The design architecture of the LSMS is inherently scalable to different reach and payload requirements. The specific values for the prototype were selected based on evaluations of several architecture studies at the time (see Ref. 3) that defined reach and payload mass requirements. The largest group of payloads were in the range of 300 kg to 3000 kg, with a required reach of 5 m to 15 m for offloading from a lander or from the surface, therefore values in the middle of these ranges were selected for the prototype device. Static proof load tests and correlated analysis of the structure were used to validate the design, and operational tests of payload offloading were conducted during the 2008 Desert Research and Technology Studies (Desert RATS). These field tests demonstrated planned and ad-hoc lifting and manipulation capabilities of the LSMS. A feature of the LSMS is the option to lift heavier payloads at the elbow (if the arm and forearm links are the same length, then the elbow lift load is approximately twice the wrist load due to halving the moment arm). This was demonstrated at DesertRATS via the requested lift and positioning of a small habitat mock-up (Fig. 2a) on to another robot. For better positional control of the payload, lightweight, trussed lifting links were used, as shown in Fig. 1b. These shallow I-Beam members

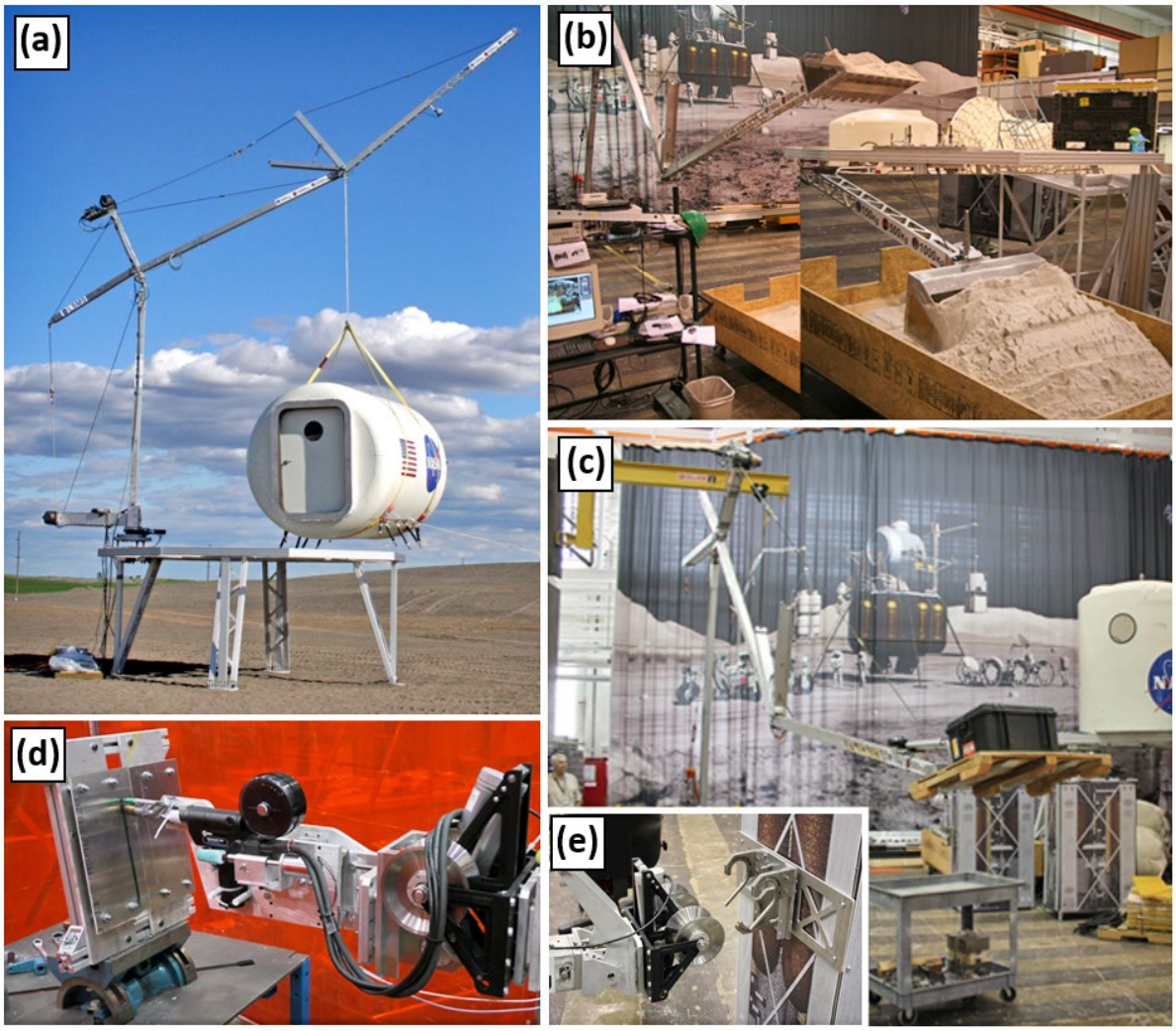


Figure 2. a) LSMS lifting mini-habitat at elbow, b) regolith digging end effector test, c) fork-lift test with pallet, d) high-precision welding end effector test, e) quick-change end effector.

provide torsional and axial stiffness when connecting to and lifting a payload that a single cable hoist does not provide and are easily attached via pin-connection to the LSMS at the elbow or wrist.

Several custom end effectors were developed as part of the original LSMS program to demonstrate the ability to perform additional functions that were known to be likely tasks or needed capabilities for long-term surface missions. The first two utilized a unique pose capability for a cable-tensioned device, to lower the forearm almost parallel to the ground for digging and fork-lift operations. Digging and maneuvering of lunar regolith (Fig. 2b) is needed for In-Situ Resource Utilization (ISRU) and processing, leveling and trenching for landing areas or outposts, providing material for radiation protection of living quarters, and for additive manufacturing stock and construction. Having a heavy-lift, and high load capable digging device enables these operations to be performed in a similar fashion to site preparation and construction on Earth. The fork-lift end effector (Fig. 2c) demonstrated the ability to lift payload pallets that could be used for grouping smaller payloads on a launch or for transport. The mechanical leverage and load capability at the wrist are enhanced in these modes by the passive disengagement of the tension rod from the top of the elbow spreaders. This can be seen in Fig. 2c where after disengagement the rod elements run directly from the top shoulder spreader to the wrist. In addition, grappling a payload from the side was demonstrated, and in combination with the standard offloading and fork-lift modes, illustrated how the LSMS could be used to pick up and maneuver payloads from the top, side or underneath. This ability allows a high level of commonality in payload handling procedures used on Earth and on the destination planetary surface. The same lift points and hardware can be used for both operations without

requiring additional interface hardware on either the payload or the payload handling device. This significantly reduces risk versus two entirely different handling approaches and allows easier ground testing and qualification of the procedures. In addition to these heavier lift/load end effectors, that only required coarse precision, two other developments demonstrated the ability to quickly swap out new tools and perform precision operations. A quick-change end effector (Fig. 2e) was developed in collaboration with HoneyBee Robotics, that provided a dust-proof electromechanical connection to a tool or payload. This was demonstrated with a welding end effector (Fig. 2d) to precision weld beads or lines between metallic parts. This tool would be replaced with an electron beam (E-beam) welder for space applications and could be used for construction where reach and precision are both of high value.

II. Protoflight LSMS Development Project

Under the Artemis program, there is new impetus to develop and demonstrate a heavy-lift, long-reach offloading capability on the Moon. Therefore, building on the design and heritage testing of the LSMS prototype, a 4-year project was initiated this fiscal year under NASA's Space Technology Mission Directorate (STMD) Game Changing Development (GCD) program, to develop and build a protoflight unit of the LSMS. This variant would again target mid-range payloads of up to 1000 kg, with a reach of 8-m, based on the maximum expected lander deck diameter and required reach to the surface. Payloads in this class are expected to be the most frequent and numerous, and needed earlier in the Artemis timeline than larger 5 metric ton to 15 metric ton elements, and therefore present the best opportunity for application of the first LSMS. In addition, the vision for the LSMS architecture is to provide a multi-functional tool that can be built at several different scales to address a suite of landers and surface operation tasks. Therefore, the reach, operational envelope, and load capacity of the protoflight LSMS is designed to be able to accommodate future end effectors and applications beyond offloading without major modification. The target mission is to fly as a technology demonstrator on a commercial cargo lander and validate self-leveling, deployment, and payload handling operations on the lunar surface. This initial demonstration mission would perform one or more payload offloading operations over a period of two weeks, or one lunar day (to reduce requirements on lunar night survival) and is classified as a Class-D (lower cost, higher risk) mission.

The LSMS project is following a stepwise development and test program to design and build both a full-scale engineering model (EM) and protoflight LSMS. Work in the first year of the project focused on analysis and design development. A parametric sizing and analysis tool was developed to optimize the geometry and cross-sections of the structural components of the LSMS based on expected static and dynamic load cases across all required joint angles. A detailed kinematic model is also being finalized to analyze and aid in the design of the deployment scheme. These modeling tools allow for both the optimization of the current design and provide flexibility to changing requirements, or future applications of the design to different scales. The project did not receive the full complement of personnel or the procurement budget that was originally proposed, owing to a lower than expected STMD budget for FY21 in the first year, therefore the design effort was focused on the parts and assemblies that were new or significantly different than the prototype LSMS, including the leveling base, the packaging and deployment scheme and components, and the use of webbing in place of cables. Design and analysis will continue into next year in preparation for the preliminary design review (PDR), and initial testing will begin at a component level.

The project plan for the subsequent three years includes component, sub-component, and full-scale testing to characterize and mature the design. Component and sub-component testing includes load and relevant environment testing of the leveling base, the mechanical components, and their assemblies, especially the hoist, pulley and webbing system, and the electrical systems including the EM and protoflight actuators and motor controllers. The LSMS project is also working with several groups at NASA for input on dust mitigation and required design impacts, although for the target demonstration mission duration of two weeks, dust impact is expected to be minimal. The components and full-scale units will be primarily fabricated in-house at NASA LaRC, with the three primary structural extrusions used for the vertical kingpost and two arm links outsourced for fabrication due to their size. The LSMS EM components and electronic systems will be integrated and then operationally verified for the required operational angles, and proof loaded at full reach. The EM will also be used for testing the packaging and deployment scheme and will be put through multiple fold / deploy cycles, prior to being packaged for shipment to, and vibration testing at, NASA Goddard Space Flight Center (GSFC)'s launch load testing facility. The results from the component, sub-component, and EM testing will be used to determine any necessary modifications to be incorporated into the protoflight LSMS design. The protoflight LSMS will follow the same fabrication path as the EM with but with flight required quality assurance (QA) inspection and documentation. Protoflight qualification testing will include electrical system and basic

operational tests, proof loading, and a final packaged vibration test at NASA GSFC. Due to the size of the full-scale EM and protoflight units, relevant environment testing, including thermal vacuum, can only be performed at a sub-system level.

A. Program Goals and Objectives

The primary goal of the project is to design, build, and ground test a protoflight 8-m reach LSMS, with a 1000 kg lift capability on the Moon at maximum reach, that is ready for pre-integration onto a large commercial cargo lander. Protoflight is a term used for prototype flight hardware, where qualification testing is performed on the flight unit as opposed to separate qualification and flight units. This reduces cost and increases risk, but is an approach often used for a technology demonstrator. The GCD LSMS project is focused on the hardware development of the protoflight LSMS only; therefore, the mechanical interfaces and high-level flight software development for integration with a lander, and system level testing of the integrated lander and arm, are not included in the current project. This is due in part to the landers themselves still being in development by the commercial space industry, several of which could be a potential host for the LSMS. The approach is therefore to keep the design as generic as possible, to be adaptable to the landers available at the end of the current development project.

The three main goals of the demonstration that drive the design requirements for the protoflight LSMS are:

- Self-leveling: Ability to level the base of the LSMS with respect to the lander deck up to ±15 degrees.
- Self-Deployment: Deploy on command from a packaged launch state to a nominal horizontal pose.
- Payload Offloading: Demonstrate payload offloading a mass of ≤ 1000 kg at up to 8-m reach.

The structural efficiency of the LSMS, like a terrestrial crane, is due in large part to concentrating the structural depth and high mechanical advantage in a plane that is parallel to the gravity vector. Leveling of the LSMS is therefore required to maintain this favorable alignment of the structural loads. For the original prototype LSMS, leveling was accomplished via a simple arrangement of three large threaded rods that attached the base of the LSMS to either a base mount (Fig. 1b) or lander mockup (Fig. 2a). Nuts attached to the threaded rods could be manually adjusted up and down to level by approximately ±5 degrees. For the current project, it was determined that a larger angular tilt range was desired due to expected requirements for landing at the lunar south pole (the focus area for Artemis missions), and the unknown capabilities of the lander to self-level. Therefore, a conservative ±15 degree tilt capability is used. In addition, the leveling has to be performed via remote command, so at least two actuators and a tilt angle sensor are required to achieve the first goal. Automated deployment from a packaged state was not a feature of the prototype LSMS (it has to be partially dismantled to stow) therefore the packaging and deployment approach from a launch locked configuration, the kinematics of the folding scheme, and the required components to actualize it have to be designed and analyzed to meet the second goal. Lastly, payload handling operations on Earth have been proven with the prototype LSMS but will need to be qualified and proof tested with the new protoflight unit, and then demonstrated on the lunar surface.

B. Design Philosophy and Features of the LSMS

The LSMS provides a core capability that addresses both a current critical gap in lunar surface architectures for offloading landers, and provides a platform for enabling future services via task-specific end effectors. This reduces the need for developing entirely new systems for each service or task, and reduces the cost and time to add critical functions by focusing the development solely on the end effector. This approach also allows smaller companies to contribute to and enable larger-scale capabilities than would otherwise be feasible. The features that guide the architectural approach of the LSMS are detailed in the list below. This was baselined on the design goals and features of the original LSMS but reflects additions and updates that are being incorporated into the protoflight LSMS that have evolved over a decade of testing and developing the prototype device. LSMS features include:

- **Scalable architecture -** Design approach is applicable to variants with payloads and reaches from small, approximately 2 m and 100 kg, to large, approximately 15 m and 10,000 kg+, respectively.
- **Versatility** - Can perform precision payload positioning and can add secondary capabilities including but not limited to: inspection/site survey, digging/excavation, deployment of other structures/experiments, precision assembly/welding, 3D printing, and astronaut positioning/elevator.

- **Robustness** - Reliable and simple. Minimize number of complex components and minimize DOF to only those essential for expected primary and secondary tasks, which reduces control complexity. Place actuators and motor controllers at base or wrist (end effectors), for ease of maintenance or upgradability.
- **Minimize mass** - High-efficiency structural design like a crane, designed with high stiffness in the gravity plane, and high mechanical advantage at joints.
- **Minimize footprint** - Increases mounting options and minimizes deck space on lander or mobility asset.
- **Quasi-static motion** - Slow operations allow for higher gear ratios and smaller actuators. This reduces mass and power required, and reduces dynamic loading, or load amplification due to dynamics. Reduces risk of critical payload operations by increasing the time to address any off-nominal event or issue.
- **Large reach and grapple envelope** - Reach payloads from close to the base to opposite of a large payload deck and provide reach to place payloads in large touch-down reach zone. Can grapple payloads from top, side or bottom as needed using same hard points as ground handling equipment.
- **Manufacturing and production simplicity** - Use heritage hardware where possible, lightweight metallic structure vs. composites (for protoflight version), light-weighted / trussed regular extrusions (rectangular, I-Beam, C-Channel) for primary compression members. Rods and webbings for tensile members.
- **Modular -** Ability to remove leveling-base system if capability is built into the lander or mobility asset that is hosting the LSMS. Ability to remove second link without design change for certain missions. Doubles lift capacity and reduces system mass at half the reach.

C. Protoflight LSMS Design and Components Overview

The baseline design of the protoflight LSMS incorporates many novel features to actualize the desired range of motion, structural efficiency, and load carrying capability. This section provides an overview of all components that are being matured as part of the design. Figure 3 shows a boilerplate CAD model of the LSMS with the naming convention for all structural members provided, along with the major component assemblies and actuator locations

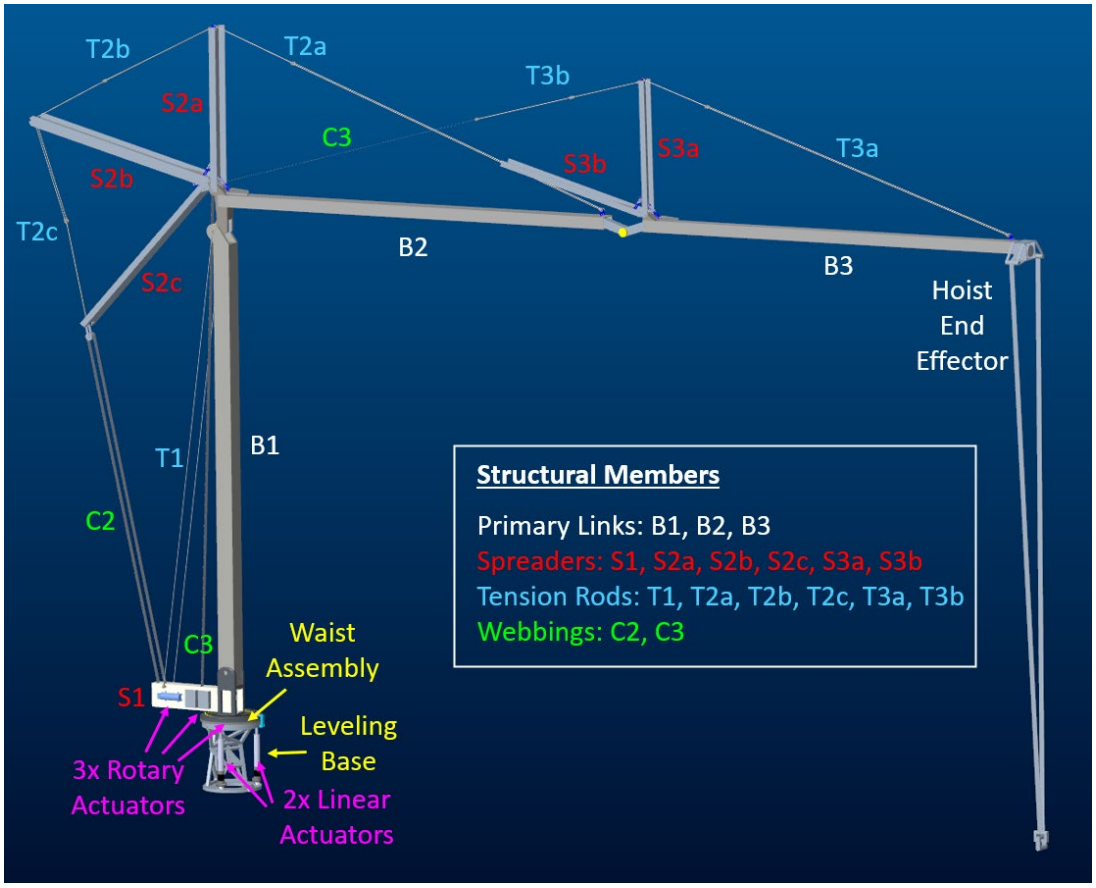


Figure 3. LSMS primary components and naming convention.

noted. Figures 4 and 5 provide detail views of the webbings (with and without coating), base components, the top of the kingpost, with associated components, and the spreaders packaged and mid-deployment.

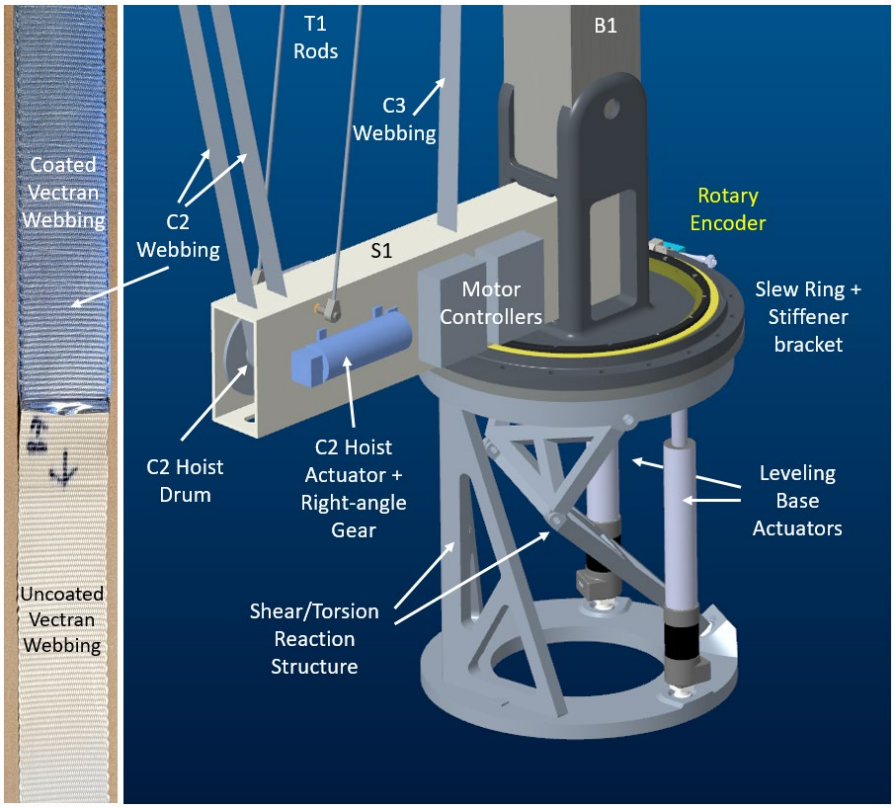


Figure 4. Webbing and base detail with S1, T1, B1, waist assembly, and leveling base.

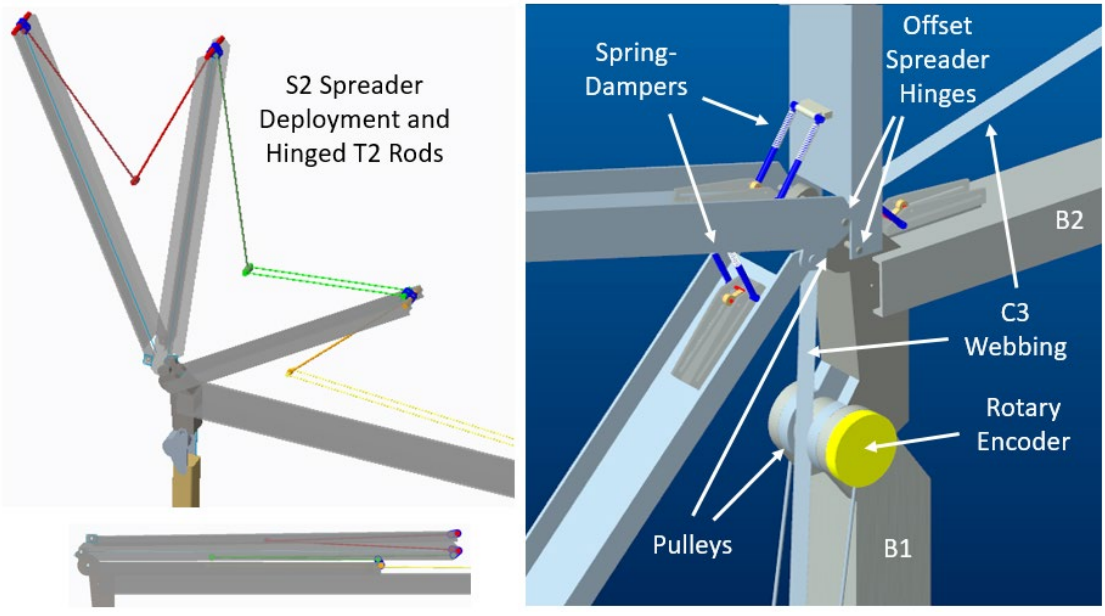


Figure 5. S2 spreaders folded and deploying, and detail view of the top of B1.

Leveling Base

The initial leveling base design sought to add actuators to the simple three-lead screw tilt table used on the prior LSMS prototype. Analysis of this actuated base design however led to a requirement for higher torsional and shear stiffness based on operational and launch loads, and a need to eliminate bending loads on the linear actuators that are used. Additional research was performed to explore alternative approaches, however, either a higher number of actuators (leading to increased mass and power for a nominally one time operation, such as a Stewart platform), or a significantly different design approach would have become necessary to *possibly* address the load and stiffness requirements. A second option was therefore investigated to modify the initial design to meet requirements. A solution was found, by replacing one of the three actuators with a truss-supported vertical post, and adding an articulating shear structure, as can be seen in Fig. 4. The combination of these two structures reacts torsional and shear loads, and the trussed post also takes axial loads along with the linear actuators. The linear actuators are structurally sized to react the high moment-induced operational and launch loads when not being driven. The leveling operation is only performed with the arm fully retracted and unloaded so only the self-mass of the LSMS is being reacted when driving the leveling base, and the CG of the LSMS is kept as close to the center of the base as possible during the tilt operation. In addition, the leveling base is driven extremely slowly, with a nominal full 15-degree tilt operation being targeted at taking 10 minutes. The leveling base is being designed as a self-contained system that interfaces to the waist assembly on the LSMS and that carries its own motor controllers for the linear actuators. This allows the leveling base to be removed if the host vehicle has a tilt capability built in. The components of the leveling base are:

- Linear actuators and motor controllers: Specified based on loads, base diameter and ±15 degrees of motion.
- Tilt sensor: Inertial Measurement Unit (IMU) or at minimum a 2-axis inclinometer (<0.1 degrees) is required.
- Space- and load-rated pins and bushings: Designed to take the high moment, shear and torsion loads induced by launch and operational use.
- Shear/ torsion reaction structure: Truss-supported post and shear frame.
- Structural connection plate/components: At base and at top to interface to host vehicle and waist assembly.
- Dust / thermal control: Dust protection cover and radiator / heater elements for electronics.

Waist Assembly

The waist assembly connects the leveling base with the LSMS kingpost and base spreader and provides the components for driving the rotation of the LSMS and tracking its absolute angle. The components of the waist assembly include:

- Slew bearing: High moment capable ring bearing with integral inner gear teeth.
- Ring stiffeners: Integrated with slew bearing directly or attached. Shell cylindrical stiffening brackets attached above and below slew bearing to meet required dimensional flatness.
- Rotary encoder: Measures absolute rotation angle of LSMS to high precision (≤ 0.002 m at wrist)
- Rotary actuator and controller: Inline motor and multi-stage planetary gear set, with final gear designed concurrently to mesh with the slew bearing inner gear. Controller is mounted to base spreader.
- Dust / thermal control: Dust protection cover on actuator and radiator / heater elements for electronics. Brush seal on slew bearing is being considered, dependent on risk assessment for target mission.

Structural Members

The core structural architecture of the LSMS consists of lightweight tension / compression elements. For the protoflight LSMS all components other than the actuating tendons are metallic due to cost and schedule considerations, and ease of fabrication and analysis. Synthetic webbing is used in place of cables as detailed below. As illustrated in Fig. 3., the structural components include:

- Primary structural links: B1 (kingpost, vertical link), B2 (upper arm, between shoulder and elbow), and B3 (forearm, between elbow and wrist).
    - All will be open-grid truss beams machined from rectangular tubular extrusions.
    - Truss pattern design and optimization is part of ongoing analysis.
- Spreaders: S1 (base spreader, notionally an open grid truss beam), S2 spreaders (I-beam and two C-channel members located near shoulder joint), S3 spreaders (two C-channel members located near elbow joint).

- The three S2 spreaders (S2a to S2c) enable an extremely wide range of shoulder angles (-75° to +85°) while maintaining high mechanical advantage at the joint. Only two spreaders (S3a, S3b) are required at the elbow to provide the total desired range of motion in the LSMS (See section II.D)
- S2 and S3 spreaders are designed to nest for packaging, while allowing for the tension rods to fold in between. A significant effort was put into finding the best nesting scheme for the spreaders and rods. Nesting the spreaders using the same hinge line was too constrictive and did not provide favorable locations to integrate the folding of the tension rods. Therefore, offset hinge lines were used to stack the spreaders and allow the required space for the rods. To determine the required locations of the hinge positions for both the spreaders and the fold lines for the rods, an analytical tool was built in Microsoft® Excel® to account for the kinematics of the rod linkages and the geometry of the spreaders. The output from this tool is fed back into the CAD model (Fig. 5) and the packaging and deployment simulation is detailed in section IV. B.

- Tension Rods: T1 (double rod between S1 base spreader and shoulder joint), T2 rods (hinged, folding connecting rods between the S2 spreaders and the elbow), T3 rods (hinged, folding connecting rods between S3 spreaders and the wrist). Note T1 and T2a use double rods to allow the webbing to pass between them.
- Webbing: C2 (used to actuate the shoulder joint, spools from a hoist housed in S1, runs up and over a pulley connected to a short rod near S2c, and connects back to the S1 beam), C3 (actuates the elbow joint, runs up and intermittently, based on pose angle, contacts two pulleys on B1 and B2, connects to T3b rod).
  - Kuraray Vectran™ webbing is used, as it provides several advantages over a twisted-wire steel cable. It has a higher strength-to-stiffness ratio, a low CTE, is more flexible and stronger at cold temperatures, and is highly abrasion resistant. In addition, a webbing has lower contact stresses than a cable and enables use of a much smaller diameter hoist due to the webbing's thickness and flexibility versus an equivalent strength cable, which reduces the mass of the required hoist drum, and reduces the torque required at the actuator.
  - Webbing maintains axial alignment of the load path inherently without a fairlead, or fleet angle, as it doesn't track back and forth on the drum like a cable. On the prior prototype LSMS, the cables would occasionally cause misalignment when the spreaders were re-engaged which caused snagging and sudden snap-in that resulted in dynamic movement and vibration at the wrist.
  - Coatings are currently being evaluated to provide UV and abrasion resistance, and aid in reducing or eliminating thermal snap (sudden temperature swings) due to passing in and out of the sun when slewing. A multi-layer webbing is also within the trade space if a coating does not meet requirements. This would combine an inner Vectran core with a woven in external protective layer.
  - A bellows style sleeve that would attach to an enclosed hoist was deemed to be unfeasible as the webbing length change during operation is large (thus there would be a lot of loose material to manage) and the C3 webbing lifts off the kingpost pulley where one of the enclosed connections would be required.
  - The load in the C2 webbing is halved by running it over a pulley near S2c, which, due to the moment arms at the shoulder (8-m) and elbow (4-m) results in C2 and C3 loads being approximately the same. This enables the same webbing specification to be used for both shoulder and elbow hoists, reducing the amount of required testing, and the reuse of the same coating approach for both.

Shoulder and Elbow Actuation System

The second and third DOF of the LSMS are via the actuation of the shoulder and elbow. These are driven by actuators and hoists located on the S1 spreader (Fig. 4). As the actuators are non-collocated with the joints, rotary encoders are attached at the shoulder and elbow joints to directly measure the joint angles. The components of the shoulder and elbow actuation system include:

- Two rotary actuators and controllers: Inline motor and multi-stage planetary gear set, with final right-angle gear that interfaces directly to the hoist drum. Controller boxes and actuators mount directly to S1. Non-back-drivable motors include brakes that are active when the power is off.
- Hoist drums: 0.076 m diameter hoist drums with side flanges sized for required spool length.
- Hoists (internally), actuators and motor controllers (externally) mounted to S1.
- Pulleys: Pulley and short rod on C2 (Fig. 3 at intersection of C2 and S2c), and same pulleys used at shoulder joint and top of B2 (Fig. 5). Pulleys will be designed with a flared lip on each edge to aid capture (engaging / disengaging) and guide the webbings.

- Rotary Encoders: Measure absolute rotation angles at shoulder and elbow joints to high precision (provides worst case measurement of ≤ 0.002 m at wrist).
- Dust / thermal control: Dust protection cover on actuator and radiator / heater elements for electronics.

Interfaces and other Structural Components

A number of additional structural components are required to connect the structural members together and provide features for risk mitigation during operations. Additional structural components include:

- End fitting designs and interfaces between B1, B2, and B3 extrusions (Fig. 3): Each primary link has a different cross-section based on structural optimization, thus the interconnecting structure between the links and the pin-joint is tailored based on the final sized configuration.
- Pin and bushing at joints at shoulder, elbow, and base of kingpost. Requires high load, space-rated precision, no-slop rotation points as any slop is magnified at 8-m. The pin joints also must be robust to temperature extremes, low CTE is desired, they must be resistant to dust intrusion (abrasion, binding) and must take high operational stresses while maintaining those tight tolerances.
- Pin capture device at ends of spreaders for smooth engagement/disengagement with tension rods.
    - The prototype LSMS had a flattened v-notch style capture slot on the spreaders to engage the tension rods during a change in pose. This is being modified to have a smoother and more robust capture envelope to remove the possibility for sticking or binding as the spreaders engage/disengage.
- Hard Stops: mechanical hard stops are built in at the primary joints at the B1 base, B2 shoulder and B3 elbow.
    - These provide positive and passive structural stops on the angular range of the joints just outside of the software controlled joint range. As a tension driven device these are required features to mitigate against entering an off-nominal pose that is non-recoverable.

Wrist end effector for payload handling

Interfacing with payloads to enable their capture, maneuvering and release can be done with either a simple and robust passive mechanical system, which is currently the baseline implementation for the protoflight LSMS, or otherwise some degree of actuation can be implemented via active components. Attributes of the approaches include:

- Passive approach:
    - A structural plate with a rigid lifting link is attached at the wrist and engages and releases a payload via a pin and hook connection to a payload. Even if lifting from an angled deck it is possible to rig the payload with a passive self-aligning rope/pulley system that can be used to center the LSMS wrist over the payload CG Placement on the surface would be corner first however.
- Active approach:
    - A hoist end effector (Fig. 3) would add an additional rotary actuator at the wrist and utilize a bifilar pendulum hoist. This would provide stiffness in the slew direction, and higher torsional stiffness and control versus a single cable, while providing a much longer lowering capability for tall landers. A passive pin and hook scheme could still be used, or an active payload grapple mechanism could be added for positive engagement. There has also been some initial research and development of active payload angle control at NASA LaRC using two additional actuated DOF at the end of the hoist. Rigging to the payload can be manipulated in an analogous way to a passively aligning rope/pulley system, allowing for control of the tilt angle of the payload when picking it up and placing it on the surface.

Features for packaging and deployment

The LSMS is stowed in a vertical configuration with all structural members folded together parallel to the kingpost. The packaged LSMS has to be restrained for launch and then fully deployed for use. Several components specific to these operations are being studied in the design of the protoflight LSMS but have not yet been designed. Attributes of the systems include:

- Launch Restraint System
    - Minimal number of controlled-release launch locks would be used to hold the stowed LSMS tightly together for launch. Nominally, one launch lock is needed near the base to hold together B1, B2 and

B3, and a second is used to hold together B2 and B3, which are released sequentially during the deployment.
    - The folded tension rods between the spreaders would have passive damping blocks attached to the spreaders, to keep the rods restrained during launch.
- Spring/Damper systems
    - Spreaders: Each spreader is designed to deploy to a set angle to provide mechanical advantage across the entire operational envelope. To maintain these angles during spreader disengagement a spring-damper is used between each spreader, mounted near the hinge point of each (Fig. 5). These spring-dampers are also used to aid and dampen the motion of the spreaders during deployment. The spring constants and damping values will be estimated by the kinematic deployment simulation (see II.E).

D. Protoflight LSMS Operational Envelope and Articulation

The protoflight design will include the ability to demonstrate a large range of articulation (Fig. 6) that enables functions beyond payload handling. This is to allow for possible additional services or functions that may be included in the first or subsequent flights of the LSMS, without requiring major redesign or modification. The LSMS is designed with a maximum elevation angle at the shoulder of +85-degrees, combined with an equivalent down angle at the elbow to bring the wrist as close as possible to the kingpost. A lifting link or hoist is used to pick up payloads close to the base in this configuration. The LSMS is also designed with a maximum down angle of -75-degrees to provide maximum range of forward movement for fork-lift and digging operations. The analysis and sizing ensure the maximum payload of 1,000 kg can be held and maneuvered across all operational poses.

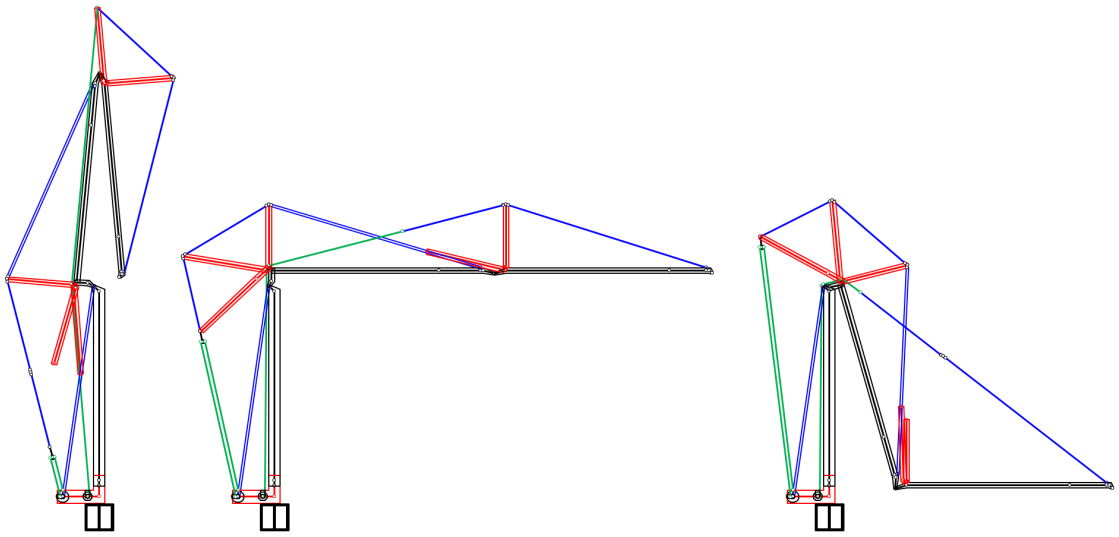


Figure 6. LSMS core operational poses, a) 85-degree up angle, b) full-reach 8-m horizontal, c) 75-degree down angle for fork-lift or digging operations.

E. Structural sizing, Load Analyses and Deployment Simulation

Parametric Sizing Tool Development and Load Analyses

A key part of the first year work for the LSMS project was to build a robust architecture and design approach that could be quickly updated and analyzed to size the geometry and cross-sections of the structural components based on the required load cases and desired operational angles. This was both to support the current protoflight effort but also to reduce development time of future variants that may be scaled to different reach and payload mass requirements. A custom Excel-based parametric analysis and sizing tool was therefore developed and continues to be evolved to address this need. The user starts by inputting the desired lengths of the primary links and spreaders, the spreader set angles (i.e. the desired deployed angles), the joint angle range, and the maximum load at the wrist. The forward kinematics, and contact relationships between elements are included to allow the articulation of the design through its

operational envelope. This allows the user to determine if the initially selected geometry is appropriate for the intended operations or needs updating. The tool graphically represents the LSMS as shown in Fig. 6, including member thicknesses and offsets, and accurately displays the engagement/disengagement of the spreaders and the webbing with the pulleys. Within the Excel tool the user can run static load cases across the entire pose range as a single batch run and receive back plots of the loads in all members across all angles, with the maximum loads identified for each. The load calculations account for the offsets at joints and interfaces, via a Renton finite difference formulation that includes bending effects [9]. Based on the maximum loads in each member, the cross-sections can be sized for the primary links, spreaders, rods and webbing. Rectangular tubes are used for the links, I-Beam or C-channel cross-sections are used for the spreaders, and solid circular and rectangular cross-sections are used for the rods and webbings, respectively. A built-in area moment of inertia calculator allows the additional automatic calculation of local buckling loads to ensure the sized members meet load and stiffness requirements. As the goal is to simplify fabrication, and reduce custom parts where possible, the tool can provide both exact required sizes and industry standard sizes for components that meet the minimum specification from the analysis.

Once the initial sizing of the structural components is complete, the tool can directly output Abaqus (Dassault Systèmes, 2019) input files to perform higher fidelity analyses beyond static loading and local buckling. Abaqus is an industry standard finite element analysis (FEA) code [10]. To analyze all operational poses, the Excel tool outputs input decks for each pose, including whether the spreaders are engaged or disengaged in that pose, and whether the C3 webbing is in contact with either pulley on the B1 or B2 links (Fig. 3). All parameters for the component materials, cross-sections, connectivity, and constraints are included in the input decks along with the desired analysis type and outputs. The analyses in Abaqus include verification and validation of the static loads calculated within the tool, global buckling and frequency analyses, and transient dynamic analyses. Dynamic analyses specifically include modeling slewing and lifting motions, and the launch vibration environment. These analyses inform the selection of a dynamic amplification factor based on the required concept of operations and operational speed. Parametric analyses can easily be setup and performed to determine sensitivities, e.g., to out-of-plane loading or other eccentricities, which can help determine design values such as the required precision in the leveling base, and can drive design updates and resizing as needed. Targets for static, dynamic and buckling loads included design factors that were derived using both NASA's standard for spaceflight hardware [11] and crane design standards [12, 13]. This was to find a balance of system mass versus robustness needed in a lifting device. In comparison to terrestrial lifting operations, every payload lift operation performed on a planetary surface will have the benefit of detailed knowledge of both the asset LSMS is attached to and the payload it is lifting. Although the lunar environment is harsh, the environment is relatively less dynamic than terrestrial lift sites; without wind, rain, or other atmospheric events; thus, can be modeled quite precisely.

Kinematic Deployment Analyses

The parametric analysis tool incorporates a kinematic model of the LSMS that can place the device in any operational pose and account for spreader lift-off or engagement and pulley contact, however it does not model the kinematics of the deployment from a stowed state, nor the induced dynamic loads that may occur. In addition, dynamic analyses in Abaqus are based on a fixed pose. Therefore, a detailed kinematic model of the deployment sequence from a stowed state is being developed using MSC ADAMS (MSC Software Company's Automated Dynamic Analysis of Mechanical Systems) simulation software [14]. The kinematic model includes: the actuation of the hoists and spooling of the webbing; contact interactions between the structural elements, including the folded rods and spreaders, and between the webbing and pulleys; spring-damper features attached at the spreaders; and correctly sized structural components and masses from the Excel sizing analysis and accompanying FEA. The ADAMS model is critical for fully understanding the deployment kinematics and is aiding in the design development of the required components that support a smooth deployment. These features can then be included in the FEA and CAD models to evolve and mature the design and deployment sequence.

III. Concluding Remarks

Over the next three years of development, the LSMS project will not only be maturing the design, analysis methodology, and test heritage of the LSMS toward a protoflight unit, but will also be collaborating internally at NASA and with the space industry on opportunities for expanding the capabilities of the LSMS (Fig. 7). The GCD LSMS project is focused on developing the protoflight LSMS hardware to the point where it is ready for system-level

integration with a host lander. Prior to a manifested flight to perform the technology demonstration, there will be additional development needed of the specific mechanical and electronic interfaces that connect the LSMS to the lander and its onboard systems for power and telemetry. In addition, flight software for controlling the 3-DOF LSMS will need to be developed. Two current independent research programs are expected to accelerate this software development. The first is a NASA Announcement of Collaboration Opportunity (ACO) developing a new spaceflight certifiable version of the Robotic Operating System (ROS), called SpaceROS. This joint effort between NASA, the Air Force Research Lab (AFRL) and Blue Origin is developing the software architecture framework to build and implement robotic control software in a more efficient and cross-cutting way than typical flight software developments, that are often unique to a specific robot. Blue Origin recently signed a 1-year research license to use the prototype LSMS as an offloading device for their cargo lander development program and as a target application for a SpaceROS-based control program. In addition, a NASA LaRC Early Career Initiative (ECI) proposal was recently awarded, called the LSMS AutoNomy capabilities Development for surface Operations and construction (LANDO) project. This project will develop and demonstrate supervised autonomous surface operations, including payload handling, via application to and use of the LSMS architecture. They will be building a small scale mini-LSMS for development of the software, but with the intent to mirror and implement the design developments of the GCD

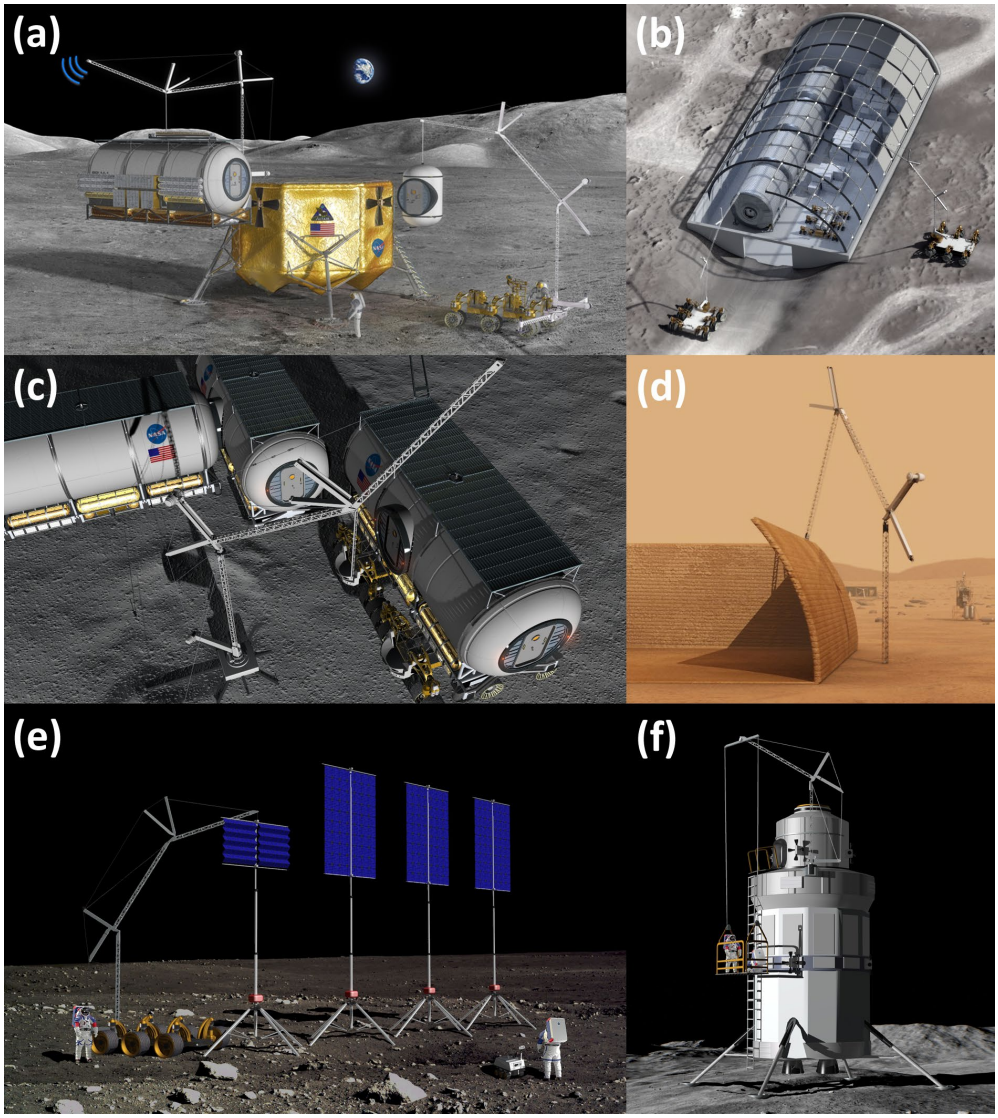


Figure 7. LSMS extended functions. a) offloading, inspection, site surveying, b) assembly, regolith excavation and handling, c) connections, E-beam welding, d) large-scale 3D printing, e) deploying structures + science payloads, f) astronaut elevator.

LSMS and to provide an autonomous control framework that is applicable to any of the current or future variants of the LSMS.

The Lightweight Surface Manipulation System, once demonstrated on the lunar surface, will be a significant leap forward in planetary surface manipulators, enabling load and reach capabilities that are orders of magnitude larger than previous surface robotic arms. This will open up opportunities to partner with the space industry on the development of customized end effectors for a number of additional functions as conceptualized in Fig. 7. In addition, variants of the LSMS, based on the demonstrated protoflight architecture could be built at smaller or larger scales for application to a wide range of CLPS missions for science and exploration, cargo missions, and Human Lander System (HLS) missions for offloading the largest surface elements such as pressurized rovers and habitats.

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