Design Development of a Stable, Lightweight, Tall and Self-Deploying Lunar Tower

Alex S. Miller,
George Lordos, Paul Portman,
Avril Studstill, Joshua Rohrbaugh,
Wilhelm Schoeman, Christian Williams,
Emma Rutherford, John Z. Zhang,
Palak B. Patel, Olivier de Weck, Jeffrey Hoffman
Massachusetts Institute of Technology
77 Massachusetts Ave., 33-409
Cambridge, MA 02139
asmiller@mit.edu

Natasha Stamler
Eindhoven University of Technology
Het Kranenveld 8
5612 AZ Eindhoven
The Netherlands

Benjamin C. Martell
Space Exploration Technologies Corp.
2100 Les Maulden Rd
Brownsville, TX 78521

Juan M. Fernandez
NASA Langley Research Center
Hampton, VA 23681, USA

Abstract—**Deployable composite booms with spaceflight heritage are being investigated at the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) and the Massachusetts Institute of Technology (MIT) Space Resources Workshop for their potential to be vertically deployed in the lunar gravity field, in support of the NASA Artemis campaign. This paper reports new design development results—after the original presentation at the NASA 2020 BIG Idea Challenge—for a 16.5-meter-tall, compact, self-deploying composite tower intended to support the exploration of lunar permanently shadowed regions by nearby robotic assets or humans. Possible applications include vertical solar arrays and the provision of elevated lines-of-sight to science or engineering payloads, in support of nearby targets operating in areas of interest that may be hard to reach. Useful elevated payloads include radio repeaters, remote sensing and imaging, navigation and power beaming systems. However, while these lightweight rollable booms have an excellent height to mass ratio, they typically exhibit axial curvature upon deployment resulting in appreciable lateral dead-load deflection of the tip mass relative to the tower base. This static deflection increases with tower height and tip mass, not only constraining the value delivered by the tower but also endangering its integrity. To develop a competitive, lightweight deployable composite boom tower, a capability to correct static deflections during and after deployment will be required. In this paper, a deployable guy wire stability system will be presented for the MIT / LaRC self-erecting composite boom lunar tower that provides real time measurements, maintains tension both actively (during deployment) and passively (post-deployment), and can serve as a reconfigurable platform to test and trade alternative stability system configurations, such as with added spreaders inspired by sailing boat masts. Using a calibrated photogrammetry system, the natural lateral deflection of the boom tip relative to the boom base at different deployed heights was recorded for different configurations. With real-time force measurements it was found that tensioned guy wires can significantly reduce the static tip deflection of a deployable composite boom under dead load and can dampen a dynamic oscillation in under a minute. It was also found that control authority is greatest where it is needed most, i.e., for the lever arm closest to being opposite the direction of deflection. For a tower height of at least 11 m and spreader length of at least 60 cm, a solution of differential tension in all three arms exists and, in principle, provides sufficient control authority to correct or significantly reduce boom tip deflections. Notably, natural deflections occur almost entirely normal to the seams of the boom cross-section, but the natural boom tip lateral deflection under dead load upon deployment was approximately 5% of boom deployed length, exceeding the manufacturing acceptance specification of 1%. Ongoing and future work includes the further investigation towards mitigating manufacture-caused lateral deflection, trading of alternative guy wire system designs, as well as the design development of a second-generation tower incorporating a more capable boom design with the learnings from the proof-of-concept system presented here.**

Table of Contents

1. Introduction

As part of the Artemis program, NASA intends to return humans to the surface of the Moon. However, before humans land on the Moon once again, rigorous exploration must be performed autonomously to reduce risks for manned missions. The permanently shadowed regions (PSRs) near the lunar poles, which have remained dark for billions of years, are of special interest due to their likelihood to contain water or other hydrogen-rich deposits that could support a mission on the surface [1], [2]. The extreme cold, complete darkness and uncertain terrain of PSRs present substantial logistical challenges to both humans and machines operating inside these regions. One of these challenges is the lack of a line-of-sight to nearby landers situated in sunlight outside crater rims. While investigating potential mission-enabling lunar infrastructure, the idea that the top of a tall tower just outside the PSR would have multiple lines of sight to the Earth, Sun, the lander, and the lunar surface inside and outside the PSR was explored. Therefore, based on the principle of "location, location, location," it was determined that a tall tower may be an highly desirable element of future lunar infrastructure supporting the exploration of PSRs by robotic and human assets.

Specifically, the vision for a lightweight, tall, self-deploying lunar tower with a payload deck on top to support an extended robotic ecosystem within or around PSRs on the lunar surface, alleviates limitations imposed by the terrain of those regions. A successful demonstration of such a technology on a Commercial Lunar Payload Services (CLPS) mission would establish it as an enabling or supportive technology for future lunar missions within the Artemis program. NASA established the CLPS program in 2018, which facilitates and encourages the U.S. commercial space industry to develop new technologies to deliver payloads to the lunar surface. The first CLPS payload deliveries will begin circa 2023 with two companies delivering sixteen instruments to the lunar surface to pave the way for human explorers [3].

Among other uses, by robotically deploying a tall tower near a landing area as shown in Figure 1 adapted from [4], future missions can enjoy increased operational capabilities at relatively low costs: improved range and reliability of surface communications, stereoscopic mapping of the vicinity of a lander, identification of potential routes into or out of a PSR, wireless energy transfer in the form of reflected sunlight, microwaves or lasers, and more. A tower would offer an elevated payload platform benefiting any payload that can use its high vantage point, multiple lines of sight, and plug-and-play services. Teams at MIT reported on the initial technology readiness level (TRL)-3-to-4 development efforts for such a tower, named Multifunctional Expandable Lunar Lightweight and Tall Tower (MELLTT), as well as on potential use cases and applications [4], [5].

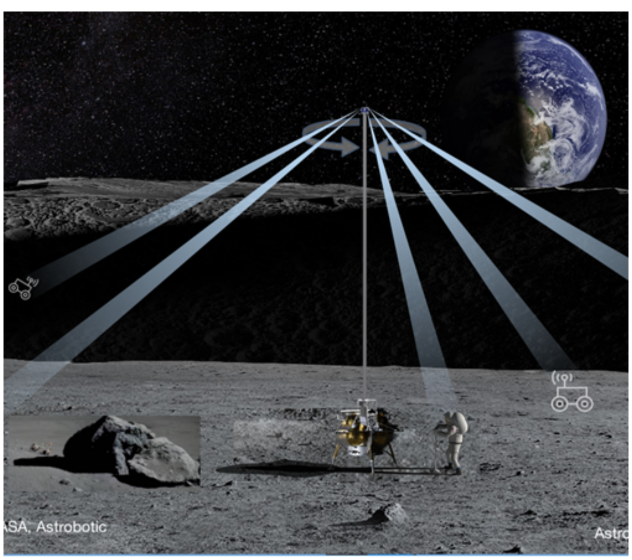


Figure 1. **Artistic rendering of MELLTT providing data relay services to multiple assets at the lunar South pole.**

The first MIT lunar tower test article in 2020 was developed using a 2m boom loaned by the Deployable Composite Booms team at the NASA Langley Research Center (LaRC). This test article was only deployed to a 2 m height, which was insufficient to test the functionality of a tall, loaded tower. However, realistic deployed carbon fiber reinforced polymer (CFRP) composite booms are expected to exhibit a non-zero axial curvature for one or more of the following reasons: manufacturing errors [6], long-term stowage creep/relaxation [7], and thermally-induced deformations [8]. If, upon deployment to a useful height (i.e., >10 m), the boom shape has or acquires an axial curvature (bow) resulting in a lateral deflection of the elevated platform, the risk of buckling increases, limiting the value of the tower. If the loading and deflection exceed a critical limit, the integrity of the tower may be endangered. Guy wires are a typical solution to this problem for tall masts in Earth applications, such as sailboat masts and communication poles.

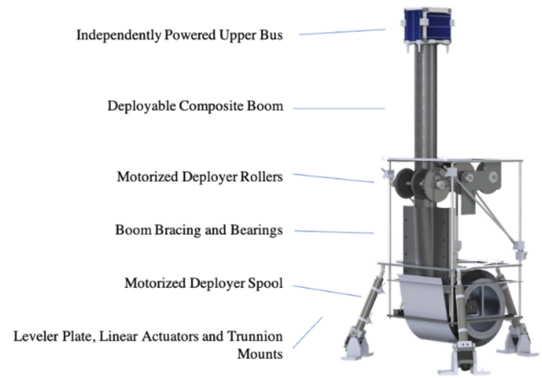


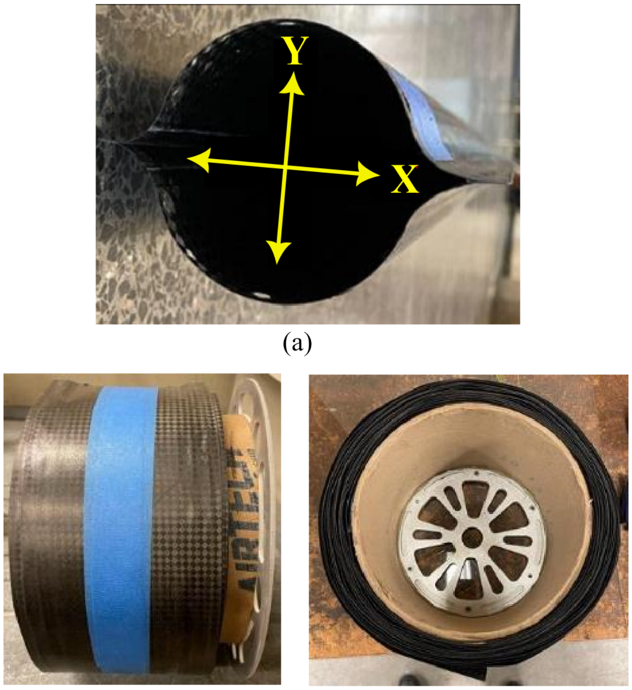
Figure 2. **MELLTT developed at MIT in collaboration with LaRC Deployable Composite Booms team can self-level in the lunar gravity field and is envisioned to elevate a CubeSat payload package of up to 3U to a height of up to 16.5 m above the lander deck.**

2. DESIGN EVOLUTION AND SYSTEM DEVELOPMENT

Overview of MELLTT System

The MELLTT system was a proof-of-concept technology development by MIT in response to the NASA 2020 BIG Idea Challenge, for which the NASA Deployable Composite Boom (DCB) project loaned a boom to MIT for experimentation [4], [9]. MELLTT is shown in Figure 2, as built and demonstrated by the MIT team to an initial height of 2 m.

A new collaborative effort between LaRC and MIT under a 3-year Space Act Agreement will advance technologies to support improved versions of the lunar tower. The Self-Erectable Lunar Tower for Instruments (SELTI) is a technology under development at NASA in collaboration with MIT. SELTI will take advantage of the relatively weak lunar gravity and lack of atmosphere to deploy science and engineering payloads at elevations up to 16.5 m above the lander deck. Elevated payloads can include radio relay, navigation beacons, multispectral and stereoscopic imaging, scanning LiDAR (light detection and ranging), and lasers, lenses, or mirrors for beamed or reflected power. The line-of-sight provided by a lunar tower is a key enabler for small, distributed payloads and autonomous robots to explore and operate in and around PSRs. A number of networked applications for SELTI have been explored at MIT by Johanson et al (2020) [5].



(a)

(b) (c)

Figure 3. CTM boom (a) in the deployed state, showing two omega-shaped thin shells connected in the X-axis direction, and in its stowed state, showing its (b) outer carbon fiber plain-weave and (c) thin layers when the boom is collapsed and rolled.

Subsystem Overview

Boom Mast—The MELLTT system revolved around a collapsible tubular mast, on loan from NASA LaRC. The thin-ply carbon fiber/epoxy plain-weave and unidirectional ply technology reduces boom wall thickness and enables small bending radii that result in compact rolling stowage of the booms [6], [10]. The two omega-shaped thin shells form a closed cross-section, yielding high stiffness in its deployed state and providing high dimensional stability [11], [12]. Additionally, incorporating a collapsible tubular mast (CTM) boom into a low-cost technology demonstration flight is feasible for a near-term CLPS flight since similar booms are being flight qualified under the NASA Advanced Composite Solar Sail System (ACS3) project to launch circa 2023 [13]. The structural properties of the DCB boom and its manufacturing process are described in detail by Fernandez et al. (2019) [14] and Stohlman et al. (2021) [15]. The NASA Space Technology Mission Directorate (STMD) DCB project is a collaboration between NASA LaRC and the German Aerospace Center (DLR) to advance compact deployable composite boom technology [6], [16], [12]. A 13 m CTM boom on loan to MIT from NASA LaRC is shown in Figure 3.

Boom Deployer—The thin-shell CFRP boom is rolled flat around a motorized spool. During powered deployment, the boom is unrolled to form a lenticular cross-section that resists torsion, bending, and buckling. A set of powered rollers assists deployment, and the deployed boom is braced to support loading under gravity. The deployer can be used with booms of different lengths. A retraction capability for mobile use cases is currently under development.

Base Leveler—The deployer and boom are mounted onto a kinematic base consisting of three linear actuators and a mounting plate. The desired pose and attitude of the tower is fine-tuned using both open- and closed-loop feedback control based on accelerometer data. The leveler functions to align the axis of the boom with the lunar gravitational field, compensate for effects of vibrations or shocks and re-align tower axis in event of boom bending. The leveler is passively locking, and is capable of leveling on slopes up to 12 degrees.

Payload—A payload platform at the top of the tower provides client payloads an elevated vantage point for service delivery. Based on a 1U CubeSat to leverage commercial-off-the-shelf (COTS) parts, and with four exterior solar panels, the primary function of the platform is to provide mounting, power, communications and pointing to payloads. These payloads may include power beaming, radio, navigation and imaging services.

Mock Lander—A testbed which simulates a CLPS lander and holds the leveler and rigging electronics is able to be adjusted to provide arbitrary rotations and representative slopes for the tower.

Design developments in SELTI

While tests of MELLTT were successful in limited elevation of payloads, striving towards increased reliability, taller heights, and greater payload mass necessitated a reevaluation of the systems architecture. The realization of this architecture is shown in as shown in Figure 4. In particular, a deployable rigging subsystem shows a path to higher system performance in SELTI.

Guy wire and rigging systems on cell towers, cranes, and sailboats serve as major sources of inspiration for this concept. Such rigging systems have been a staple of Earth-bound lightweight tower construction. Guy wires are often used in cell and radio antenna towers, such as in Figure 5 (a), to reduce shear loads on the central structure and prevent a stress concentration at the base. When guy wires are employed around a central truss structure, the central truss becomes a quasi-tensegrity structure.

Rigging systems on sailboats, such as in Figure 5 (b), are designed to sustain dynamic loads and are rapidly reconfigurable for different wind conditions and sail structures. Sailboat guy wire systems often feature multiple mid-mast spreaders, dynamically moving pulleys and compliant structural elements. Deployable tensegrity designs for space applications, such as Chen et al. [17] necessitate a higher number of structural elements compared to a single piece deployable, adding complexity and mass. Deployable terrestrial military applications also exist, such as Rolatube, however these are meant for manual deployment and are not designed for the space environment [18].

While guy wire systems on Earth are well developed, space deployable structures present unique challenges that make them a topic of active research. Autonomously deployable towers with guy wires delivered by small landers such as CLPS must have self-deployable guy wire arms and active tensioning, especially if guy wire support is needed throughout deployment. In addition, most space systems have volume constraints that cause the guy wires to be much closer to the tower compared to Earth systems, causing a reduction in controllability and an increase in corresponding additional compressive force. Furthermore, space guy wire systems will

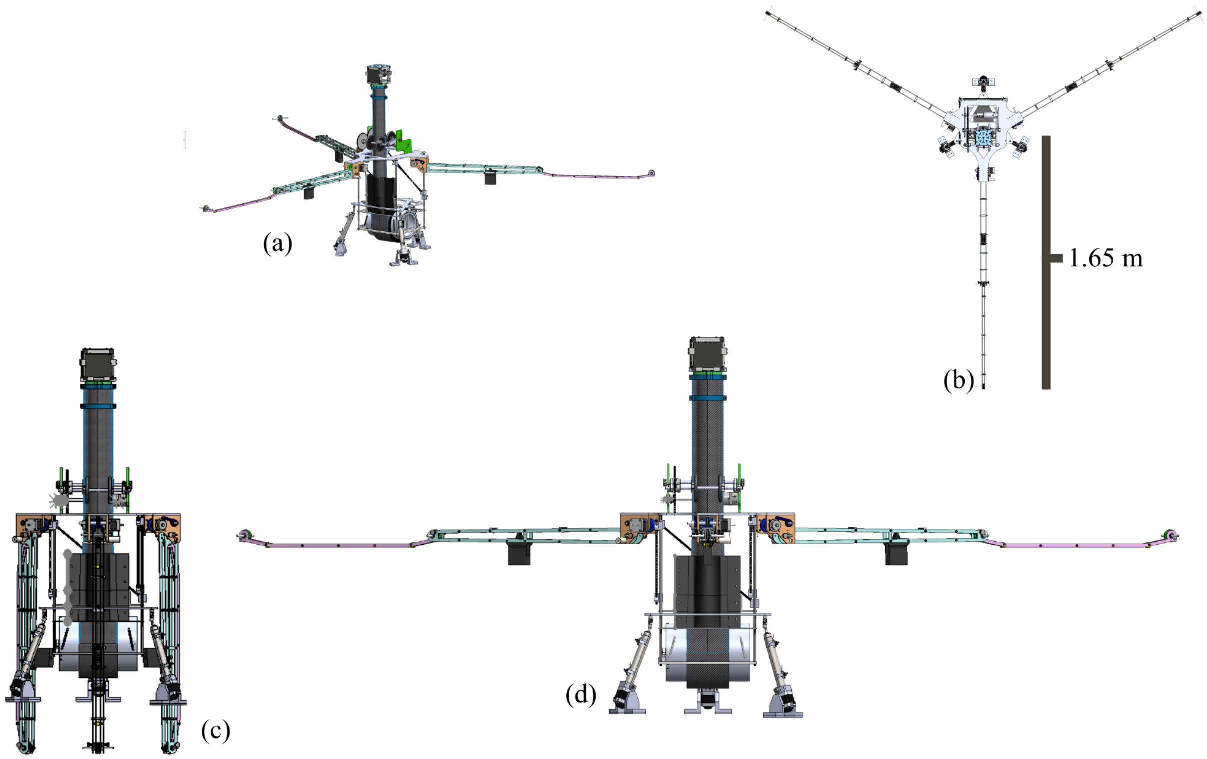


Figure 4. SELTI improves upon the MELLTT prototype with a deployable rigging system, and has been tested to 11 m deployment height. This depicts SELTI with Generation 2 deployable rigging arms and a 1U-CubeSat-sized payload in (a) angled view. (b) top view. (c) side view, stowed. (d) side view, unfolded.

have a more costly tradeoff between mass and stiffness in the support arms and other rigid structures.

Guy wires in practice: from requirements to working design

To assess the feasibility and utility of guy wire rigging systems for DCB-based lunar towers, a test platform was conceptualized, designed, and built to evaluate guy wire systems in static tests.

Deployable Rigging Generation 1

To meet the requirements listed in Table 1, the SELTI team designed a modular, deployable three-arm structure anchored to the deployer-leveler interface plate. Each 0.6 m-long arm deploys from a vertical stowed position using a linear actuator with potentiometer feedback. After unfolding, the guy wire system may be tensioned with a 270 KV brushless motor controlled by an ODrive[2] motor controller with feedback from an 8192-count-per-revolution encoder. In this design, guy wire tension can be controlled by both actuating the brushless spool motor and also adjusting the angle of the spreader arms. During deployment, the guy wire deployment arms have a ratchet and pawl that maintain tension on the arm, and allow that tension to be passively sustained after deployment; to facilitate retraction, a simple linear actuator releases the spring-loaded pawl and thus the tension on the guy wires. The tension of the guy wires is measured in real time with load cells integrated into each guy wire arm.

Custom-machined components for the modular guy wire structure were made out of computer numerical control (CNC) milled and waterjet aluminum for a balance of minimum weight and maximum stiffness. Stiffness was a priority in the system design as it will greatly ease control algorithm development during later stages of this project. In addition to the structural stiffness, all 33 joints employ press-fit ball bearings, allowing the arm system to be treated as a rigid body.

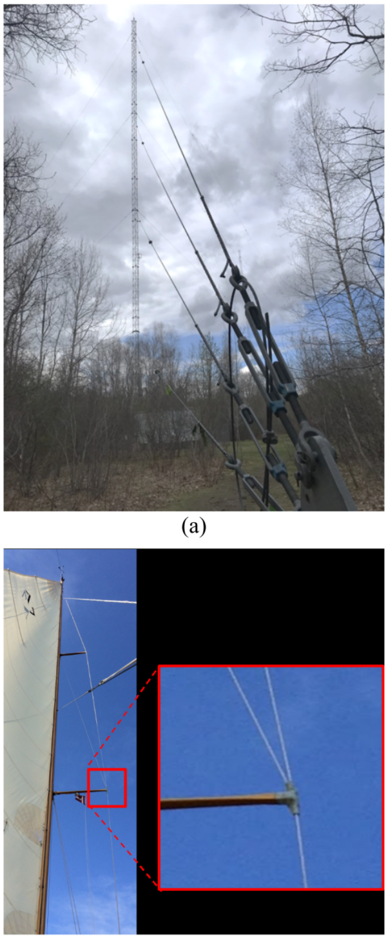
The guy wires were Spectra PowerPro 30-lb-test fishing wire due to its low stretch in comparison to monofilament, and linear stiffness that reduces knotting and provides for high spooling consistency. The guy wires run from a spool attached to the brushless motor across a load cell, then the pulley at the end of the spreader arm, and are ultimately anchored to a fixed attachment directly under the SELTI upper platform payload deck. System components are labeled in Figure 6 (a) and the general arrangement of the three-arm guy wire system, together with detail of the load cell design and the ratchet and pawl subsystem, are shown in Figure 6 (b).

Deployable Rigging Generation 2

After the initial testing success of the Generation (Gen) 1 rigging, the SELTI team designed a Gen 2 rigging system with the primary goals of reducing actuator count, increasing the control authority via implementing a longer 1.65 m arm, and allowing for simpler control systems which exploit the quasistatic deployment of the tower.

The Gen 2 deployable rigging system uses a folding design which stows in the vertical position shown in Figure 7, and

[2]Any mention of a product, vendor or analysis is for clarity and not an endorsement by the authors.



(a)

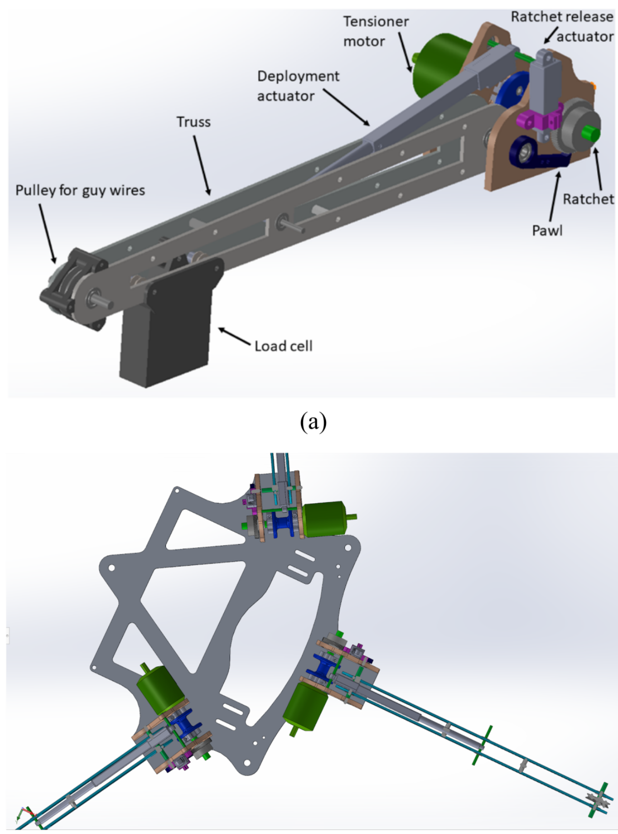
(b)

Figure 5. **Sources of inspiration: (a) Guy wires supporting a radio tower in Newton, MA. (b) Rigging arrangement on the MIT classic sailing yacht, Mashnee, a recently restored 1902 Buzzards Bay 30 designed by renowned naval architect Nathaniel Greene Herreshoff, MIT Class of 1870. Photo credits: (a) Alex Miller (b) George Lordos.**

is locked in the stowed position by a solenoid actuator. In Figure 4 (c) with the arms folded, the arms rest lower than the leveler base; SELTI will either be mounted on a lander structure which allows this or the SELTI deployer structure will be increased in height to raise the stowed arms above the leveler base. During deployment, the solenoid actuator releases, the outermost part of the arm swings down with help of a torsional spring and locks in the straight position, pointing downwards; and the winch motor tensions the guy wire, bringing the arm into the deployed position. Compared to the Gen 1 system, which uses a servo linear actuator for deployment, the use of an on-off pin puller solenoid is a significant systems simplification. Details of the locking and release mechanisms are pictured in Figure 8. During the deployment stage shown in Figure 8 (c), the motion paths must be planned around the physical constraints of the lander system. Planning around these constraints may be done by placing the tower system in an area where there is clearance for the full motion, synchronizing the torsional spring with the tensioning action, incorporating a set of small parallelogram bars between the two segments of the arm to enforce synchronous deployment action, inverting the

Table 1. **Requirements for guy wire testing platform.**

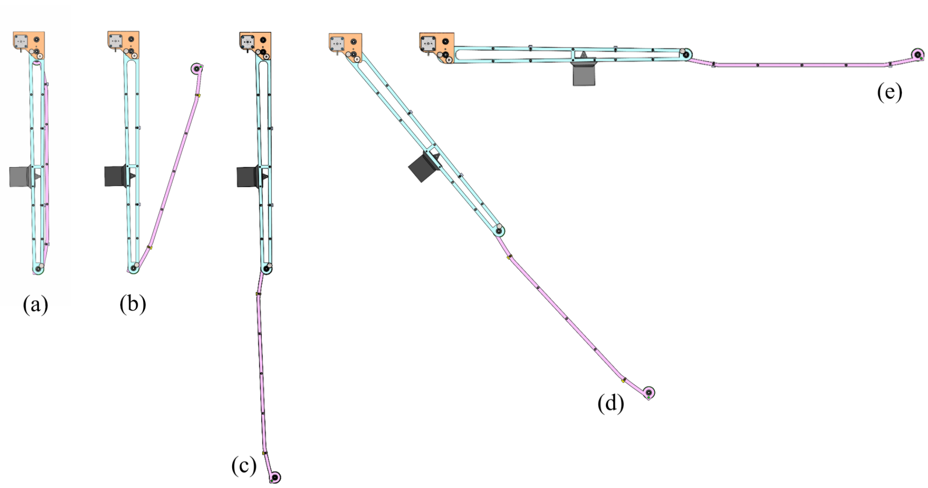
Requirement	Description
GW 001: Configurable	System supports testing of multiple configurations, including guy wires at the top, guy wires on a mid-boom spreader arm, and pulleys that link multiple guy wire configurations.
GW 002: Measurable	Guy wire system supports measurement of guy wire tension in real time.
GW 003: Actuation	System can be tensioned using both hand tightening and precision motor control.
GW 004: Passive Locking	Tensioned guy wires can passively lock in tensioned position without any expended power.
GW 005: Deployable	Guy wire system folds into a small package and deploys into a usable position and size.



(a)

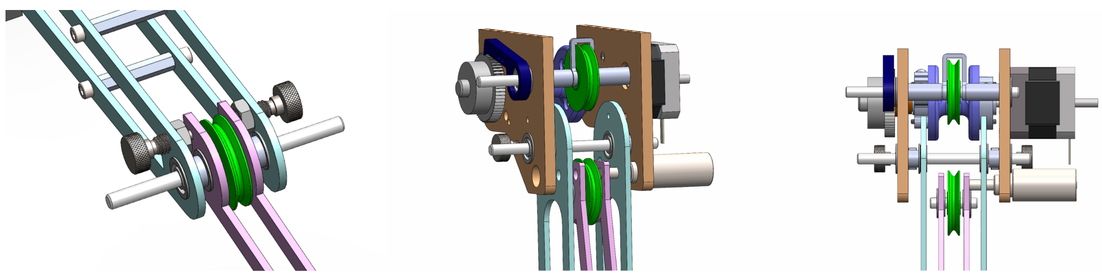
(b)

Figure 6. **(a) Guy wire arm system components. (b) Guy wire arms on deployer-leveler interface plate, top view.**



(a) (b) (c) (d) (e)

Figure 7. Generation 2 deployable guy wire arms. (a) Guy wire arm in stowed and locked position, side view. (b) Guy wire arm in first phase of deployment under spring power, side view. (c) Guy wire arm partially deployed with the mid-arm joint locked, side view. (d) Guy wire arm partially deployed with the winch motor pulling up the arm structure, side view. (e) Guy wire arm locked in the fully deployed position, side view. Variations to deployment sequence and method to fit with varying lander constraints are discussed.



(a) (b) (c)

Figure 8. Close up views of generation 2 deployable guy wire arms. (a) Mid-arm joint in the pin-locked position after deployment. (b) Guy wire arms in stowed position, showing the ratchet and pawl on the left. (c) Guy wire arms in stowed position showing the solenoid pin-puller locking the assembly in the stowed position. Also depicted are the winding spool in purple, stepper motor on the right, and locking pins for the deployed position on both the left and right.

assembly, downsizing the arms, or a combination thereof. In addition, after more review of the system concept of operations (CONOPS), it became clear that the ratchet release actuator on the Gen 1 system is not needed, since the guy wires will not need to retract. These design changes reduce the actuator count from a brushless motor and two servo linear actuators to a stepper motor and a pin-puller solenoid.

In-progress control system for Generation 2 Rigging System

The in-progress control system for Gen 2 rigging system consists of a bang-bang controller that adjusts the position of the stepper motor based on the measured and desired tension. Since the boom is deployed quasistatically, very low control bandwidth is needed (around 1 Hz), and motor steps can be taken conservatively. Thus, a tensioning system for when the tower is stationary may also be used when the tower is being deployed upwards quasistatically. With multiple factors affecting the tension at the top guy wire anchor, such as stress relaxation in the Spectra guy wire and inline spring, slippage of the knot, and deformation of the plastic mounting points, the control system must make small continuous adjustments to maintain tension.

3. EXPERIMENTAL METHODS TO EVALUATE RIGGING SYSTEM PERFORMANCE

Design of experiment to assess feasibility of an active solution to the static deflection challenge

Given a boom cross-section diameter, d, the delivered value of a lunar tower is a function of height, h, elevated payload tip mass, m, and tower robustness (i.e. resistance to buckling). In idealized form, this value function assumes an as-deployed boom with zero axial curvature, i.e., a perfect column. However, assuming a more realistic non-zero axial curvature, i.e., an imperfect column, the higher h is, the greater the lateral deflection at the tip relative to the fixed cross-section of the boom d at the base and the less the tip mass, m the tower can robustly and safely bear. Further, given boom cross-section, d and tip mass, m, there will be a critical height, h_c above which buckling failure should be expected. All other parameters being equal, the higher m is, and the higher the curvature of the boom, the lower h_c will be.

Hence, lateral deflection caused by boom curvature limits tower value by enforcing an undesirable trade between tower height, h, and payload mass, m, i.e., a trade between the two key drivers of the value function of the lunar tower. To preserve the engineering and science value of a realistic lightweight lunar tower, it is essential to address the boom curvature / static deflection challenge up front as a key step in the system architecting of the tower.

Given a tip payload mass m and a non-zero axial curvature, the deployed height, h, is constrained by $h < h_c$, compromising value delivery relative to the ideal maximum. In this situation, there are generally three families of approaches to protect the delivered value of a realistic tower which exhibits non-zero axial curvature:

1. Use a boom with a larger cross-section that would be capable of coping (quasistatically) with the maximum expected boom tip mass center of gravity offsets, at the cost of added size, weight and power (SWaP) for the deployer system.
2. Provide a capability to control and correct static curvatures/deflections during and after deployment, at the cost of added SWaP and complexity.
3. Use a different boom material and/or design that may exhibit lower natural or induced post-deployment axial curvature, at the cost of added boom mass and longer development time due to the missed opportunity to use booms that have flight heritage.

The experiment in this work tested for the functional existence of at least one instance of the second family of solutions, i.e., an active capability to correct deflections of a naturally curved boom. Using a validated photogrammetry system, the control capability of a simple three-wire rigging system at different tension levels was demonstrated. The main objective of the experiment was to investigate whether a simple three guy wire system with differential tension control for each wire had sufficient control capability to correct natural boom deflections and restore the center of gravity of the tip mass to be within the bounds of the perimeter of the tower base.

Guy wire simulation and initial trade studies

Initial simulations were conducted of guy wire systems in the tnxTower nonlinear finite element analysis (FEA) software package (tnxTower 8.0.5, 2020). This program was created specifically for communication towers and allows for rapid iteration in comparison with general purpose FEA tools. It was observed that for a hypothetical 30-m-tall monopole steel tower with a 5 kg tip payload, guy wires yielded a significant improvement of up to 43% in static tilt performance, and further improvements during seismic load cases compared to a tower without guy wires. Furthermore, the large variance in guy wire performance across modeled configurations of "3-at-the-top," "3-at-midpoint," and "3-at-the-top and 3-at-midpoint," as shown in Figure 9, warranted further research.

In these simulations, the "3-at-midpoint" configuration outperformed the "3-at-the-top," and "3-at-the-top and 3-at-midpoint" configurations in dead load conditions; since these simulations were conducted assuming a much larger steel tower than SELTI the variance between configurations is more significant than the finding itself. Due to the relative simplicity of the "3-at-the-top" configuration, the "3-at-the-top" configuration was selected to test in this paper, along with an additional variation with mid-boom spreaders. Other configurations will be evaluated in future research together with their associated increase in complexity and risk.

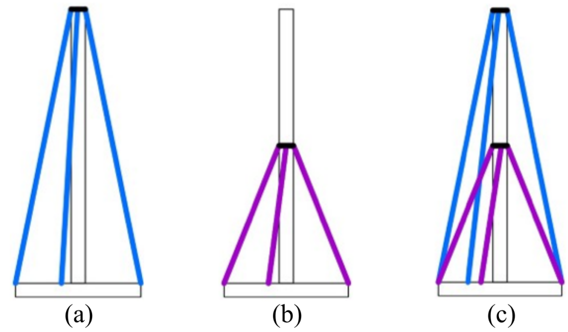


Figure 9. **Three initially proposed guy wire configurations: (a) "3-at-the top," (b) "3-at-midpoint," and (c) "3-at-the-top and 3-at-midpoint."**

While FEA simulations allow for rapid case studies, their limitations motivate practical experimentation. Tower-specific FEA packages such as tnxTower, which can only model homogeneous construction materials like steel, underestimate the potential for local buckling in the composite laminate of the thin-walled SELTI structure. General purpose FEA packages such as Abaqus and Ansys require an ultrafine mesh due to the thinness of the boom, causing long run-times. Additionally, obtaining meaningful simulation results requires extensive parametric study to model a range in operating conditions and an accurate description of simulation boundary conditions, which depend greatly on physical system implementation. Due to these limitations, testing several configurations is crucial to the SELTI path to flight.

Photogrammetry for characterizing static boom behavior

Photogrammetry uses the known position and angle of multiple cameras to form highly accurate three-dimensional visualizations of objects in space. Some photogrammetry systems use specific targets to track rigid bodies in space. Photogrammetry can thus be used to measure small displacements of the boom by placing target markers at various locations along its height. The locations of markers with respect to each other can then be analyzed to characterize bending and variation in boom deflection.

Photogrammetry has the potential to yield more insights into the mechanics of the lunar tower than a discrete number of accelerometers or gyroscopes due to its ability to track a large number of points along the boom at the same time. Photogrammetry was used to characterize the dynamic behavior of the roll-out solar arrays (ROSA) that use deployable slit-tube composite booms at the International Space Station (ISS) in 2017 [19]. Researchers at NASA LaRC and DLR have used photogrammetry to characterize the 13 m long CTM boom structure under evaluation in this paper both in a vertical configuration in a one Earth-gravity (1-g) field [14], and more recently in a horizontal configuration on a zero-gravity (0-g) parabolic flight [12].

To measure the deflection of the boom under static dead load a COTS Optitrack V120: Trio photogrammetry system was purchased. This model consists of three infrared light cameras in line with each other with built-in light emitting diode (LED) 850 nm infrared (IR) light rings, capable of achieving submillimeter accuracy at 120 frames per second with a horizontal field of view of 57.5°.

Four retroreflective circular targets of 1.25 cm in diameter, approximately 5 cm apart, arranged in an uneven diamond pattern, were placed at the tip of the boom and 1.28 m below. Each diamond was set to be a rigid body since it is assumed that very little bending occurs within the small distance between markers. The centroid location of each diamond of markers was tracked by the cameras.

The accuracy of the photogrammetry system was validated before proceeding with experimental testing of the full SELTI system. First, a fixed rigid frame was constructed next to the boom for consistent measurements; then the photogrammetry system was calibrated by affixing a physical "ground plane" reference square to the frame structure. Finally, measurements were taken of the tower position using both a ruler and the photogrammetry system before and after inducing a small deflection in the boom. By comparing the results of the ruler and photogrammetry, it was shown that the photogrammetry system was consistent with conventional measuring tools and accurate to the nearest millimeter.

Static test setup and procedures

To evaluate the advances of the SELTI systems design, and to evaluate the efficacy of guy wires for decreasing boom off-nominal offsets and reducing the likelihood of boom buckling, tests were designed to measure the position of the boom using photogrammetry with a range of guy wire tensions at several boom heights were carried out.

During all testing, the top of the boom was belayed using a safety harness. Unlike a gravity offload, this belay was never under tension during the test, and instead was there as an emergency safety net in case of boom buckling. This belay was attended throughout the duration of the tests.

To maintain a consistent reference for the position of the boom across each of the test heights, the coordinate system of the photogrammetry camera was calibrated using a calibration square of known dimensions. In addition, the base of the tower was leveled using multiple two-axis levels to ensure straight deployment, as shown in Figure 10. At each height, the position of the calibration square was measured relative to two plumb-bob wires that were hung from 12 m above the floor of the test area. These plumb wires acted as a reference position of the tower. The arrangement of the equipment prior to the 8.5-m-deployed-height tests is shown in Figure 11.

The tests of the SELTI guy wire system were conducted in the MIT Stata Center stairwell 3 and the MIT AeroAstro Hangar. For the early tests, since the focus was on reducing the static deflection of the boom with guy wires and not on automatic control or deployment, all operations were manually actuated including the guy wire spreader arm deployment and the guy wire tensioning.

4. Results

Test 1: Boom tip deflection at different heights with varying single guy wire tension, and Gen 1 rigging arms

For the first set of tests, the boom was deployed to 4.2 m, 6.2 m and 8.5 m heights, with a 0.9 kg payload and guy wires tensioned from 0 N to 10.8 N using the Generation 1

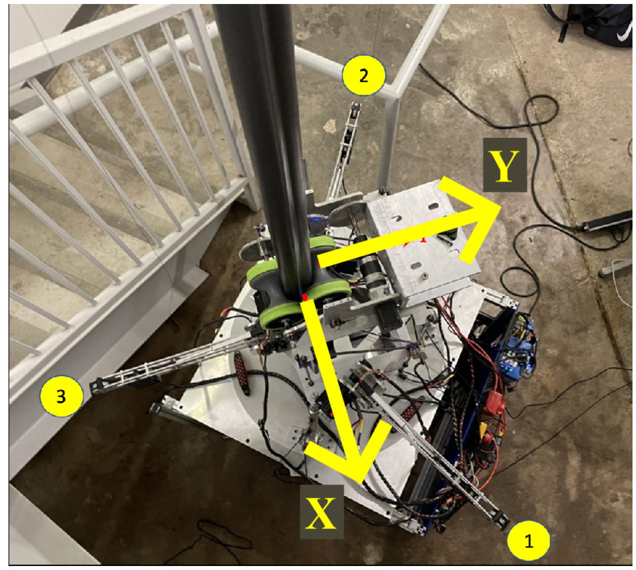


Figure 10. Boom deployer, from above, showing the orientation of the three guy wire arms relative to the orientation of the cross-section of the boom in the X and Y planes. Arms are 120° apart and are labeled in the photo. Arm 3 is located in the direction of lowest bending stiffness for the boom. The boom is pulled out of the spool between two green rollers, and once deployed it can be stabilized with the three arms that provide tension to the guy wires.

deployable guy wire system. The results of these tests are presented in Figure 12.

As height increases, natural lateral boom tip deflection increases. As expected, nearly all natural deflection takes place in the Y-axis. The individual wire control capability for the arm opposite the direction of deflection is demonstrated in Figure 12 (a), (b), (c) . As an additional level of tension was applied to arm #3 (10.8 N) in Figure 12 (c), an additional reduction in deflection was observed. Using the available control capability with differential tension in the guy wires, it was possible to correct part of the deflection and bring the center of the tip mass closer to the boom base, located at the plot origin. Thus, with a superposition of guy wire arm tensions, the boom tip may be moved to an arbitrary position within its range of motion.

This static deflection test of the SELTI deployable guy wire system indicates that a simple guy wire system for a deployable composite boom tower of 8.5 m height, with an arm length of 60 cm and maximum tension forces limited to below 20 N, has at least partial control capability to position the top of the boom, reducing static lateral deflections compared to the untensioned control position of the top of the boom. Furthermore, as shown in Figure 12, the test indicates that control capability provided by the guy wire system is greatest where it is needed most, i.e., along the Y-axis, where the natural deflections are observed to be an order of magnitude greater than along the X-axis.

Test 2: Boom tip deflection at 11 m height with and without spreaders, and Gen 1 rigging arms

For the second set of tests, the boom was deployed to 11 m, the tallest the MIT team has deployed to, with a 0.9 kg payload, and the Gen 1 rigging arms. Tests were

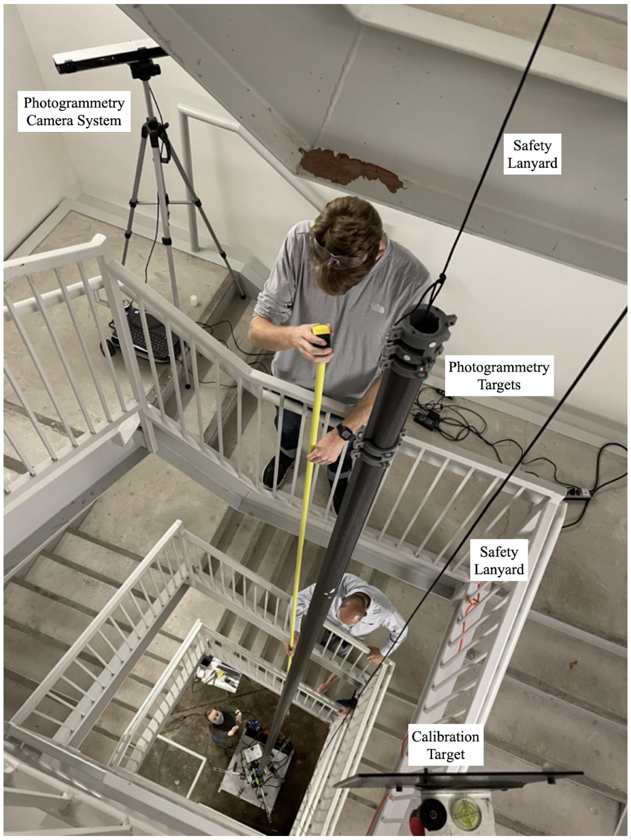
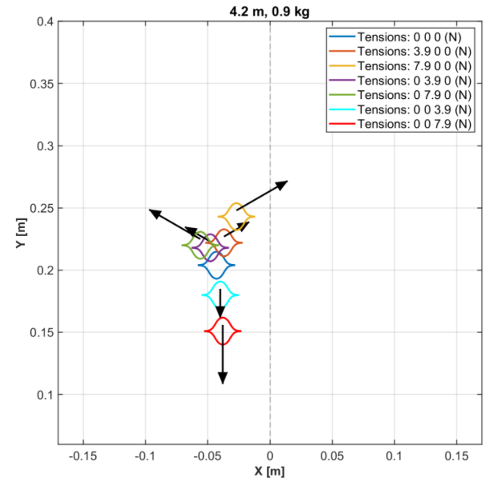


Figure 11. The boom is deployed to 8.5 m in the stairwell to allow easy access at all points during deployment. The tip of the boom is attached to a safety lanyard, which is in case of emergency buckling scenarios, and was monitored but not tensioned throughout the test. In the top left of the figure, the photogrammetry camera system is positioned so that both the photogrammetry targets at the top of the boom and the calibration target (bottom right) are in view.

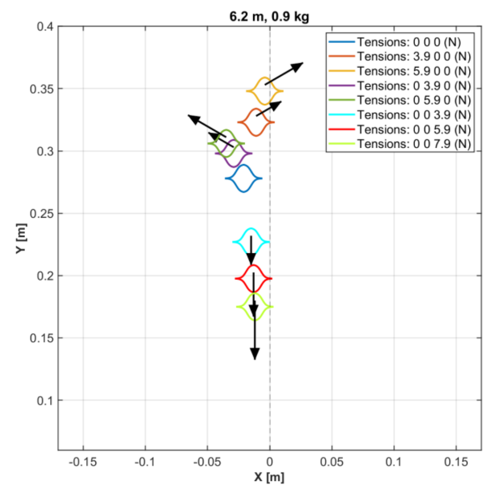
conducted with and without mid-height spreaders, which were placed near the middle of the boom. During the design phase, it was hypothesized that spreaders, inspired by Figure 5 (b) would reduce bowing in the boom by resisting deflection in the middle of the boom, while simultaneously reducing deflection at the boom tip. A survey of many different tensions, listed in Figure 13, was conducted. The initial data in Figure 13 show that spreaders did not have a significant impact on the position of the boom tip in most cases. However, the evenly tensioned 5 N trial was moved much closer to the boom root with spreaders than without spreaders, warranting future consideration with additional photogrammetry targets half-way down the boom to assess curvature.

Test 3: Boom tip deflection at 6.1 m height with Gen 2 rigging arms

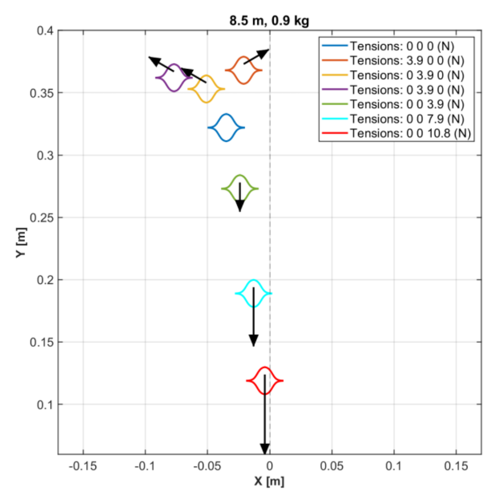
In the third set of tests, the boom was deployed to 6.1 m, with a 1.5 kg payload, and the longer 1.7 m Gen 2 rigging arms, as shown in Figure 14. A survey of different tension combinations was conducted. During the initial guy wire tensioning for this test, one of the guy wires was over-tensioned, causing the boom to bend excessively to one side causing local damage to the composite boom thin-wall shell, as shown in Figure 15. This damage was repaired



(a)

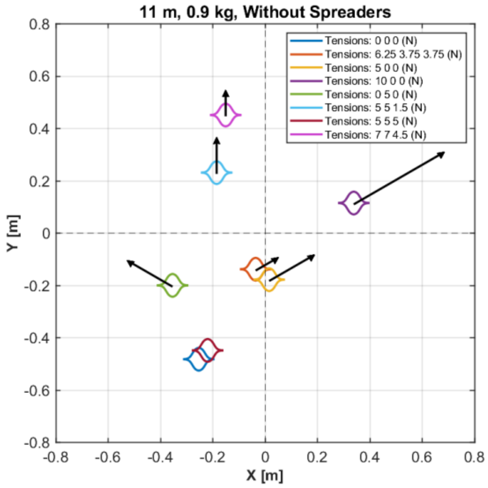


(b)

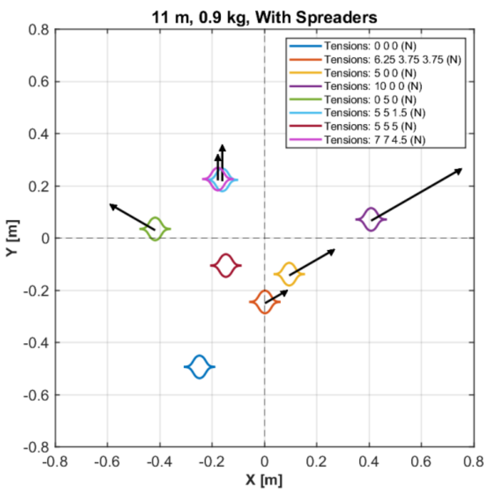


(c)

Figure 12. Static deflection photogrammetry test results showing all three single-arm experiments in the same diagram for each height (a) 4.2 m, (b) 6.2 m and (c) 8.5 m. Note the much smaller X axis deflections relative to the larger Y-axis deflections. All tests were conducted with the Generation 1 guy wire arms, and a 0.9 kg payload. The root of the boom is positioned at the origin, and the arrows indicate the net force by the guy wires. The boom graphic is shown at 0.25x scale for clarity.



(a)



(b)

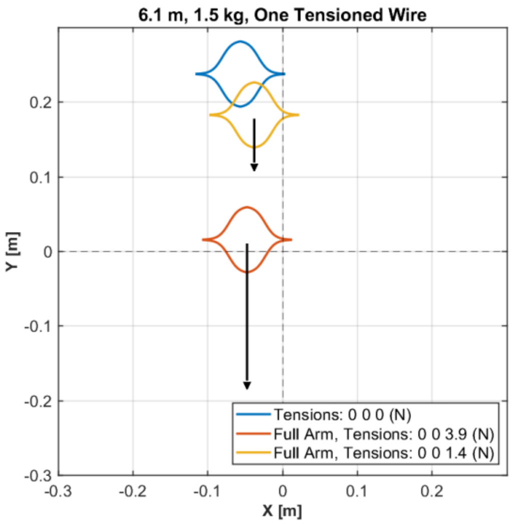
Figure 13. Static deflection photogrammetry test results showing tests with a variety of guy wire tensions at 11 m deployed height (a) without mid-boom spreaders, and (b) with mid-boom spreaders. All tests were conducted with the Generation 1 guy wire arms, and a 0.9 kg payload. The root of the boom is positioned at the origin, and the red arrows indicate the net force direction and magnitude applied by the guy wires. The boom graphic is shown at 1x scale.

with tape which did not mitigate the effect of the composite damage but provided some structural integrity. New baselines were taken, and the testing was resumed with the damaged test article.

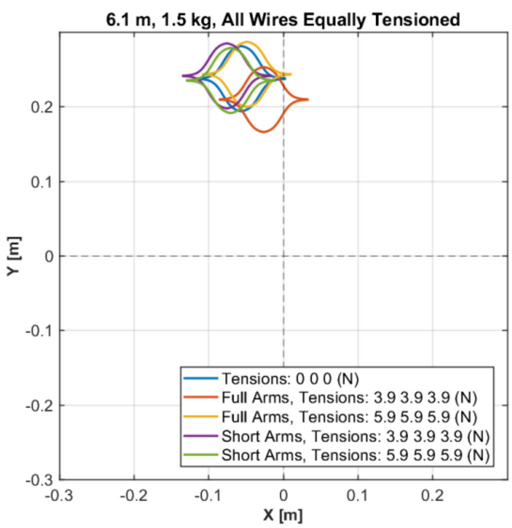
Compared to the shorter Gen 1 guy wire arms, the Gen 2 guy wire arms were able to reduce tip deflection more for a given guy wire tension, as can be seen from comparing Figure 16 (a) to Figure 12 (b). As seen in Figure 16 (b), when equal tension is applied to all three wires, there is little change in deflection, corroborating hypothesis from Test 2 observable in Figure 13 (a) that the boom is naturally bowed.

Figure 14. Deployment of boom with Gen 2 rigging system.

Figure 15. Damaged composite boom test article before application of repair tape.



(a)



(b)

Figure 16. Static deflection photogrammetry test results showing tests with the Gen 2 guy wire arms and a variety of guy wire tensions at 6.1 m height (a) with only one guy wire tensioned and (b) with all guy wires equally tensioned. The root of the boom is positioned at the origin, and the red arrows indicate the net force direction and magnitude applied by the guy wires. The boom graphic is shown at 1x scale.

5. Conclusions and Discussion

Experiments with a simple guy wire system confirmed that tension-adjustable guy wire rigging is capable of controlling the position of the payload mass over several possible boom heights. We observed that adding tension on the arm closest to the direction opposite to the deflection provides the most significant correction of the boom deflection towards the ideal centered position. However, under the range of single-arm tension loads used (3.9 N to 10.8 N), the boom tip offsets could not be completely removed at any of the tested heights.

It was observed that for given levels of tension, absolute and relative correction capability is increased as height increases. This increase in correction capability is evident by a comparison of the effectiveness of the 7.9 N tension level applied via arm #3 at the 4.2 m, 6.2 m and 8.5 m heights. The resulting correction was 25%, 37% and 41% respectively, as can be seen from Figure 12 (a), (b), (c) Even though the angle of attack gets smaller as tower height increases, due to the fixed arm length and orientation, the moment arm also increases and tension is more effective.

Additionally, the Generation 2 guy wire system provided a significant increase in control authority for a given tension compared to the Generation 1 system, while simultaneously reducing actuator count. The Generation 2 guy wire system increases the value of a deployable riggings system, making it worth the added complexity for a wider range of mission types.

It was observed that for all tests, the natural lateral boom tip offsets under 1 g loading (boom self-weight plus tip mass) were of the order of 5% of the deployed height, which is significantly greater than the 1% manufactured tolerance for the boom. Potential explanations include long-term stowage creep, as this boom remained spooled almost continuously for about 22 months from its date of manufacturing. This observation is consistent with the finding that the deflections under dead load occur almost entirely in the in-plane Y-axis in the direction of rolling the boom. Also, a very small misalignment of the boom exit angle from the deployer with respect to the gravity vector could lead to an unwanted additional boom moment and lateral tip deflection. Further testing under controlled conditions with different booms will be needed to better understand the reasons for the significant deflections.

In conclusion, we find that control capability is greatest for the rigging lever arm opposite the direction of deflection, and that for a deployable-composite-boom-based tower height of at least 8.5 m with an arm length of at least 60 cm, a simple guy wire system using the opposing arm alone with tension limited to 11 N or less has sufficient control capability to reduce boom deflections by 63%. Furthermore, with rigging arm lengths of at least 1.6 m, much lower tensions can achieve the same reduction in boom deflection. Finally, through iterative design, a foldable Generation 2 deployable guy wire arm system with only a pin puller actuator and winch motor was developed. This folding feature increases the value of deployable rigging systems for applications of deployable composite booms in a gravity field.

6. Limitations and Future Work

A limitation of this investigation is that while static testing confirmed that guy wires can be used to reduce the deflection of the tip payload, the photogrammetry approach measured only the position of the top of the boom, not the curvature across the length of the boom. Thus, for some high-tension configurations, with small tip deflections, the total boom curvature may be very high. Specifically, for the 8.5 m test at 10.8 N tension on arm #3, it was visually confirmed that the boom showed a slight bow. The lateral deflection at the top of the boom was mostly corrected, but potentially introduced bowing or curvature in the direction of the applied tension. Future work on more diverse rigging configurations will assess not only the tip deflection, but also the curvature over the length of the boom. Future work which includes curvature measurements will support the investigation towards an optimal guy wire configuration that balances complexity and mass with rigging system performance.

Additional ongoing and future collaborative work at NASA LaRC and MIT includes the further investigation of the unexpected magnitude of the natural lateral deflection under dead load as well as continued testing of alternative guy wire system designs and a greater focus on developing automated control capabilities. Follow-on experiments are expected to inform trade studies of costs and benefits of an optimized guy wire system over other types of static stability solutions. Future work will also include additional development work on an automated guy wire tension controller.

Even though the scope of this paper is limited to static testing, dynamic characteristics of the boom system are of interest to ensure a safe deployment, and protect system payloads from dynamic events such as moonquakes or landing of near-by assets. Future work on dynamics will investigate how the tower and rigging system responds at different frequencies, and how rigging can be used to mitigate dynamic instabilities and to adjust the systems natural resonant frequencies. Dynamics studies will require new modeling development, since the behavior of ropes is highly chaotic during dynamic events; additionally, modeling dynamic stability of the tower system during deployment routine is difficult because the deployed section is changing length with time.

ACKNOWLEDGMENTS

This research was sponsored by the 2020 BIG Idea Challenge, a collaboration between the Space Technology Mission Directorate (STMD) Game Changing Development (GCDP) program and the Office of STEM Engagement Space Grant Consortium and managed by the National Institute of Aerospace. The STMD/GCDP Deployable Composite Booms project that mentored and loaned the 13 m boom test article to the MIT team is greatly acknowledged. Thank you to the MIT Department of Aeronautics and Astronautics for space and facilities, including Dan Hastings and Anthony Zolnik, as well as MIT Laboratory for Manufacturing and Productivity (LMP) for access to machining facilities. Alex Miller is generously funded by the Fannie and John Hertz Foundation Fellowship and by the National Science Foundation Graduate Research Fellowship under Grant No. 2141064. Emma Rutherford, Joshua Rohrbaugh, Christian Williams, and Wilhelm Schoeman were supported by the MIT Undergraduate Research Opportunities Program (UROP). Avril Studstill and Paul Portmann were supported by Massachusetts Space Grant Fellowships. Natasha Stamler, Avril Studstill, and Paul Portmann were supported by the NASA Internships, Fellowships, and Scholarships (NIFS) Program at NASA LaRC. Thank you to tnxTower for free access to their tower program modeling program.

Thank you also to past and current MELLTT team members and mentors: Caleb Amy, Marc-André Bégin, Becca Browder, Manwei Chan, Charles Dawson, Paula do Vale Pereira, Travis J. Hank, Eric Hinterman, Cormac O'Neill, Vineet J. Padia, Jessica Todd, Nieky Wang, and Dava J. Newman. Thank you to Mike Brown, Marianna Lordou, Pascal Spino, Melissa Bauer, and Marcos Espitia-Alvarez for testing support.

REFERENCES

[1] J. E. Kleinhenz and A. Paz, "Case studies for lunar isru systems utilizing polar water," in *ASCEND 2020*, 2020, p. 4042.

[2] S. Li, P. G. Lucey, R. E. Milliken, P. O. Hayne, E. Fisher, J.-P. Williams, D. M. Hurley, and R. C. Elphic, "Direct evidence of surface exposed water ice in the lunar polar regions," *Proceedings of the National Academy of Sciences*, vol. 115, no. 36, pp. 8907–8912, 2018.

[3] M. Smith, D. Craig, N. Herrmann, E. Mahoney, J. Krezel, N. McIntyre, and K. Goodliff, "The Artemis program: an overview of NASA's activities to return humans to the moon," in *2020 IEEE Aerospace Conference*. IEEE, 2020, pp. 1–10.

[4] G. C. Lordos, C. Amy, B. Browder, M. Chan, C. Dawson, P. do Vale Pereira, S. I. Dolan, T. Hank, E. D. Hinterman, B. Martell *et al.*, "Autonomously deployable tower infrastructure for exploration and communication in lunar permanently shadowed regions," in *ASCEND 2020*, 2020, p. 4109.

[5] R. T. Johanson, D. Jang, E. Kononov, M. Luu, S. J. Morgan, J. Todd, M. Blevins, M. Contreras, D. Erkel, A. Garcia *et al.*, "What could we do with a 20 meter tower on the lunar south pole? applications of the multifunctional expandable lunar lite & tall tower (melltt)." in *ASCEND 2020*, 2020, p. 4108.

[6] J. Fernandez, S. Krizan, and R. Dyke, "Thin-shell deployable composite booms for solar sails: Design, manufacturing and qualification," in *5th International Symposium on Solar Sailing, Aachen, Germany*, vol. 30, 2019.

[7] J. E. Salazar and J. M. Fernandez, "Experimental characterization of the dimensional stability of deployable composite booms during stowage," in *AIAA SciTech 2021 Forum*, 2021, p. 0195.

[8] O. R. Stohlman and E. R. Loper, "Thermal deformation of very slender triangular rollable and collapsible booms," in *2016 AIAA SciTech Conference*, no. NF1676L-21678, 2016.

[9] G. Lordos, C. Amy, B. Browder, C. D. M. Chan, P. do Vale Pereira, S. Dolan, E. H. T. Hank, B. Martell, K. McDonough, A. Miller, C. O'Neill, N. Stamler, J. Todd, Z. Wadia, D. N. N. Wang, O. de Weck, and J. Hoffman, "MELLTT: Multifunctional expandable lunar lightweight & tall tower," http://bigidea.nianet.org/wp-content/uploads/2020-BIG-Idea-Technical-Paper_MIT.pdf, BIG Idea Forum, Tech. Rep., 2021.

[10] J. M. Fernandez, "Advanced deployable shell-based composite booms for small satellite structural applications including solar sails," in *International Symposium on Solar Sailing 2017*, no. NF1676L-25486, 2017.

[11] A. J. Lee and J. M. Fernandez, "Inducing bistability in collapsible tubular mast booms with thin-ply composite shells," *Composite Structures*, vol. 225, p. 111166, 2019.

[12] M. Richter, J. M. Fernandez, M. Straubel, M. E. Zander, J. E. Salazar, and M. K. Chamberlain, "Experimental methods using force application of a single boom for a 500-m²-class solar sail," in *AIAA Scitech 2023 Forum*, 2023.

[13] W. K. Wilkie, "Overview of the NASA advanced composite solar sail system (acs3) technology demonstration project," in *AIAA Scitech 2021 Forum*, 2021, p. 1260.

[14] J. M. Fernandez, J. Salazar, M. Y. Hamillage, A. Gomez-Delrio, and K. Kwok, "Large deformation bending relaxation of thin-ply composite laminates," in *22nd International Conference on Composite Materials (ICCM22)*, 2019, pp. 11–16.

[15] O. R. Stohlman, M. E. Zander, and J. M. Fernandez, "Characterization and modeling of large collapsible tubular mast booms," in *AIAA Scitech 2021 Forum*, 2021, p. 0903.

[16] M. Richter, M. Straubel, J. M. Fernandez, O. R. Stohlman, and W. K. Wilkie, "Compact deployment control mechanism for the deployable backbone structure of a 500-m^2-class solar sail," in *5th International Symposium on Solar Sailing, Aachen, Germany*, vol. 30, 2019.

[17] M. Chen, R. Goyal, M. Majji, and R. E. Skelton, "Deployable tensegrity lunar tower," in *Earth and Space*, 2021, pp. 1079–1092.

[18] Rolatube Technology. Rollable composite masts. [Online]. Available: https://www.rolatube.com/lightest-mast-systems/

[19] M. K. Chamberlain, S. H. Kiefer, and J. Banik, "Photogrammetry-based analysis of the on-orbit structural dynamics of the roll-out solar array," in *AIAA SciTech 2019 Forum*, 2019, p. 2375.

BIOGRAPHY

Alex S. Miller *is a graduate researcher at Massachusetts Institute of Technology in the AeroAstro Department with a B.S. in Physics and in Electrical Engineering and Computer Science from MIT. Alex has interned with teams at NASA Jet Propulsion Laboratory, X (formerly Google [X]), Microsoft Research, and DeepMind. Alex's graduate work is generously funded by the Fannie and John Hertz Foundation Fellowship. Alex's current interests include exploration systems for icy moons, physics, underwater vehicles, and cello performance.*

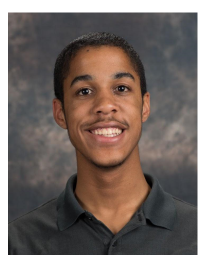
George Lordos *is a PhD candidate at Massachusetts Institute of Technology in the Department of Aeronautics and Astronautics, the founder of MIT Space Resources Workshop and a member of AIAA Space Resources Technical Committee. He received a B.A. in Philosophy, Politics and Economics from the University of Oxford in 1991, a MBA from MIT Sloan School of Management in 2000 and a Masters in Engineering and Management from MIT System Design and Management Program in 2018. George is researching the industrial ecology of human settlements on the Moon and Mars and previously had a 25-year professional career as a technical project manager, strategy consultant, system architect, company director and entrepreneur.*

Victor P. Portmann *is a senior at MIT studying Mechanical Engineering. He is continuing the work he started in summer 2022 on controls, modeling, and experimental design. The primary goals of his work are stabilizing the tower and manipulating the tip of the boom to optimize the positioning of instruments. His interests include humanitarian projects, bio-inspired robotics, and aerospace.*

Avril Studstill *is a sophomore at Massachusetts Institute of Technology studying Electrical Engineering and Computer Science. She worked on electronics integration and software controls over the 2022 summer term to control the tower, and continues to work on an automatic tensioning system. Her interests include computing systems research, medicine, and aerospace.*

Joshua Rohrbaugh *is a senior at the Massachusetts Institute of Technology studying Mechanical Engineering. He worked with the composite boom team over the summer term to integrate the guy wire system with the deployer system. His interests include aerospace, transportation, and robotics.*

Wilhelm Schoeman *is a junior exchange student from the University of Pretoria, currently at MIT studying Aeronautics and Astronautics. He started working in summer 2022 on designing and manufacturing the 2nd generation of the deployable rigging system. His interests include composite manufacturing, automotive engineering and aerodynamic design.*

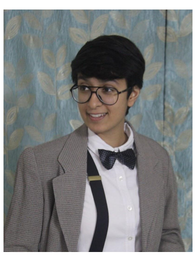


Christian Williams *is a senior at MIT studying Mechanical Engineering. He started working with the composite boom team over the summer of 2022 with the mechanical design and manufacturing of the leveler system. His interests include product design, prototyping, and manufacturing.*

Emma Rutherford *is a senior at MIT studying Mechanical Engineering and Physics. She worked with the composite boom team over the summer to improve the mechanisms for deployment, allowing for testing at greater heights. Her past research has focused on computational fluid dynamics of aerosols, and she is currently pursuing work in robotics.*

Natasha Stamler *is a Fulbright Fellow at the Eindhoven University of Technology, where she researches energy-efficient buildings. She received a B.S. in Mechanical Engineering and Urban Planning from the Massachusetts Institute of Technology and has interned at the NASA Langley Research Center and the NASA Goddard Flight Center Institute for Space Studies. Her interests include passive systems and applying space-based technologies to improve urban sustainability.*

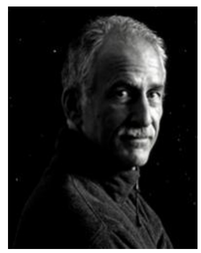
John Z. Zhang *is a PhD student at MIT in the Department of Mechanical Engineering. His research focuses on electromechanical sensing and actuation in a range of environments from medical implants to space structures. His interests include the intersection of art and science, electromechanics, control, and simulation.*



Palak B. Patel *is a PhD student at MIT in the Department of Mechanical Engineering. Her PhD research focuses on high temperature resistant and high strength ceramic matrix nanocomposites for space applications. She received her MS in Mechanical Engineering at MIT while she researched nanoengineering multifunctionalities in aerospace composite structures in the Department of Aeronautics and Astronautics. She has interned at the Indian Space Research Organization. Her interests include high strength materials, manufacturing, and space systems.*

Benjamin C. Martell *is an engineer at SpaceX working to build an interplanetary future. He received his SM in AeroAstro from MIT and his BS in Mechanical Engineering from the University of Rochester. He has experience with researching and engineering electrostatics, fluids, plasmas, and space systems.*

Prof. Olivier de Weck *is the Apollo Program Professor of Aeronautics and Astronautics and Engineering Systems at MIT and a Fellow of INCOSE and Associate Fellow of AIAA. He focuses on systems engineering related to space logistics and space exploration, technology infusion analysis in human and robotic systems over time as well as multidisciplinary design optimization. He has published over 300 peer reviewed papers and 3 books and received 12 best paper awards since 2001. From 2013-2018 he served as Editor-in-Chief of the journal Systems Engineering, and more recently as Senior Vice President for Technology Planning and Roadmapping at Airbus. He is the Editor-in-Chief of the Journal of Spacecraft and Rockets.*



Prof. Jeffrey A. Hoffman *is a Professor of the Practice of Aeronautics and Astronautics at MIT since 2002, and co-director of MIT Human Systems Lab since 2015. He is interested in the future of human spaceflight and in the use of the International Space Station as a testbed for future aerospace technology, especially in: human-machine interactions, extravehicular activity (EVA), flight operations and conducting laboratory research in space. From 1978-1997 he served as a NASA astronaut (five flights) and from 1997 – 2001 as NASA European representative.*

Dr. Juan M. (Johnny) Fernandez *serves as the flexible composite technology lead at NASA Langley Research Center. He holds a BSc in Aeronautical Engineering from the Technical University of Madrid, Spain, a MSc in Space Technology and a PhD in Space Engineering from the University of Surrey, UK. He is the Principal Investigator for the NASA Deployable Composite Booms (DCB) project, and the Advanced Packaging Reflector Methods (APRM) project, and Principal Technologist for the Advanced Composites-Based Solar Sail System (ACS3) flight demonstration. He chairs the AIAA High Strain Composites section of the larger AIAA Spacecraft Structures Technical Committee. He holds several patents on composite boom designs and fabrication methods. He manages a NASA STTR subtopic for small businesses and research institutions on thin-ply composite technology.*