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Introduction: The Lunar Underactuated Arm (LUnA) Project is a technology development effort exploring the feasibility of maturing minimal or under-actuated robotic arm technology from Technology Readiness Level (TRL) 4 (Breadboard validation in a laboratory environment) to TRL 6 (Prototype demonstrated in a relevant environment).

Background:

Robotic arms are typically fully actuated in that there is an actuator for each degree of freedom. This traditional approach provides excellent controllability but is not without drawbacks. Actuators are a large mass and power contributor within an arm, and controlled actuation of each joint negatively impacts power consumption. The infrastructure supporting each actuator (e.g., motor controllers, encoders, heaters, etc.) further impacts mass, power, and system complexity, along with the increased cost and labor associated with actuator build and qualification, as well as need for drive electronics for each joint.

Underactuated arms seek to lessen the impacts of this traditional approach by using less actuators than degrees of freedom. Minimal actuation provides joint control with a single actuator. While this architecture can restrict the number of joints that can be controlled simultaneously, this approach provides promise in optimizing two critical factors to spaceflight missions: mass and power. Underactuation has been applied to a variety of systems including cranes, with bar linkages; LUnA is a minimally actuated arm with an internal drivetrain.

At the inset of the project, the first major task was defining what constituted exit criteria for TRL 6 ("demonstrated in a relevant environment"). A notional Concept of Operations was developed based on a notional Commercial Lunar Payload Services (CLPS) mission, which helped establish mission level requirements, from which system and lower-level requirements were decomposed.

A relevant mission task such as deploying a payload or positioning and holding an instrument near the lunar surface was selected as the demonstration use case. For LUnA, this became moving a set of test masses within the robotic arm's workspace. After thermal analysis the relevant environment was defined as operation of the use case at various steps within the anticipated -40 to +65C thermal range for lunar operations. Additionally, there was an opportunity to validate LUnA's dust migration strategy, using a rotary joint design consistent with Maxar's previous robotic arms that have operated on the Martian surface.

The development of metrics such as Technical Performance Measures (TPMs) and Key Performance Parameters (KPPs), was critical in quantifying potential applications of the LUnA technology and utilized by the team throughout the project.

LUnA consists of a four degree-of-freedom arm with a 1.1-meter total length in a Yaw-Pitch-Pitch-Pitch configuration. Torque from the actuator is transmitted to the four joints of the arm equally via a drivetrain system. Movement at each joint is controlled by a brake subsystem, with joint motion occurring one at a time depending on which brake is unlocked. Motion planning for a robotic arm with a single active joint and multiple passive joints requires a discretized trajectory, actuating one passive joint at a time. To accomplish this, novel control software was developed, built on top of our in-house flight soft-ware framework, used on previous flight projects.

Figure 1: LUnA conducting functional demonstration during dust mitigation testing at the Lunar Testbed Facility, Colorado School of Mines

Status: LUnA underwent three successful demonstrations as a path to establish TRL 6:

1. Functional performance at ambient temperature and pressure to verify Key Performance Parameters (KPPs). No issues were reported.

2. Functional testing in thermal vacuum conditions to verify KPPs, through the cycles of operational and survival temperatures anticipated for a lunar surface mission. Drive train mechanics and trajectory algorithms and tensioning performed well at ambient and cold, but at high temperatures there were challenges holding the pretension torques and handling the same movements (i.e., picking up the heavy payload and manipulating it).

3. Demonstration of the LUnA Robotic Arm conducting its functional checkout under ambient conditions while exposed both statically and dynamically to lunar regolith simulant (CSM-LHT-1 Lunar Highlands Type simulant; mean particle diameter = 122.0±2.1 am, compared to 101–268 mm for Apollo 16 highlands regolith). This demonstration was conducted at the Lunar Testbed Facility at the Colorado School of Mines (Figure 1). No dust intrusion was found in the actuator and arm upon disassembly, thus validating the dust mitigation design.

While at the Lunar Testbed Facility, there was also an opportunity to experiment with the scoop that will be used on the upcoming SAMPLR[1] mission, Not only was LUnA able to accomplish simple scooping, but it was also able to perform trench digging (see Figure 2).

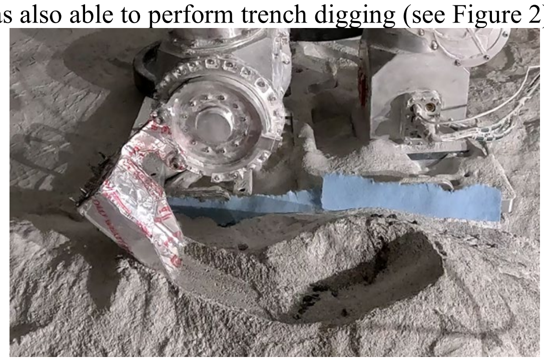

Figure 2: LUnA preforming trench digging using the SAMPLR scoop at the Lunar Testbed Facility, Colorado School of Mines

[1] The Sample Acquisition, Morphology Filtering, and Probing of Lunar Regolith (SAMPLR) Project is a five degree-of-freedom robotic arm that will collect samples of lunar regolith for other on-board instrument analysis, demonstrate the use of a robotic scoop that can filter and isolate particles of different sizes, and utilize a penetrometer to help determine properties of the regolith [1].

Conclusion: One of the overarching themes of this project was that the development of the prototype would inform the design of the future flight article. As a result, an 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. Such modifications would also include 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, etc. Of particular interest is optimization of the braking system to include an analysis of alternatives over the subsystem that was selected as a rapid alternative to the originally proposed electrostatic design.

Applications of this technology are not limited to the single use case ("pick and place") that was demonstrated in this effort. An analysis of other potential applications was also conducted, not only for robotic arms, but also in other categories such as mobility and control of deployable structures.

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References:

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