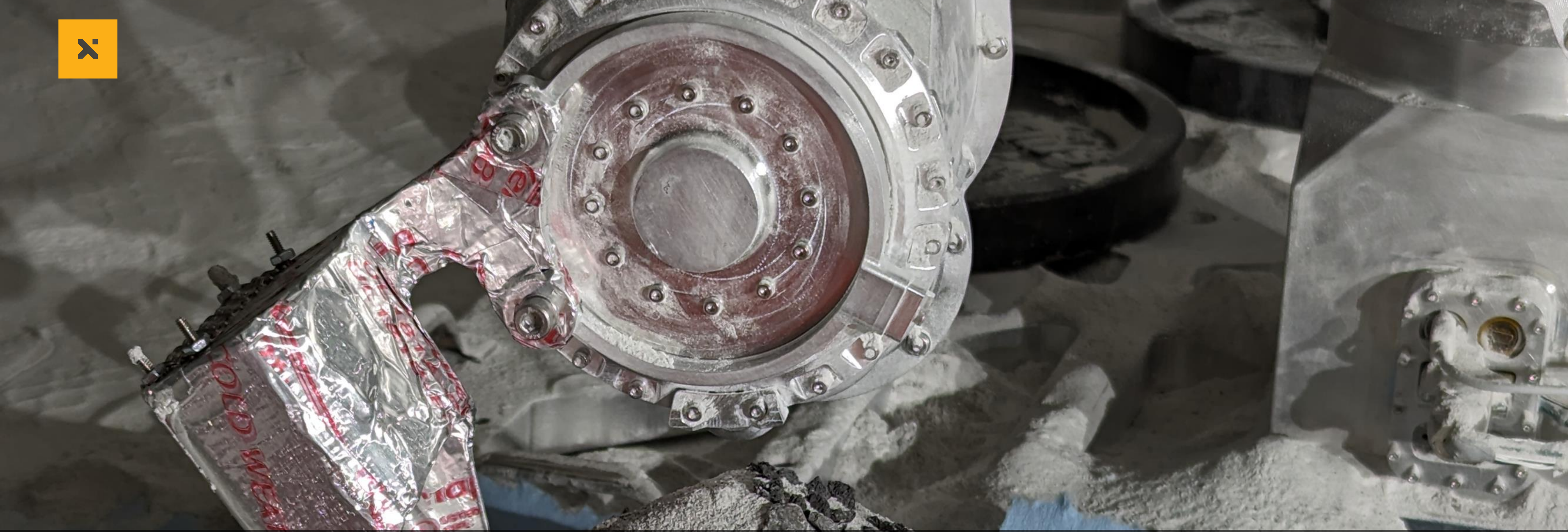

Lunar Underactuated Arm (LUnA) Project

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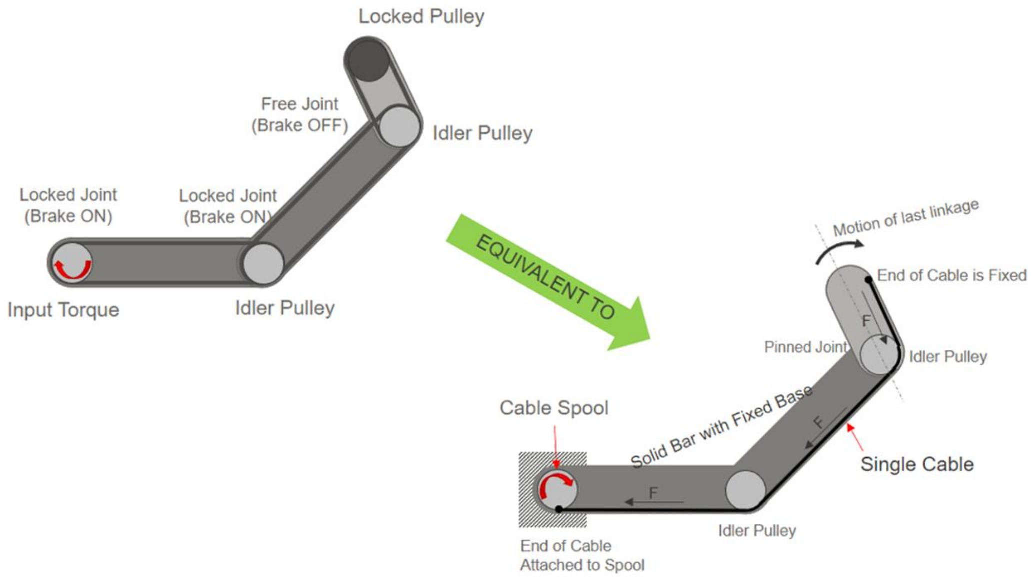
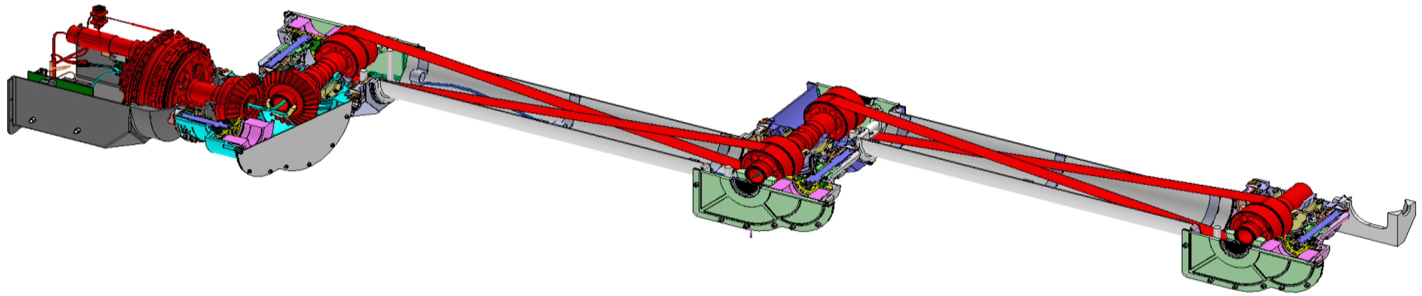
Lunar Underactuated Arm (LUnA) Project Overview

- Explored feasibility of maturing minimal/underactuated robotic arm technology
- LUnA is a 4 Degrees-of-Freedom (DOF) arm with a single actuator at the shoulder.
- Movement at each joint controlled by a brake subsystem.
- Effort bridged Technology Readiness Level (TRL) 4 (Breadboard validation in a laboratory environment) to TRL 6 (Prototype demonstrated in a relevant environment).
- Design is scalable up to 7 DOF with a single actuator
- Use of a single actuator at the shoulder -- benefits:
  - Better thermal and radiation protection.
  - Reduced mass, power, and recurring cost.
- Payload deployment and retrieval use case was selected to demonstrate technology.
- Relevant environments included
  - Demonstration under thermal/vacuum conditions.
  - Demonstration at the Colorado School of Mines Lunar Testbed Facility to validate dust mitigation techniques.

Minimal Actuation Concept

- Typical robotic arms are fully actuated, i.e., an actuator exists at each joint.
- An underactuated arm has less actuators than joints.
- LUnA is a *minimally* actuated arm; it has a single actuator at the base and a series of drive tapes and brakes that control the joints.
- Torque from the actuator is transmitted to the four joints of the arm (in a Yaw-Pitch-Pitch-Pitch configuration) equally via a drivetrain system.
- Joints move one at a time, depending on which brake is unlocked.
- *Single actuator at shoulder allows for better thermal and radiation protection of sensitive avionics, and potential mass and cost savings.*





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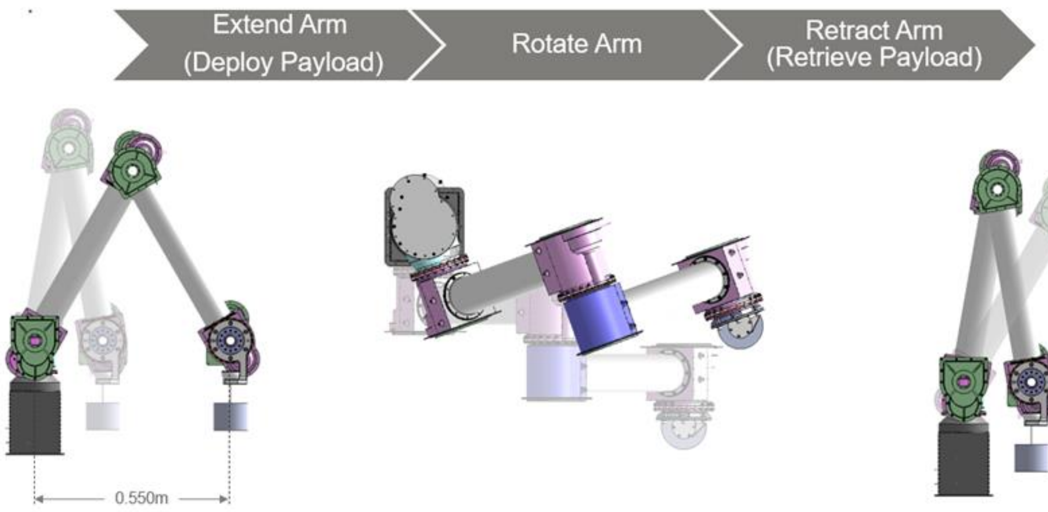
Demonstration Campaign

- Selected use case for demonstrations was Pick-and-Place.
  - 2kg and 4kg payloads placed at various locations from arm base.
  - This allowed the arm to navigate to them for the pickup and move operation.
  - Linux laptop running control software was located alongside and connected via the arms bulkhead connection.
- Three demonstrations:
  1. Prototype demonstrated in laboratory environment – TRL 5.
  2. Prototype demonstrated in relevant environment (Thermal/Vacuum) – TRL 6.
  3. Prototype demonstrated in relevant environment (Lunar Dust) – TRL 6.

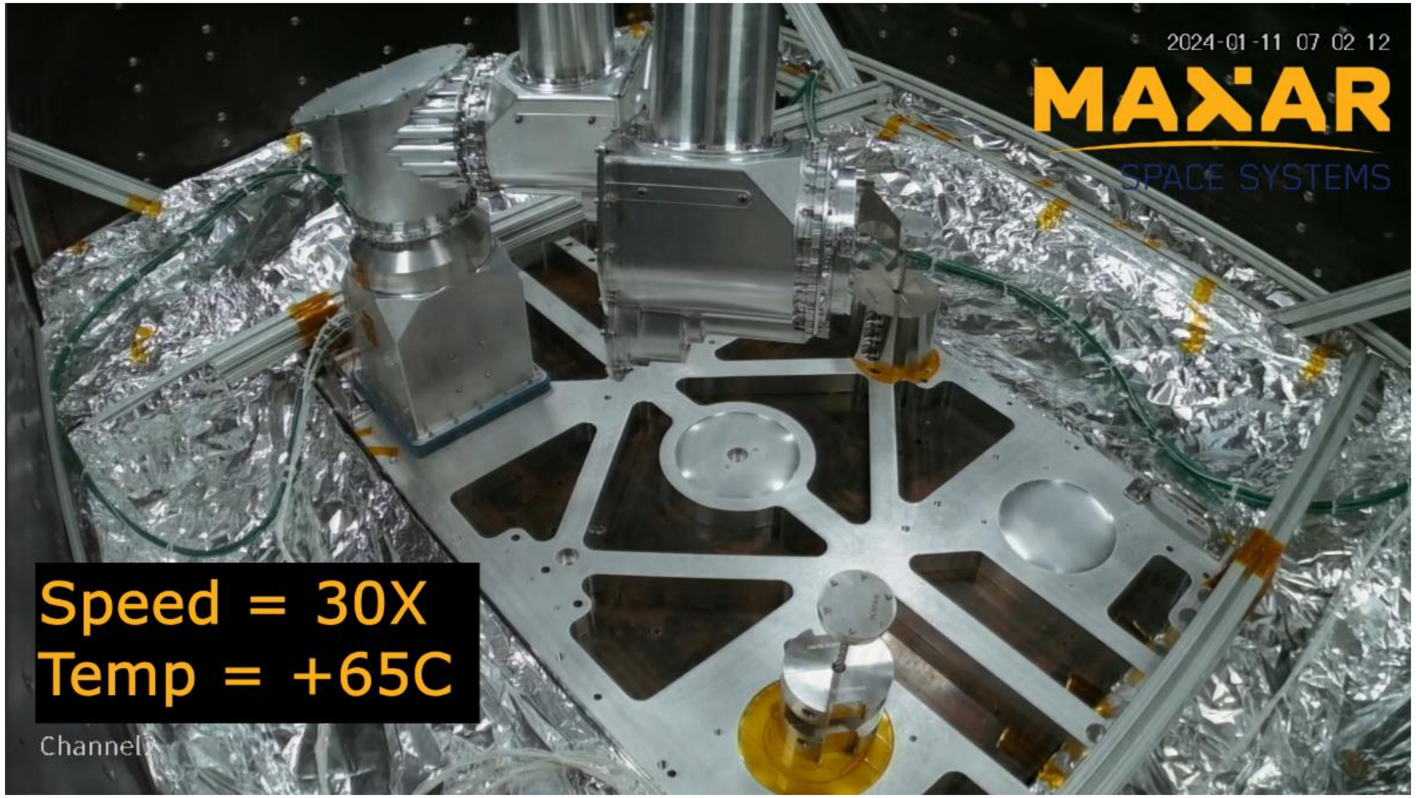


Demonstration 1: Laboratory Environment

- Demonstration of use case in a laboratory environment
- Acceptance criteria for this demonstration were:
  - LUnA arm provides all telemetry without faults and at 100Hz or better.
  - The payload was successfully engaged and carried throughout test motions and deployed on the desired target.
  - The test scripts returned successfully without faults.
  - All test data was collected without interruption and stored for data reduction.

Demonstration 2: Thermal / Vacuum (TRL6)

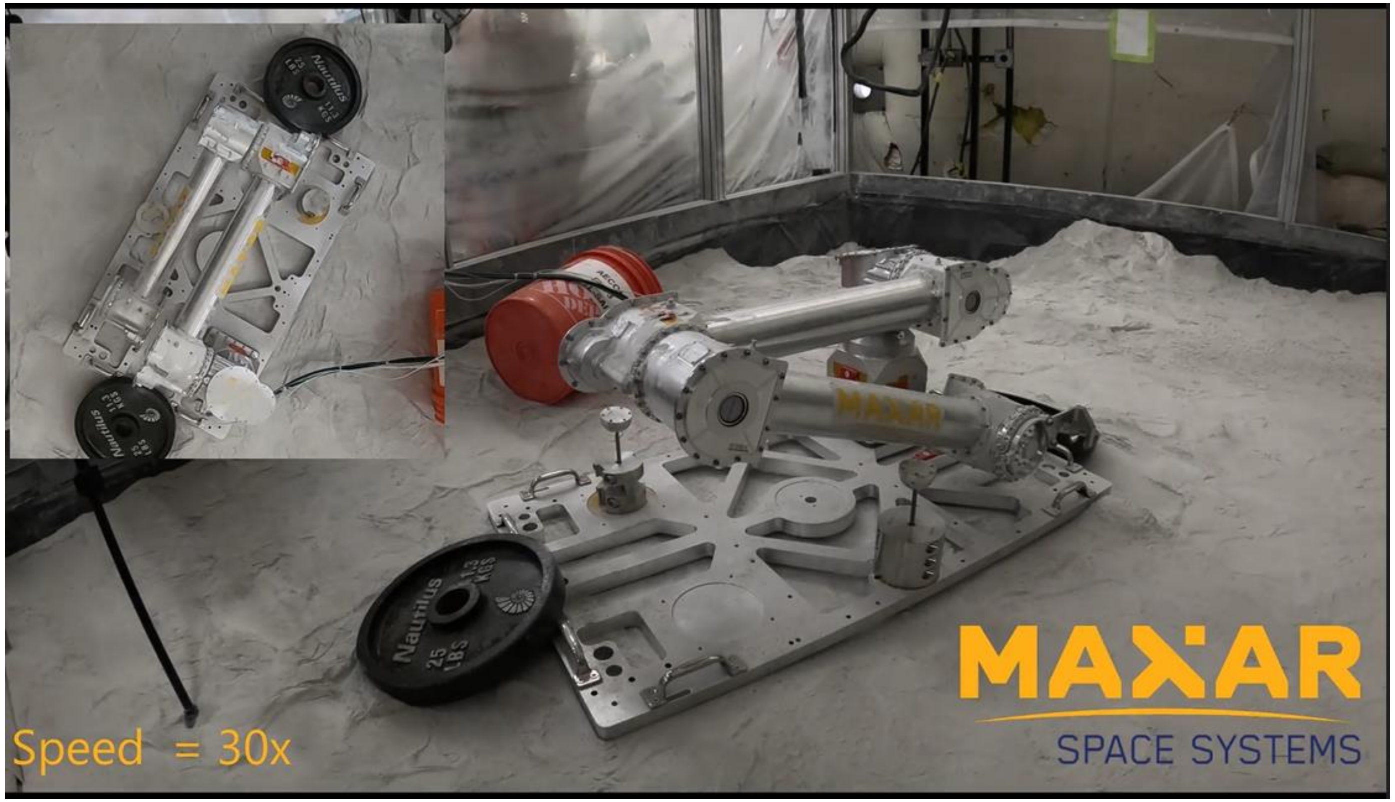
- Demonstration of use case in a relevant environment (-40C to +65C).
- Functional checkout at 20C under vacuum
- The next demonstration setpoint was at -40C, followed by the last setpoint of +65C.
- Quick functional check performed from ambient to cold at 10C, -10C, and -30C and involved moving each joint 4º forward and back to verify arm function.
- Also performed from the cold to hot at +30C, +40C, +50C, and +60C.
- Acceptance criteria for this demonstration were the same as Demo 1 and evaluated at the three operational temperature setpoints.
- Drive train mechanics, trajectory algorithms, and tensioning performed well at ambient and cold.
- There were challenges at high temperatures holding the pretension torques and handling the same movements (i.e., picking up the payload and manipulating it).



LUnA D2 +65C (30x).mp4

Demonstration 3: Lunar Regolith Testbed (TRL6)

- Demonstration of use case in a relevant environment.
- Same operational acceptance criteria as Demos 1 and 2.
- Conducted at Lunar Testbed Facility at Colorado School of Mines.
- Demo 3A involved static dirty test where regolith was applied to the arm prior to movement.
- Demo 3B involved dynamic dirty test where regolith actively applied to the arm throughout movement.
- Simulant used was CSM-LHT-1 Lunar Highlands Type simulant , mean particle diameter of 122.0 ± 2.1 µm.
- Meets the intent of NASA-STD-1008
- No dust intrusion found in the actuator and arm upon disassembly, thus validating the dust mitigation design.



LUnA D3 Test B Dual View (30x).mp4

 Public – External Recipients

Scooping Operations Lunar Regolith Testbed

- Opportunity to attach functional copy of scoop planned for use on upcoming SAMPLR mission.
- Able to demonstrate scooping (video) and simple trench digging (image below).
- Sieving was problematic, as LUnA was not designed to impart lateral motion.
- Information gathered during this activity will be of benefit to SAMPLR mission planning.

LUnA D3 Test C and D Dual View (30x).mp4

Conclusions

- Overarching philosophy: development of LUnA prototype informs design of future flight article.
- Limitation of this technology is that only one joint at a time can be moved
  - Extra time is required to lock and unlock the joints between moves.
  - Unable to have a straight-line trajectory like a fully actuated arm.
- Analysis was conducted on potential “next steps” in improvements to the initial design that would improve operational effectivity in a flight-qualified robotic arm, including:
  - Optimizing the design for better mass reduction.
  - Increasing the degrees of freedom of the arm.
  - Improvements in the drivetrain and structure (e.g., designing for ease of assembly, selection of alternative components, etc.).
  - Improvements to the control system.
- Of particular interest is optimization of the braking system.
- Future Use cases:
  - Scooping and trenching
  - Deployable structures
  - Cranes

Acknowledgements

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Thanks to the Colorado School of Mines Center for Space Resources for the use of their Lunar Testbed Facility.

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BACKUPS

Prototype Capabilities

Parameter	Specification
Physical Attributes	
Degrees of freedom	4 (Yaw-Pitch-Pitch-Pitch)
Total Length	1.1m
Actuators	1 (Maxar Z17)
Total mass	17kg
Structural Material	Aluminum
Performance Characteristics	
Joint Torque Capability	67Nm
Joint Range of Motion	±161.8° at all joints (hard stop limited)
Tip Force	>49N at 0.5m reach
Tip Accuracy	.015m at 0.5m reach
Tip Repeatability	.007m at 0.5m reach
Tip Velocity	>0.026 m/s
Operational Power	28W Operational, 29.5W Peak
Idle Power	9W

Parameter	Specification
Electrical	
Arm Computer	Xiphos Q7
Motor Control Board	Elmo Gold Bee MCB
Sensing	- Actuator output position - Motor position - Actuator output torque - Joint position - Joint temperature
Operating Voltage	32V Max
Current Limit	1.5A
Heaters	-Motor Case -Actuator Housing -All Joint Brakes
Interface	Bulkhead Micro-D Connectors at Base
Environmental	
Operational Temperature Range	-40°C to +65°C
Vacuum	10^{-6} Torr
Lunar Regolith Exposure	Mitigations in design to prevent intrusion