Conceptual Design, Manufacturing, and Assembly of a Tall Lunar Tower

Marina Konstantatou[1]
Specialist Modelling Group,
Foster + Partners, London, UK

Aran Sena
Specialist Modelling Group,
Foster + Partners, London, UK

George Cann
Specialist Modelling Group,
Foster + Partners, London, UK

Irene Gallou
Specialist Modelling Group,
Foster + Partners, London, UK

Salvador Navarro Perez
Specialist Modelling Group,
Foster + Partners, London, UK

Orla Punch
Foster + Partners, San Francisco,
CA, USA

Marc Guberman
Foster + Partners, Los Angeles,
CA, USA

David Goodloe
Branch Technology, Chattanooga,
TN, USA

Platt Boyd
Branch Technology, Chattanooga,
TN, USA

Abstract

This research paper presents the results of a NASA-funded collaborative project between Foster + Partners and Branch Technology that developed the design, manufacturing, and assembly of an optimised 50m tall lunar tower for solar energy generation at the Moon's South Pole. The tower's structure is characterised by a helical diagrid geometry with integrated spiralling rails, designed to enable crane-free manufacturing, solar array deployment, and maintenance. The tower's unique geometry is designed to be compatible with a freeform 3D printing and cellular fabrication strategy, creating opportunities for *in-situ* resource utilisation and load path optimisation. Particular attention was placed into developing a site-specific design that takes into consideration the unique environmental and lighting conditions of the Lunar South Pole. Two demonstrators were fabricated by the consortium: a 1:50 scale functional prototype with a robotically-deployed rotating solar array and a 1:1 scale 5m section of the tower. Both were showcased in March 2025 during the "Earth to Space" exhibition at the Kennedy Space Centre in Washington DC. This project contributes to the efforts of developing supporting infrastructure, such as power and communications networks, which will enable lunar exploration and a sustained human presence on our Moon and beyond.

2012 ACM Subject Classification Applied computing → Computers in other domains

Keywords and phrases Space Architecture, Lunar Infrastructure, Lunar Tower, Additive Manufacturing, In Situ Resource Utilisation (ISRU), Solar Energy

Digital Object Identifier 10.4230/OASIcs.SpaceCHI.2025.12

Funding NASA Small Business Innovation Research (SBIR) Phase I Program Award.

1 Introduction

The sustained and sustainable presence on the Moon, Mars, and beyond depends on the development of core infrastructure that can enable power generation, life support, and food and water production.

[1] Corresponding author

Advancing Human-Computer Interaction for Space Exploration (SpaceCHI 2025).
Editors: Leonie Bensch, Tommy Nilsson, Martin Nisser, Pat Pataranutaporn, Albrecht Schmidt, and Valentina Sumini; Article No. 12; pp. 12:1–12:13
OpenAccess Series in Informatics
OASICS Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl Publishing, Germany

The design and deployment of space systems is closely coupled to mission objectives, launch vehicle payload capacity, and environmental conditions. As the development of lunar settlements and industries such as mining advance over the coming years, there will be an increasing demand for lunar power and communication systems. Existing and proposed systems are constrained by launch vehicle mass and volume limitations. This can result in complex deployable systems with many moving parts that may be prone to failure and less payload availability for other critical supplies. The development and use of *in-situ* Resource Utilisation (ISRU) manufacturing practices for structural components, outfitting, solar cells, and more, is widely viewed as an important enabling technology for the expansion of exploration, settlement and industrialisation activities on the lunar surface, and their long-term viability [1, 2, 11, 13].

In this context, Foster + Partners and Branch Technology supported by NASA's Small Business Innovation Research (SBIR) Phase I program award, developed the design for a 50m Tall Lunar Tower (TLT) at the Moon's South Pole capable of supporting solar energy equipment. The tower's geometry provides clear load paths for resisting vertical and lateral loads whilst minimising material use through advanced manufacturing techniques. At the same time, it is optimised for autonomous manufacturing and deployment strategies through the integration of support rail geometry that can be used by robotic platforms for vertical movement across the manufacturing, outfitting and maintenance stages of deployment. Lastly, it contributes to the reduction of thermal loading through the use of a permeable diagrid structure; thus, helping it to endure the extreme temperature fluctuations found at the Lunar South Pole. This research paper presents the conceptual design, manufacturing, and assembly of the final tower design and the demonstrators fabricated by the consortium.

Lunar infrastructure precedents

Lunar infrastructure is currently limited to operational and defunct orbiters, landers, and material left from prior exploration programs (e.g., Apollo's Laser Ranging Retroreflectors (LRRR)). Whilst designs for long-term lunar infrastructure, capable of supporting human settlements have been proposed since before the beginning of the space age, all designs remain conceptual (for a detailed literature review the reader is pointed to [10]). Recent Foster + Partners research in this area includes the development of a component-based lunar habitat dome which provides radiation shielding and encapsulates a pre-fabricated inflatable dome [9]. The horizon goal of a pre-fabricated ISRU permanent habitat is predicated on developing sustainable infrastructure required to support such a habitat. Lunar infrastructure required to support long-term human settlements includes the development of environmentally tolerant energy, communication, and transportation networks.

2 Environmental constraints

The proposed site of the TLT, at 89.44° S, 222°E, elevation of 1958m, is along the Shackleton Crater - de Gerlache Connecting Ridge, and is adopted [8]. This location falls within NASA's Artemis 2022 candidate landing site, where the maximum solar elevation angle is approximately 2.3° degrees relative to the surface, with the surface temperature ranging from 100 – 400K. The lunar synodic period of 29.53 days leads to a lunar night of 14.77 days; however, local illumination at the poles varies significantly. These site-specific extreme environmental conditions provide design constraints for the development of lunar infrastructure in the following sections.

Power Systems: Solar Arrays

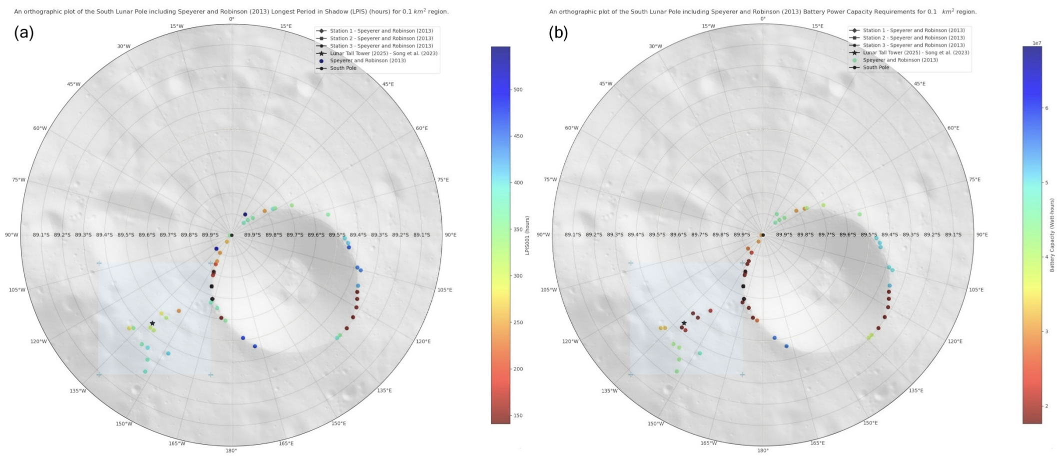


Figure 1 South Polar orthographic projections from 89-90 S°, light blue box indicates the location NASA's Artemis 2022 Connecting Ridge candidate landing site. (a) An orthographic plot of the South Lunar Pole including Longest Period in Shadow (LPIS) (h) targets with TLT location. (b) An orthographic plot of the South Lunar Pole including locations from [7] using a fixed power output 100kW, with location LPIS to defined battery power capacity requirements (Wh).

A lunar habitat will require a power system to support functions such as environmental control and life support systems (ECLSS), lighting, and communications. The Lunar South Pole is of particular interest for future human exploration as there exist regions that provide near constant solar illumination for extensive periods, due to the Moon's low axial tilt (1.5° w.r.t. the ecliptic normal) and the region's highland topography, [7]. While no region on the lunar surface is observed to be in constant illumination (i.e., the Sun eventually sets for all locations), these locations provide the optimal sites for power generating systems using solar cells.

Figure 1 shows the LPIS for a range of candidate lunar exploration sites derived from [7] combined with the TLT suggested location [8]. Long-term sustainable settlements require systems able to survive and operate during harsh lunar nighttime conditions. Comparison of prior studies characterising these conditions provides validation and tower design constraints. We note that the nearest [7] location to the [8] proposed TLT location is at 89.418° S, 221.3°E, with LPIS over 0.1, 0.25, 1, 2.25, and 4km^2 regions centred on the location of 308, 294, 197, 141, and 89 hours respectively.

As part of outfitting a TLT, we consider the integration and deployment of a 100kW solar array which is in line with NASA's SBIR Phase II requirements. Given a location, the LPIS, surface illumination percentages, and a defined power requirement, solar photovoltaic power systems can be estimated in terms of solar array mass, area, and volume [6]. Our calculations assume solar flux = 1367.5 Wm^{-2}, noting that an approximately 3.5% variation occurs over the course of a year due to the Earth's orbit. We also assume a maximum solar elevation angle of 2.3° at the TLT location, and assume that the solar array rotates to track the Sun. A standard conversion efficiency of modern perovskite-silicon tandem photovoltaic cells of 30% is adopted, and a solar cell packing efficiency of 90%. For a 100kW generating solar tower, we estimate the solar cell area to be approximately 271.06 m^2, noting that the area required is likely to be greater due to additional factors leading to conversion inefficiencies, such as radiation damage, micrometeorite damage, and lunar dust contamination. Further details are shown in Appendix A.

3 Geometry

The starting point for the design evolution was the consideration of the unique lunar environment constraints and challenges in conjunction to the adoption of advanced manufacturing methods and particularly of 3D printing technologies. These hold the promise both for maximising ISRU and material efficiency whilst allowing for geometric freedom in defining and realising the tower's optimised form. Initially four key parameters were considered (fig. 2). That is, directionality of printing, materiality, continuity, and assembly/erection process. The resulting permutations of the design typologies were assessed based on Key Performance Indicators (KPIs) including total mass tower, construction complexity, outfitting integration, and resilience. Furthermore, the consortium developed a matrix in which several weighted parameters were evaluated in a systematic way. Preliminary designs considered several typologies such as optimised trusses, cylindrical towers, and post-tensioned systems. The final diagrid system was selected due to its geometrical versatility, process driven design, maintenance-friendly characteristics, material-efficiency, and lastly its potential to reduce thermal shocks across the structure due to its permeable form.

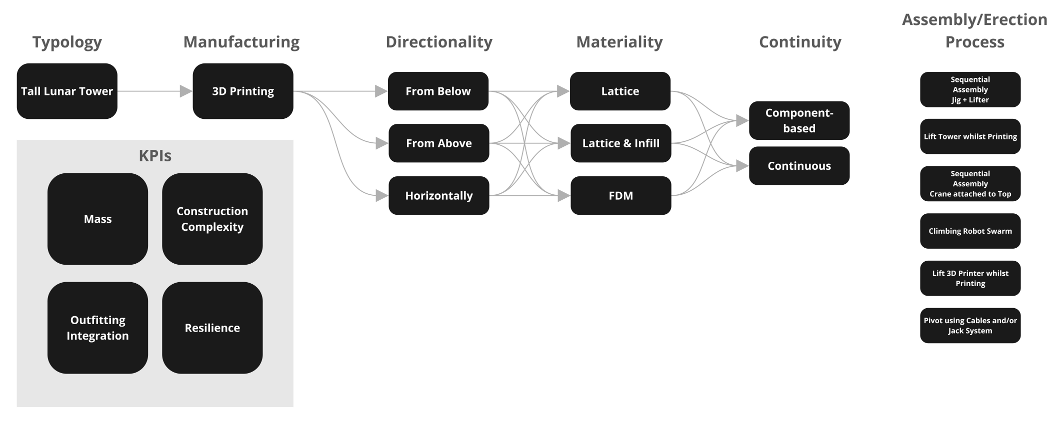


Figure 2 Initial design investigations studied parameters such as directionality of 3D printing, materiality, continuity, and assembly/erection process. The resulting permutations were assessed based on four main KPIs; namely, tower mass, construction complexity, outfitting integration, and resilience.

At the final iteration, the tower's integrated design was developed by considering the functional, environmental, manufacturing, and operational needs of the structure, from construction through to commissioning. In particular, the geometry assumes a diagrid helical form (fig. 3) which can offer clear load paths to resist a combination of loads (vertical and lateral). Specifically, the helical geometry is the defining characteristic of the tower's form as it defines the multi-functional track which enables, manufacturing, outfitting, and solar array deployment and maintenance *in-situ*. The defining dimensions of the TLT are 50m height and 1m diameter resulting in a rather slender tower ration. The computational design algorithm was developed within the Grasshopper platform of the the Rhinoceros 8 CAD software and was based on a custom-made script allowing for a completely parametric definition. This enabled the explicit control of parameters such as diagrid density and dimensions, helical track density and overhang, and structural member thickness and sizing which varied along the height of the tower.

Continuity

One of the key parameters investigated was that of continuity as it would greatly affect both the design and manufacturing of the tower. A continuous approach would allow the 3D printing of the whole structure in one go and directly on the tower location. At the same time, manufacturing resilience could potentially be decreased. This is because one error during the manufacturing process could invalidate the whole print up to that point. On the contrary, a discrete approach would imply increased manufacturing resilience due to the component-based method. However, the components would need to be transported on site; therefore, the assembly complexity could potentially be increased. In other words, the question that arises is where the complexity should be managed: at the manufacturing (component-based and sequential assembly) or assembly (continuous print in situ) stage? In this case, it was decided to opt for the former and 3D print a continuous tower *in-situ*.

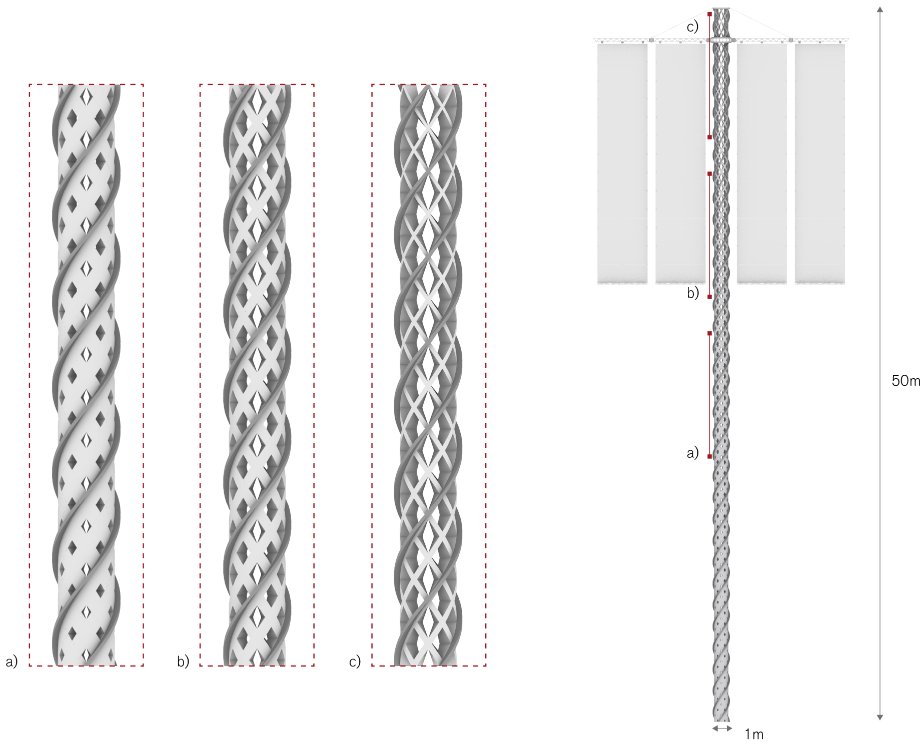


Figure 3 The geometry of the tower comprises a helical diagrid with variable thickness and an integrated helical track which enables the spiralling movement of the robotic system.

Structural analysis and optimisation

Phase I of this project was materially agnostic in the sense that several potential materials and associated 3D printing techniques were considered. The end goal would be to transition the design and manufacturing method to *in-situ* processes; for example, to use locally-sourced metal alloys such as lunar aluminium. To this end, a parametric initial structural analysis framework was developed using the Karamba FEA plugin within Rhinoceros' 8 Grasshopper platform (fig. 4). The geometry input is fully parametric, meaning that shape changes are seamlessly analysed and sized. In this script, parameters such as external loading, material, and cross-sections can be defined and analysed in terms of deflections and mass tower. Furthermore, a cross-section optimisation method was employed for material-efficient sizing of the structural members.

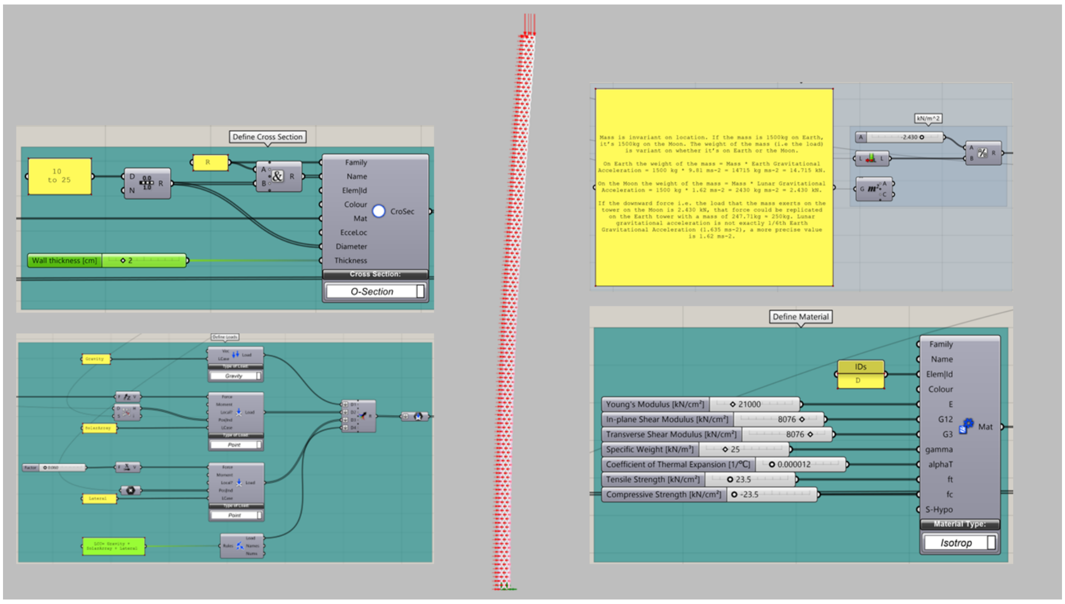


Figure 4 An initial structural analysis script was developed using Karamba FEA which allowed for the parametric definition and optimisation of cross-sections, materials, and load cases.

Outfitting strategy and stabilising ties

The tower's slender aspect ratio, combined with thermal gradient loading and natural hazards (e.g., moonquakes) could present stability risks; therefore, tie integration and outfitting strategies were considered. To this end, a robotic climber system could be used to deploy a tie point ring at a specified height (e.g., mid height for 45deg cables). Furthermore, a system of multiple climbing robots with attached stabilising ties could follow the printing construction stage of the tower to offer stability during construction. Extra tie rings could be deployed if necessary to improve resistance to thermal loading deformation. These could employ systems such as active tension control to manage deflection direction change throughout the solar cycle, as well as compensate for the effect of dynamic lateral loading resulting from moonquakes. However, a disadvantage of external tie points is that it introduces obstacles along the spiral track that could complicate movement, servicing, and maintenance of other ring modules on the tower. An alternative solution would consider internal ties through the core of the tower. This post-tensioning approach could help to remove obstacles along the tower's exterior, allowing free movement of ring modules. These ties would need to be deployed after the tower's completion, potentially leading to instability during construction which could be mitigated through the use of temporary external ties.

Once the tower is constructed, a crane system ring module could be deployed to the top of the tower. This crane system could then be used to facilitate other outfitting activities, such as fitting communications equipment or lighting, as well as serving as the hanging platforms for the solar panel arrays. This strategy reduces the load that must be transported by the climbing robot system along the tower's spiral tracks and allows easier maintenance and cleaning of the solar panel arrays. Moreover, this system could potentially be repurposed as a deployable crane system for lunar base construction, offering greater heights than previously developed Lightweight Surface Manipulation Systems (LSMS) [3, 12]. Another strategy involves directly lifting the solar panel arrays using the climbing robot system. By reusing the climbing robot system for this phase, the number of robotic systems that need to be transported could be reduced. This however could present a stability risk to the tower, and careful analysis would be need to ensure the spiral fins are not overloaded during the lift.

4 Robotics

TLT construction is intended as a precursor to human presence on the Moon and will contribute towards providing the critical power systems infrastructure required for safe, long duration human missions. During settlement expansion, when humans have begun to populate the stations, it is also desirable to limit or eliminate the construction tasks that people must perform, to reduce the need for high-risk tasks and to allow them to focus on their primary missions. Consequently, autonomous manufacturing systems will play an important role in the future of space development and exploration.

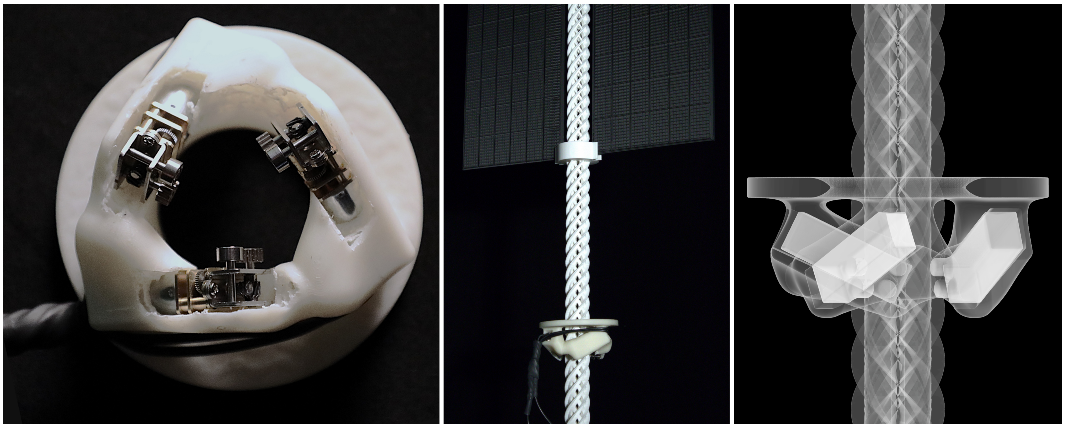
While many autonomous systems have been explored for excavation works and low-height lunar construction, the domain of autonomous tall structure construction is less explored. The NASA developed ARMADAS system [4] uses swarm robot technology to offer a modular construction system using pre-fabricated building blocks, that can rapidly scale to large structures while offering redundancy through the use of a fleet of systems. The applicability of such methods to ISRU manufacturing and diverse infrastructure typologies is an active field of research.

It is envisaged that the robot systems for our TLT will be built upon a base configuration that enables vertical travel along the tower, that can be augmented to specific roles such as 3D printing for construction, manipulation platforms for outfitting, or crane systems for solar panel lifts. At this early phase of the project, the robotic systems a developed conceptually to provide the functionality required to support the proposed manufacturing process with concepts grounded in scale-model mechanisms.

Spiral track geometry

One of the challenges with constructing tall structures on the lunar surface is the absence of conventional lifting equipment such as cranes. The tallest LSMSs developed to date have been focused on off-loading tasks from landing modules, and relatively low-height construction tasks. By utilising an *in-situ* 3D printed manufacturing process, this challenge can be resolved by adapting the tower geometry to serve a functional role in the manufacturing process. In other words, the proposed tower can 3D print itself. To this end, the outer edge of selected helical struts of the proposed diagrid geometry are extended radially to provide an integrated travel rail.

This geometry adaptation provides the vertical lift required for tall structure construction, by providing travel surfaces for climbing mechanisms. When combined with a continuous ISRU 3D printing process, the height of the tower is only limited by the material properties of the construction media. These rails approximately transform the tower into a large multi-start screw, with the pitch and number of starts influencing the force required to raise a platform up the tower, as well as affecting the transfer of load onto the tower. Approximating the spiral track geometry as a multi-start screw, we can identify the relevant parameters of the design and estimate the mechanical advantage and reduction in force required to lift a payload up the tower (see Appendix B for a detailed explanation).



(a) The geometry for the climber ensures clearances for motor installation and fit for spiral engagement.

(b) The climber system is able to raise the printed solar panel array and, depending on the tower parameters, can "deploy" an array through a friction lock.

(c) The resulting motor alignments and generated form conforms to the tower geometry.

Figure 5 The climbing system designed for the 1:50 scale model utilises implicit modelling to find a form that caters to the required motor locations and clearances.

Climbing mechanism

As discussed in 4, the tower's geometry has been designed to provide travel rails that can be used by robotic systems to move up and down the shaft. In contrast to previously developed pillar/pylon/tower climbing systems, this design helps to reduce the force required for vertical travel, though introduces the complication of non-linear travel paths. A parametric model was developed to design an arrangement of motors that conformed to the geometric constraints of the tower's travel rails, as well as the required clearances for the selected motors.

Solar panel deployment strategies

Development of a deployable solar panel system was not within the scope for this phase of the project beyond considering the payload capacity of our design; however, in the interest of developing a functional design, the geometry has been developed to be capable of accommodating the latest advances in lunar solar photovoltaic technologies. Considering the autonomous deployment goal for this design, and the constrained weight and volume payload capacity for heavy lift systems, collapsible and self-deployable panel systems are critical for lunar power systems [5].

5 Manufacturing and assembly

Freeform 3D printing is a methodology of additive manufacturing that seeks to minimize the amount of material consumed. This is achieved by filling printed volumes with Cellular Fabrication (C-Fab®), truss-like lattices as opposed to monolithic, solid layers (e.g., FDM). The process relies on geometry to create strength - shaping structurally efficient forms similarly to how natural organisms are shaped by the forces in their environment. The result is an additive manufacturing method that consumes 95% less material compared to solid-layering. With this technique, Branch Technology has completed projects on four continents, including several of the world's largest and most significant 3D printed structures to date: from the world's largest-spanning 3D printed structure; the world's largest exterior 3D printed facade; and a full-scale replica of a NASA Space Shuttle at the US Space & Rocket Center in Huntsville, AL, USA. It is the aspect of material efficiency that is in fact the most relevant benefit of C-Fab® in relation to the challenges posed by the lunar environment. This in turn also allows for structural efficiencies that can provide key benefits to NASA missions.

Material efficiency is critical to the establishment of a sustainable human presence on the Moon. This is because the necessary infrastructure will require more resources than are easily transportable or readily available. Most materials used for this purpose will need to either be launched from Earth or harvested in space. However, launching them out of Earth's gravity well is expensive because of launch mass considerations; whereas, harvesting them in space and/or the lunar surface can be difficult. As a result, material efficiency plays a key role to sustainable lunar surface operations. In addition, the trussing lattice structures produced via freeform 3D printing can also improve structural efficiency by leveraging geometries that create a much higher strength-to-weight ratio as opposed to monolithic structures. Specifically, this structural efficiency occurs at both the micro and macro scale:

1. At the micro-scale, only material at the cell's boundary is utilised. This is due to the open cellular structure of the freeform lattice.
2. At the macro-scale, structurally efficient geometries can be achieved. This is due to ability of additively manufactured designs to leverage structural optimization processes unlike other conventional methods in which the design freedom can be constrained.

In the mission to erect infrastructure such as a tall lunar tower for power and communications, construction and assembly process design can benefit from material-efficient methods that can maximize the usefulness of resources across an entire lunar outpost. Branch Technology's C-Fab® and Freeform 3D printing techniques provide a natural inspiration for this typology as they can alleviate launch mass concerns for transported materials and quantity or difficulty concerns for lunar-harvested materials which can potentially be tailored for ISRU in the future. As a result, processes that can be informed by these techniques hold the promise for creating extensible solutions and contributing towards a permanent human presence on the Moon. In the integrated design and manufacturing approach presented here, the tall lunar tower does not comprise prescriptive, prefabricated metal truss components. It is rather 3D printed in-situ with an intrinsic truss-like lattice structure which affords wider design freedom of optimized topologies. Additionally, it seamlessly integrates outfitting capabilities and several potential future applications of the technology.

6 Demonstrators

The consortium fabricated a number of demonstrators during the course of the project. These ranged from small scale 1:50 models, 3D printed at Foster + Partners London, to large scale 1:1 sections of the tower, 3D printed at Branch Technology facilities in the US (fig. 7). Specifically, a 1:50 scale model was developed as a means to evaluate the feasibility of the design, in terms of understanding the manufacturability of the tower design when using an FDM process, and the ability of a climbing model to ascend the tower using the designed-in travel rails. Additionally, the 10m-tall section of the 1:1 scale tower prototype was produced using Branch Technology's C-Fab® process. This showcased the suitability of the tower's design for large-scale fabrication and was exhibited at the "Earth to Space" exhibition which took place in spring 2025 at the Kennedy Space Centre at Washington DC.

7 Conclusion

This research paper presented the conceptual design, assembly, and manufacturing of a 50m tall lunar tower located at the Moon's South Pole (fig. 6) for solar energy generation. The several aspects of the NASA-funded project were discussed including environmental constraints, integrated design, outfitting strategies, structural analysis, robotics, manufacturing, and demonstrator prototyping. Future work will focus on raising the Technology Readiness Level (TRL) of the project by further developing and testing materials, 3D printing methods, and autonomous robotic systems.

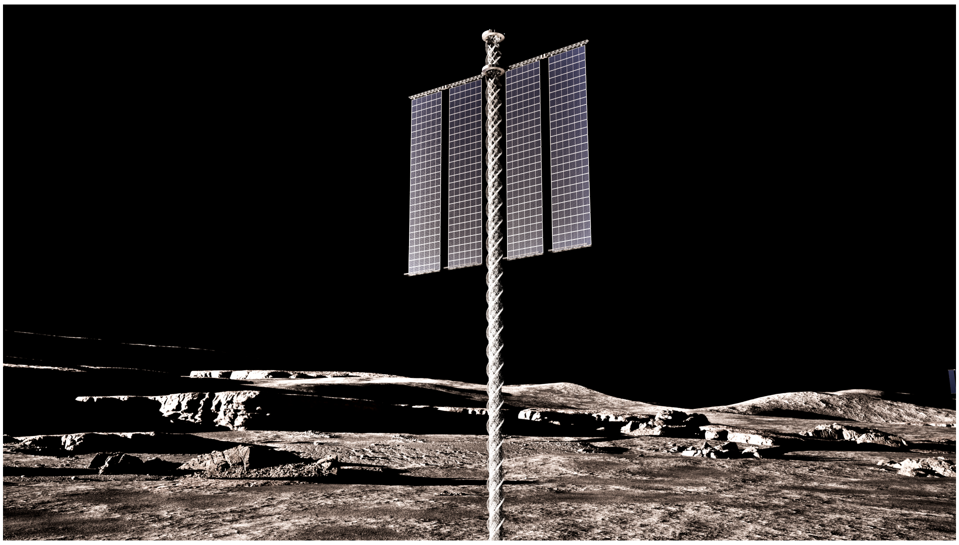


Figure 6 Artists' impression of the TLT at the Lunar South Pole. Image credits: Foster + Partners.

References

1 Ignatiev A, Freundlich A, Duke M B, and Rosenberg S D. The fabrication of silicon solar cells on the moon using in-situ resources. In *40th AIAA Aerospace Sciences Meeting & Exhibit*. AIAA, 2002. `doi:10.2514/6.2002-465`.

2 Sanders G B and Larson W E. Progress made in lunar in situ resource utilization under nasa's exploration technology and development program. *Journal of Aerospace Engineering*, 26(1):5–17, 2013. `doi:10.1061/(ASCE)AS.1943-5525.0000208`.

3 Jones T C. *A Protoflight Lightweight Surface Manipulation System to Enable High Load, Long-Reach Lunar Surface Operations*, chapter 1, page 1. AIAA, 2021. `doi:10.2514/6.2021-4167`.

4 Gregg C E and Cheung K C. Automated reconfigurable mission adaptive digital assembly systems (armadas): Robotically assembled sustainable lunar infrastructure. In *Lunar Surface Innovation Consortium Spring Meeting (LSIC 2023)*, 2023. URL: `https://ntrs.nasa.gov/citations/20230001316`.

5 Williams H, Van Ness R, Cloninger E, Vogel B, Crum R, Sanigepalli V, Zacny K, Okandan M, Wilson J, Hell K, and Rouhani K. *Lunar Array, Mast, and Power System (LAMPS) for Deployable Lunar Power Provision*, chapter 1, page 1389. AIAA, 2023. `doi:10.2514/6.2023-1389`.

6 Larson W J and Pranke L K. *Human Spaceflight: Mission Analysis and Design*. McGraw-Hill, 2000.

7 Speyerer E J and Robinson M S. Persistently illuminated regions at the lunar poles: Ideal sites for future exploration. *Icarus*, 222(1):122–136, 2013. doi:10.1016/j.icarus.2012.10.010.

8 Song K, Stark A E, Amundsen R M, Mikulas M, Mahlin K H, , and Cassady J T. Sizing, buckling, and thermal-structural analysis of tall lunar tower. In *ASCEND 2023, Las Vegas, Nevada, October 23-25, 2023*. AIAA, 2023. doi:10.2514/6.2023-4753.

9 Konstantatou M, Navarro Perez S C, Gallou I, Punch O, Guberman M, Dobbin B, Goodloe D, Loftus D J, Lesh A, and Lepech M. Modular outfitting systems for lunar habitation. In *SpaceChi 3.0, MIT Boston*, page 1, 2023.

10 Konstantatou M, Todisco L, Borg C, Piker D, Navarro Perez S C, and Gallou I. *Adaptive On- and Off-Earth Environments Springer Series in Adaptive Environments*, chapter Design and Assembly of Efficient Component-Based Off-Earth Infrastructure: From Vernacular to Contemporary Form-Finding Methods, pages 1–19. Springer International Publishing, 2024. doi:10.1007/978-3-031-50081-7_1.

11 Luther J M and Peshek T J. What would it take to manufacture perovskite solar cells in space? In *ACS Energy Letters*. American Chemical Society, 2022. doi:10.1021/acsenergylett.2c00276.

12 Miller A S, Lordos G, Portman P, Studstill A, Rohrbaugh J, Schoeman W, Williams C, Rutherford E, Zhang J Z, Patel P B, De Weck O, Hoffman J, Stamler N, Martell B C, and Fernandez J M. Design development of a stable, lightweight, tall and self-deploying lunar tower. In *2023 IEEE Aerospace Conference*, pages 1–14, 2023. doi:10.1109/AERO55745.2023.10115592.

13 Wang Y, Hao L, Li Y, Sun Q, Sun M, Huang Y, Li Z, Tang D, Wang Y, and Xiao L. In-situ utilization of regolith resource and future exploration of additive manufacturing for lunar/martian habitats: A review. *Applied Clay Science*, 229:106673, 2022. doi:10.1016/j.clay.2022.106673.

A Solar Photovoltaics

Power produced from an idealised solar array is given by,

$$P = \phi_{Sun}\eta F_p A\cos(\theta) \quad (1)$$

where P is output power (W), ϕ_{Sun} is the solar flux incident at 1 AU, 1367.5 Wm^{-2} (noting a ± 3.5% variation due to Earth's orbit), F_p is the packing fraction, the fraction of the solar panel covered by solar cells, typically between 0.85 to 0.90, A is the solar panel area m^2, η is the conversion efficiency, and θ is the angle normal to the Sun. Rearranging Eq. (1), gives Eq. (2), that can be used to estimate the solar array area,

$$A = \frac{P}{\phi_{Sun}\eta F_p \cos(\theta)} \quad (2)$$

As part of estimating the area of the panels for the TLT we assume a maximum solar elevation angle of 2.3° at the TLT location, and assume that the solar array rotates to track the Sun. We assume a standard conversion efficiency of modern perovskite-silicon tandem photovoltaic cells of η=30%, and a solar cell packing efficiency of 90%. For a P=100kW generating solar tower, we estimate the solar array area using the above formula as A = 271.06 m^2. The area required is likely to be greater due to additional factors leading to conversion inefficiencies. For example, factors such as radiation damage η_{rad}=0.85, micrometeorite damage η_{mm}=0.96, lunar dust contamination η_{dust}=0.98, Earth's aphelion η_a=0.967, array resistance and diode losses η_{rd}=0.958, UV darkening η_{uv}=0.98 [6], cumulatively lead to a 0.726 factor array efficiency reduction. Additionally considering more conservative estimates on the standard conversion efficiency η=24%, a solar cell packing efficiency of 85%, suggests a solar array area A = 494.15 m^2.

B Mechanics of spiral track geometry

To begin analysis of the mechanics we consider the work, W, done by the system. By conservation of energy,

$$W_i = W_o \tag{3}$$

This work is given by the force applied for the distance it acts. For the spiral geometry, considering one full turn of a climbing mechanism, the work in is applied radially, producing a path that travels a full circle, while the work out is applied axially, with one full turn resulting in a travel distance equivalent to the screw lead, l,

$$W_i = 2\pi r F_i \tag{4}$$

$$W_o = l F_o \tag{5}$$

The mechanical advantage for an ideal screw with no friction, MA^*, is then given by the ratio of the achieved output force for the given input force,

$$MA^* = \frac{F_o}{F_i} = \frac{2\pi r}{l}. \tag{6}$$

We can consider the effect of friction on the system by including a friction coefficient, μ, affecting the work efficiency,

$$W_o = \mu W_i \tag{7}$$

Taking the definitions in Eq. (4) and Eq. (5), we arrive at the relationship,

$$l F_o = \mu 2\pi r F_i \tag{8}$$

Assuming a minimum steady state holding force requirement equal to the weight of the payload under lunar gravity conditions, $w_p = m_p g_l$, the force required by the climbing mechanism is then given by

$$F_i = \frac{l m g_l}{\mu 2\pi r}. \tag{9}$$

This represents the total force required to hold a payload on the tower, subject to gravity and friction. For multi-start screw paths, the screw lead is a direct multiple of the pitch for the number of screw starts, N,

$$l = Np, \tag{10}$$

thus considering Eq. (9) and Eq. (10), it can be seen that increasing the number of starts will increase the force required to hold the payload in place, while increasing the friction or radius of the tower will reduce the force required. For a climbing mechanism the uses multiple actuators, the force required can be distributed over the number of actuators, $F_i = \sum_{n=0}^{N_a} F_{i,n}$.

Applying this analysis to a $50m$ tall, $1m$ diameter tower with three screw path starts, $l = 14.25$, and three actuators, and an assumed friction coefficient of $\mu = 1.0$ for an aluminium-aluminium contact surface, indicates a potential force reduction of 47.8%

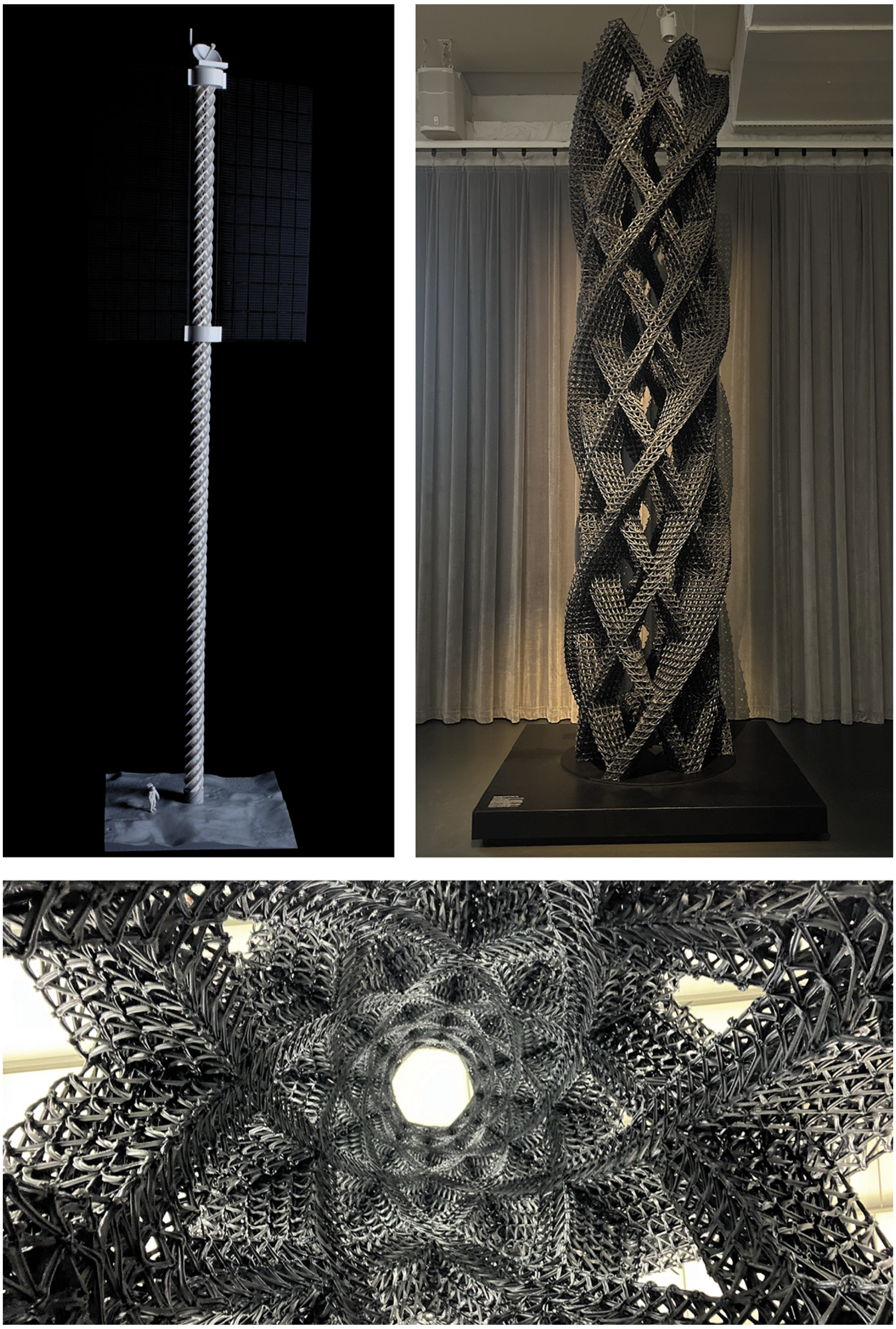


Figure 7 Top left: 1:50 scale prototype which was 3D printed using the FDM method. It included a functional robotic system for raising and lowering the solar arrays. Image credits: Foster + Partners; Top right: Section of the 1:1 scale prototype which was 3D printed by BRANCH Technology using the C-Fab® process, exhibited at the Kennedy Space Centre. Image credits: Foster + Partners; Bottom: Detail of the TLT as viewed from the inside the tower. Image credits: BRANCH Technology.