Proposed Research Project

Maximizing Post-Motor-Failure Operation of a Robotic Truss for Lunar Surface Tasks

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James Wade

I. Introduction

A sustained presence on the Moon is a key objective of current space exploration efforts, particularly through NASA's Artemis program. Achieving this goal requires lightweight, deployable structures that can 1) be efficiently transported in mass- and volume-constrained rockets, and 2) maintain structural integrity in the harsh lunar environment [1], [2]. In this proposal, we will develop and test a controller for the robot that allows it to complete tasks even when some of its driving motors fail. This increased robustness will enable the robot to be more reliable and maintain greater functionality in lunar environments when repairs are infrequent by necessity.

A. Background and Prior Work

Our research group in the Compliant Mechanisms and Robotics (CMR) Lab at Brigham Young University was recognized as a finalist in the 2024–2025 NASA BIG Idea Challenge, which focused on inflatable structures for lunar applications. Our project, for which I was a team lead, centered on an inflatable truss structure composed of pressurized tubes bent into triangular shapes, as shown in Figure 1.

Under the mentorship of Dr. Nathan Usevitch—who pioneered this robot concept during his Ph.D. at Stanford [3]—we expanded the original design to improve its robustness for lunar use, as detailed in [HERE]. As a summary of the hardware structure, each triangular face includes two active roller units and one passive roller. The active rollers contain DC motors that adjust the relative lengths of the edges by feeding tubing in or out, enabling the structure to morph dynamically while maintaining truss-like rigidity.

We applied this concept in two key configurations for our BIG Idea proposal: a solar panel mount capable of reorienting toward optimal sunlight (Figure 2), and a lunar crane designed to transport payloads across the lunar surface. Our inflatable truss design offers a promising alternative to metallic structures, combining lightweight transportability with adaptability and strength. Our work earned us national recognition as a finalist in the 2024–2025 NASA BIG Idea Challenge [4].

B. Limitations of Current Controller and Proposed Solution

One key feature of our robot is the ability to selectively move a specific corner in a desired direction—useful, for example, when maneuvering heavy objects. Our kinematics-based controller achieves this by solving a quadratic optimization problem to determine the precise rotation each active roller motor must perform. Currently, the controller assumes all active rollers are fully functional. However, in a lunar environment, motor failures are plausible. While the truss-robot remains structurally sound without power, such failures can significantly reduce its effective workspace. A robot's workspace is the region in which it can operate safely and effectively without becoming unstable or exceeding its mechanical constraints. The robot must be able to operate within this constraint. Additionally, the current controller, once it deems it can't reach its desired trajectory endpoint via a straight line, abandons its current target and switches to the next one. This, too, is undesirable behavior.

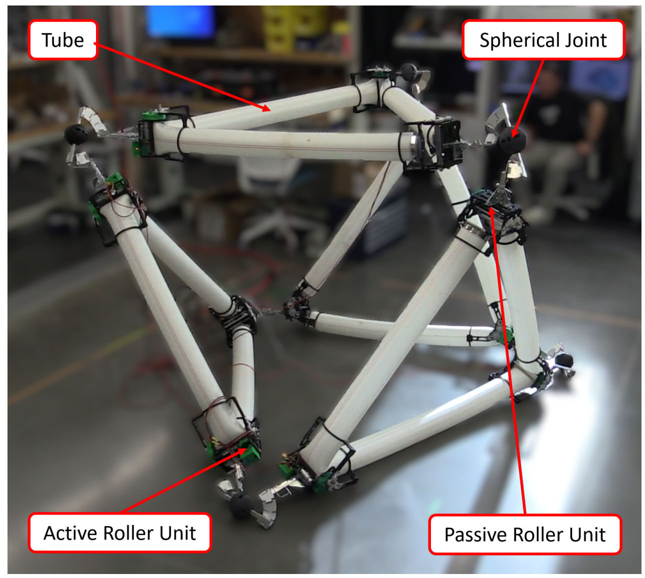

Fig. 1: An octahedron unit of the isoperimetric truss robot with its main subsystems highlighted: the inflated tubes, the spherical joints, and the active and passive roller units.

To address these limitations, I propose developing a more robust controller capable of operating under any combination of motor failures. This new controller will maximize the usable workspace despite actuation limits and employ smarter strategies to navigate along workspace boundaries. The result will be a more resilient and intelligent system, better suited for lunar operations where reliability and redundancy are critical.

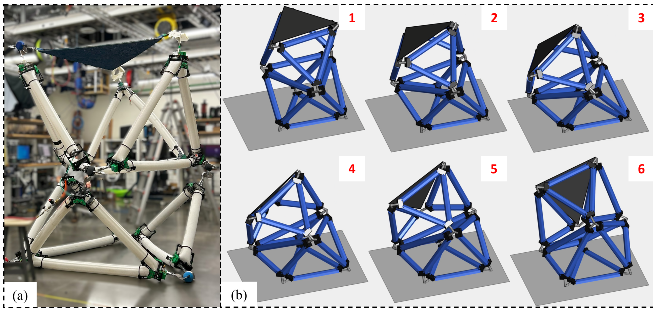

Fig. 2: (a) Solar panel array composed of six triangles and the solar panel. (b) Simulation of solar panel configuration for the robotic truss showcasing its motion that can reorient the solar panel in the direction of most sunlight.

C. Related Work

Numerous researchers, including those at NASA, have explored the feasibility of using inflatable structures as key components in the design of lunar habitats and infrastructure [5], [6], [7], including research in trusses made from lunar regolith [8] and NASA research about trusses composed of deployable beams [9]. There has even been some research into using variable geometry trusses (VGT) – a structure similar to our truss – in the lunar environment due to their naturally high strength-to-weight ratio [10]. Our truss robot differs from these structures in that it is both 1) a soft, truss robot that 2) can dynamically change depending on the loading scenario required, making it more versatile to both typical and novel use cases. Our robot's method of actuation is also markedly different than a typical VGT-type truss, which uses linear actuators to lengthen its members [11], [12].

Redundancy has long been a central topic in the field of robotics [13], and this project aims to further leverage the multiply-redundant capabilities of our truss robot. While prior work has extensively examined graph rigidity in both theory and practice, much of this research has often been situated in the context of swarm robotics [14], [15]. Some of this research has even explored motion planning for load manipulation tasks using swarms [16], similar to the load-bearing capabilities of our truss robot. However, our approach differs fundamentally. In contrast to swarms—where individual agents move semi-independently—our truss robot exhibits tightly coupled motion, where displacement of a single node induces coordinated motion across the entire structure. This intrinsic interdependence renders existing methods insufficient for our purposes and motivates the need for novel frameworks tailored to our system's unique dynamics.

II. Research Objective

The key innovation of this work is the development of a controller for the isoperimetric lunar robot that maximizes trajectory accuracy, even in the presence of system failures. This research specifically focuses on maintaining robustness against motor actuation failures, while analysis of other failure types is left for future work.

The proposed controller aims to increase the operational longevity of the robot in the lunar environment, as well as in other settings where repairs are inherently infrequent or impractical. Accordingly, the primary research objectives are as follows:

1) Design and implement a controller based on gradient descent methods to optimize trajectory tracking.
2) Validate the controller on physical hardware — on the octahedron structure and on a 2D structure.
3) Analyze and compare the controller's robustness as various roller units are deactivated.

III. Research Approach and Key Tasks

The work will progress through the following tasks:

1) *Simulation Design* — The current simulation, developed for the NASA BIG Idea Competition, models the 3D octahedral configuration of the truss robot. This simulation will be extended to support two-dimensional robotic configurations composed of the inflated triangular units that form the robot structure, as well as the ability to deactivate the actuation at any number of roller units on the robot.
2) *Controller Design* — In its current form, the controller abandons its current target point when encountering a singular configuration, immediately switching to the next target. The redesigned controller will proactively avoid singularities by navigating along the workspace boundary to search for alternative paths to the desired location.
3) *Workspace Exploration in Simulation* — The simulation will be tested across a variety of trajectories, ranging from simple geometric paths (e.g., squares) to more complex shapes such as letters. Trajectory accuracy will be evaluated by comparing a fully operational robot to one with selectively deactivated units. Additionally, I will assess the controller's robustness in scenarios where the robot reaches a target under full functionality and then experiences system failures.
4) *Hardware Verification* — Using the prototype developed for the NASA BIG Idea Competition, a motion tracking system will be employed to collect physical trajectory data as motion commands are transmitted through the robot's radio-based structure. The recorded motion will be compared against simulation results to evaluate the controller's accuracy on real hardware.
5) *Refinement of Controller* — Based on the collected data, the controller will be iteratively refined to improve alignment between simulated and physical performance.

IV. Expected Outcomes and Preliminary Results

The expected outcomes include a more intelligent controller as described previously, and comparisons between the current controller's performance and the new controller's performance in various scenarios.

A. Previous Research: Derivation of Mathematical Model

The controller operates with the principles outlined in [3]. As a brief summary, the quadratic optimizer modulates $\dot{x}$. As such, a method to convert $\dot{x}$ into $\dot{\theta}$ is needed in order to properly control each motor contained in the active roller units. The time-rate change of the truss's edge lengths, $\dot{L}$, is related to the vector linear velocities of each corner in the truss, $\dot{x}$, through the rigidity matrix $\mathcal{R}$, as shown in Equation 1 [3], [17]. $\dot{L}$ is also related to the rotational velocities of each motor $\dot{\theta}$ through the incidence matrix B, as shown in Equation 2 [3]. By combining Equations 1 and 2 together, $\dot{x}$ and $\dot{\theta}$ can be related through a matrix called the Jacobian, as shown in Equation 3 [3]. The details of this derivation can be found in [3]. Therefore, by solving for an optimal $\dot{x}$ in our quadratic solver, we have implicitly also found an optimal $\dot{\theta}$ through the relation expressed in Equation 3, and these rotational commands are transmitted through the robotic truss via a radio communication system.

$$\dot{L} = \mathcal{R}(x)\dot{x} \tag{1}$$

$$\dot{L} = B^T\dot{\theta} \tag{2}$$

$$\dot{x} = J(x)\dot{\theta} \tag{3}$$

B. New Research: Constraining Motor Actuation in Optimization to Simulate Failure

The foregoing equations have already been proven to work in both theory and in practice through our previous efforts [NASA PAPER]. But using the previously discussed relations, how can we constrain the optimization such that only a select number of motors are actuated? Even if a motor fails, its linear position in the global spatial frame can still change due to the movement of other nodes. As such, we need to force $\dot{\theta}_i = 0$ for each "broken" node, and this constraint must be in the form of $A\dot{x} = \dot{\theta} = \vec{0}$ for the optimization to work properly (i.e. the standard form for equality constraints in quadratic programming). By combining Equations 1 and 2, we can see that

$$\dot{\theta} = B^{+T}\mathcal{R}(x)\dot{x} = A_{broken}\dot{x}. \tag{4}$$

By selecting specific rows of A_{broken}, we can effectually turn off the rotational movement of select motors in the optimization function by including A_{broken} as an equality constraint.

The application of Equation 4 has yielded promising results, such as those illustrated in Figure 3, where Roller 1 was constrained to zero motion. We are excited to continue testing this theory as we simulate the robot's workspace when motors malfunction.

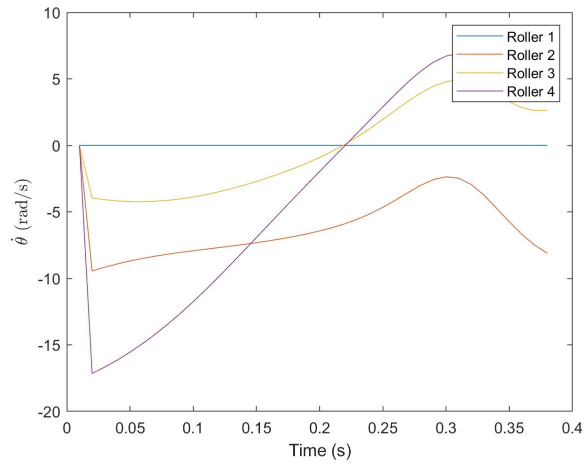

Fig. 3: Plot showing the roller velocities of each motor, including Roller 1's constrained motion

C. New Research: Traversing the Workspace Boundary

Another important aspect of this project is enhancing navigation along the workspace boundary to maximize the robot's effective reach. For rigid graphs like our truss-based robot, the rigidity matrix $\mathcal{R}$ must have exactly six zero eigenvalues in 3D (or three in 2D) to satisfy the conditions for infinitesimal rigidity [17]. Any additional zero eigenvalues indicate excess degrees of freedom beyond rigid-body motion, meaning the structure has lost rigidity and is nearing a singular configuration—a state in which the truss may collapse.

To detect this, we examine the 7th smallest eigenvalue of the rigidity matrix in 3D (or 4th in 2D), which quantifies how close the system is to becoming singular. A near-zero eigenvalue suggests that the robot is becoming singular. Its associated eigenvector should also be aligned with the normal to the workspace boundary. By identifying this normal direction, we can program a controller to traverse tangentially along the boundary, effectively extending the robot's operational workspace while avoiding singularities. Figure 4 visually shows the correlation between the desired movement direction and the normal eigenvector in finding the tangential direction required to traverse along the workspace boundary. We believe this method can be further improved as we experiment with how best to traverse the workspace boundary.

D. New Research: Verifying Performance on Hardware

Once the software reaches a satisfactory state, we will validate the simulation's performance with real motion data from our truss robot. Our lab is equipped with motion-tracking technology utilizing VIVE trackers, which will enable us to capture real-time positional data as we guide a node along a specified trajectory. To assess the effect of mechanical constraints, we will systematically restrict various combinations of rollers—evaluating scenarios where one, two, or more rollers are immobilized—and observe the

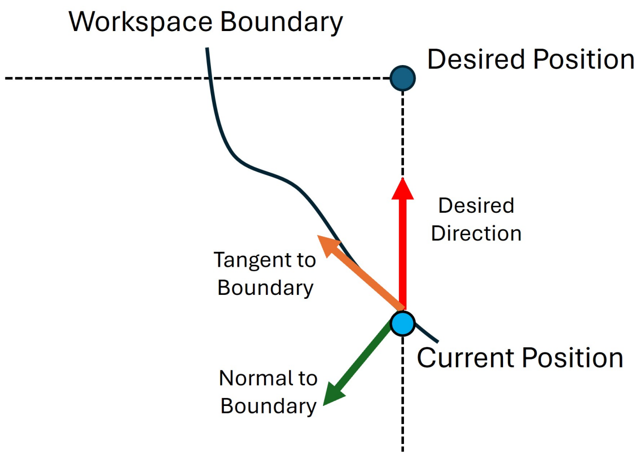

Fig. 4: The visualized method for traversing along the unknown workspace boundary by using the method of the 7th (or 4th) smallest eigenvalue

resulting changes in the robot's workspace. The simulation results will then be compared against the experimental data using the Mean Squared Error (MSE) as a quantitative measure of accuracy.

V. Resources

As part of the Compliant Mechanisms and Robotics Laboratory at Brigham Young University, I have been working under Dr. Nathan Usevitch, one of the original researchers of the isoperimetric robot design, developed during his doctoral studies at Stanford University [3]. Together, Dr. Usevitch and I led a research team within the CMR lab to redesign the robot for lunar applications. Our work was recognized as a finalist entry in the NASA BIG Idea Challenge. As a result, I now have access to a functional prototype, which I will use to pursue the research objectives outlined earlier. I also have access to motion-tracking systems in our lab space at BYU, perfect for gathering motion data and comparing it against the simulation model.

VI. Conclusion

In support of the Artemis mission objectives, continued advancements in the truss robot design could pave the way for soft, inflatable, and adaptable alternatives to traditional rigid, heavy, and metallic structures on the lunar surface. By enhancing the robot's control capabilities through the objectives outlined in this project, the truss system can achieve greater operational reliability and extended functionality in challenging environments. These improvements not only contribute to the development of sustainable infrastructure on the Moon but also demonstrate the potential of lightweight, reconfigurable robotics in future space exploration.

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