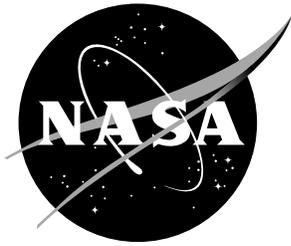


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# LuZip: Lunar Zip-line, Gondola and Cable-based Transportation for Artemis Moon Missions Mobility and Dust Avoidance

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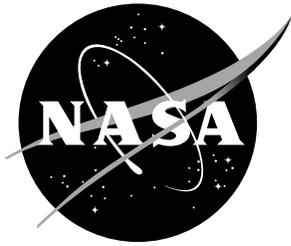
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## **Abstract**

Under the Artemis program, NASA plans to return to the surface of the Moon, this time to stay. The Apollo missions identified dust as a major challenge for operations on the lunar surface. This includes traveling from point to point. There have been efforts to develop technologies that prevent dust from entering equipment, making equipment more resilient to dust and improving dust removal. However, operating effectively in the dusty environment for long durations is still an open problem. Here, we explore the use of cable-based transportation, gondolas and zip-lines to stay above the dust for equipment and material transfer as well as human excursions. The advantages and disadvantages, potential architectures, propulsion and materials are discussed. Steps towards infusion into the already ongoing Artemis program are also presented.

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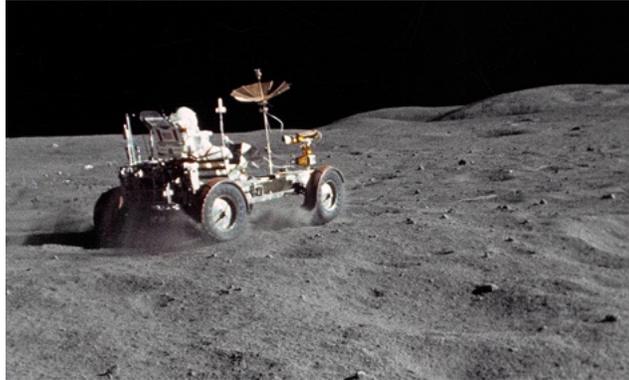
# 1 Introduction

As NASA and its commercial, and international partners look to return to the lunar surface, this time for a sustained presence under the Artemis program, technology and infrastructure are required that supports long term operations [1]. In parallel, the Defense Advanced Research Projects Agency (DARPA) is sponsoring a 10-year capability study (LunA-10) to develop a framework for an optimized, integrated lunar infrastructure that includes examining the challenges involved to enable a lunar economy [2]. Realizing the vision of a thriving lunar economy will require efficient crewed and robotic traversal of the surface. One major problem for operations on the Moon is lunar dust as shown in Figure 1. This sharp and sticky material clings to equipment, spacesuits and rover wheels [3, 4].

Dust induced problems reported during the Apollo missions included loss of traction, clogging of mechanisms and abrasion. With Artemis aiming for sustained presence and extensive activities on the lunar surface, it is expected that dust-related problems will be much worse. Currently, there are several efforts aimed at preventing dust from sticking to materials [5], removing the dust [6] and making equipment that is more resistant to the abrasive effects of this dust [5, 7]. Paving the lunar surface to create highways and lunar railways are also being considered [8, 9, 10]. An approach that has not been given as much consideration is keeping off the dusty surface in the first place. It is not possible to fly from point to point on the Moon, short of rocket propulsion or magnetic rail/coil guns, due to the lack of an atmosphere, the same reason why lunar dust is such a major challenge. However, it is possible to string cables between support towers thereby providing a means of transit while avoiding the dust.



(a) Astronaut working on the lunar surface



(b) Lunar rover kicking up dust



(c) Apollo 17 commander Eugene Cernan showing dusty gear inside the lunar module

Figure 1: (a) Apollo astronaut spacesuits quickly became covered with dust from their relatively short excursions on the lunar surface. (b) Wheeled vehicles stirred up the dust even further as can be seen for the lunar rover. (c) The dust would end up inside the lunar module. Image credit NASA.

Cable-based transportation, gondolas and zip-lines are successfully used terrestrially over widely varying and challenging terrain for activities that range from recreation to everyday transportation as shown in Figures 2. The relatively small ground footprint, robustness and ability to be integrated with other infrastructure makes them an optimal choice in difficult to access locations. Recreational zip-lines (2(a)) and theme park gondola transports (2(b)) are some example of cable-based transportation. Ski-lifts (2(c)), cable cars that go over forests (2(d)) and rivers (2(e)) as well as the cable systems that provide transportation in urban areas (2(f)) are further examples. The 4.8 km (3 mi) long Disney Skyline (2(b)) offers speeds up to 18 km/h (11 mph). The Mi Teleférico in LaPaz-El Alto metropolitan area in Bolivia (Figure 2(f)), the longest aerial cable-based transportation network in the world, is close to 32 km (20 miles) long (2014, Wikipedia).

Cable-based transportation has been used by NASA as part of the launchpad escape infrastructure at the Kennedy Space Center for crew escape in case of launchpad emergencies from the time of the Apollo program and Saturn V rockets to the latest commercial launch operations [11]. Examples of recent versions of these systems are shown in Figure 3. Both individual-harness- and gondola-based transports are used. In the case of an emergency while the rocket is on the launchpad, astronauts would use a zip-line or gondola to slide down to a safe area or waiting ground transportation. The cable-based transportation provides a robust, simple and reliable last resort escape measure that integrates with the other infrastructure at the launch site. The cable lines are over 400 m long, again illustrating the ability of cable-based transportation to cover a lot of ground. The use of cable-based transportation is a part of astronaut training, making them a familiar technology for future Artemis crews.



(a) ZipTheUSA zip-line challenge course (Texas)



(b) Disney Skyliner (Disney World, Florida)



(c) Ski-lift (Yllästunturi, Finland)



(d) Namak Abrud woodland crossing (Iran)



(e) Thames river crossing (London)



(f) Mi Teleférico urban transportation system (LaPaz-El Alto, Bolivia)

Figure 2: Examples of terrestrial applications of cable-based transportation. Image credit (a) ZipTheUsa (CC BY-SA 3.0) (b) Jedi94 (CC BY-SA 4.0) (c) Estormiz (Public Domain) (d) Alireza Javaheri (CC BY 3.0) (e) Nick Copper (CC BY-SA 3.0) (f) EEJC (CC BY-SA 4.0).



(a) Atlas V/Boeing CST-100 Emergency Egress System (EES)



(b) Space Launch System(SLS)/Orion launchpad escape gondola

Figure 3: (a) Individual harness and (b) gondola cable-based transportation used for emergency launch pad abort at the Kennedy Space Center. Image credit NASA.

Given the successful use of cable-based transportation in a range of terrestrial settings, and particularly its use over challenging terrain, the prospect arises for its use on the Moon and eventually on Mars. With the lunar dust being an ever present hazard for crew and any vehicles or other equipment dragged through it, transportation that operates above that dust, such as that shown in the artist’s rendering in Figure 4, is advantageous. Lunar cable-based transportation could enable point-to-point travel that avoids dust and other obstacles on the terrain while requiring a limited surface footprint. This small footprint also means more of the lunar surface would remain in a pristine condition for research and exploration. The mass and complexity of cable-based transportation scales well with longer travels – mostly requiring more cable and widely spaced support towers. The lower lunar gravity decreases the loads on the cables and towers, potentially leading to transport of higher cargo volumes at reduced cable and tower masses relative to terrestrially. Cable-based lunar transportation was an option discussed in the 1990’s by Bernold [12, 13, 14]. Cable-based cranes also discussed in the 1990’s [12] have seen more recent interest [15], however there has not been as much focus on the wider development and use of cable-based transportation infrastructure on the Moon save for student design challenges [16, 17]. Cable-based transportation would be part of the NASA plan to establish lunar transportation infrastructure as detailed in the Moon to Mars Strategy Objectives Development document (LI-6): *Demonstrate local, regional, and global surface transportation and mobility capabilities in support of continuous human lunar presence and a robust lunar economy* [1]. The transportation would also contribute to the infrastructure for a lunar economy called for in DARPA’s LunA-10 program [2].

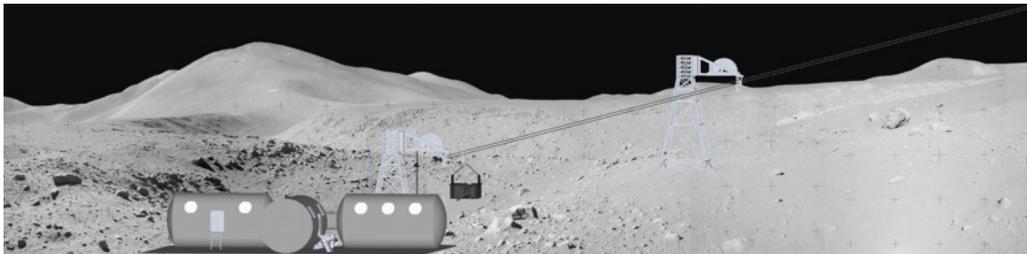


Figure 4: Artist’s impression of LuZip, gondola/cable-based transportation from a lunar outpost to a working or exploration site far in the distance. Image credit NASA.

## 2 Gondolas and zip-lines on the Moon

Considerations that must be addressed for the envisaged system include the physical components as well as operational and mission related constraints. Key components for lunar cable-based transportation are shown in Figure 5. The illustration depicts gondolas, but harnesses are also potentially feasible for crew transport in the manner shown in Figures 2(a) and 3(a). Each of the elements that will be discussed here-forth both on the hardware and other considerations for cable-based transportation requires

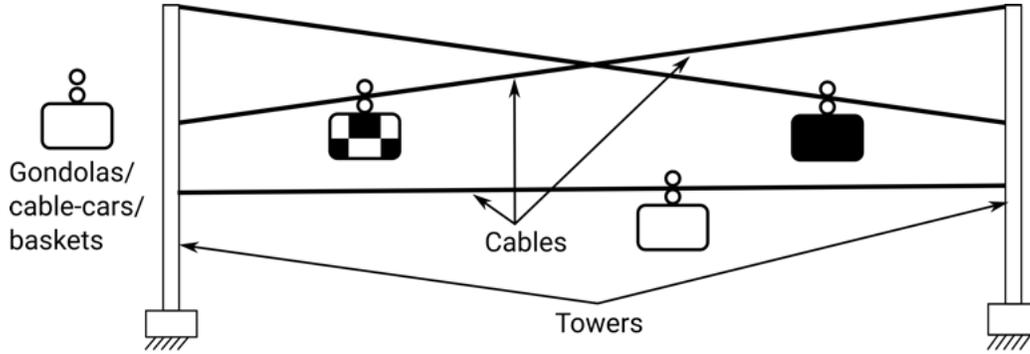


Figure 5: The basic components for cable-based transportation. Image credit NASA.

a detailed engineering, technical and cost assessment which goes beyond the scope of this paper. Instead, we broadly identify factors that detailed studies can expand on. The list is not exhaustive but should provide a basis for further evaluation of the concept. More detailed studies of specific implementations will, necessarily, have additional considerations that are not discussed here. As with all technology solutions, there are trades to be made. Cable-based transportation will need to be compared with alternatives such as improved wheeled vehicles and other dust mitigation and conveyance solutions. Feasibility on the Moon, cost and utility are all topics that would need further study. The successes of cable-based transportation in the terrestrial applications discussed in Section 1 suggest that its use on the Moon warrants serious consideration. As on Earth, not all journeys can be made along cables due to some inflexibility in the infrastructure. However, a well-designed and placed network can be enabling, opening up efficient transportation to otherwise unreachable destinations. Ski-slopes would certainly be much harder to access without cable-based transportation as would the other destinations in the use cases shown in Figure 2.

Advantages of cable-based lunar transportation, some of which will be expanded on in the sections that follow, include:

1. Enable dust avoidance - keep off the dirt
2. Hazardous terrain avoidance - keep above any obstacles
3. Simple and well understood, with a high technology readiness level in terrestrial applications
4. Cable-based transportation infrastructure is lightweight with lighter load on cables due to low lunar gravity
5. The transportation of cables/cable materials to the lunar surface can be done with high packing efficiency
6. Implementation risk can be reduced by initial use as cargo and raw material transport and then transitioning to include human transport
7. Provides the only way to “fly” on the Moon (short of rockets or gun-type methods)
8. Lunar terrain features can be used as end points (Section 2.2)
9. Shares some technology with excavators that will be used in lunar mining

- approaches such as slusher mining [18]
10. Can leverage construction capabilities that are already required for other lunar infrastructure such as power, navigation and communications towers [19] (Section 2.2)
  11. Can directly leverage power distribution, navigation and communications tower infrastructure as end points (Section 2.2)
  12. Flexible gondola/cable car/basket design options; gondolas can be collapsible and/or modular (Section 3.1)
  13. There are several options available for driving the payloads/gondolas (Section 3.2)

The following are some of the challenges that need to be considered:

1. Towers are required, unless there are suitably located natural terrain features in the region of interest
2. Some lack of flexibility in the destinations

## 2.1 Mission Profile

During the *Live* phase of the Artemis campaign [1], where it is expected that there would be both human and robotic presence for sustained periods on the lunar surface, the “working commute” for the crew as well as the transport of materials and equipment will be important, as is the case on Earth. For example, transportation will be required to ferry crew and/or equipment from an outpost to some work or exploration site. Such infrastructure could be in the form of a cable- and gondola-based implementation as shown in the artist’s impression in Figure 4. Cable-based transportation could also be placed between key sites of a lunar settlement such as landing zones, power plants, habitation and other destinations where there is frequent traffic.

Tasks that could be accomplished using the transportation include:

- Crew and equipment transportation to frequented destinations.
- Raw materials transport between extraction sites and processing plants
- Transportation of wheeled vehicles to work and exploration sites. Figure 6 shows an artist’s depiction of cable-based transportation of a rover part of the way to a destination. Such a use case combines the flexibility offered by the wheeled vehicle in the last miles of reaching a destination with reduced wear and tear on the vehicle and decreased dust agitation along the route.

## 2.2 End Points

An important consideration for point-to-point transportation is the locations of the end points, the origins and destinations of the travel. It is important that they are carefully chosen to provide the most benefit to the mission. Some potential end points to support various mission scenarios for Artemis are shown in Figure 7. End points can be located to connect strategic locations of the ground infrastructure or vehicles. End points can also be chosen that take advantage of existing infrastructure

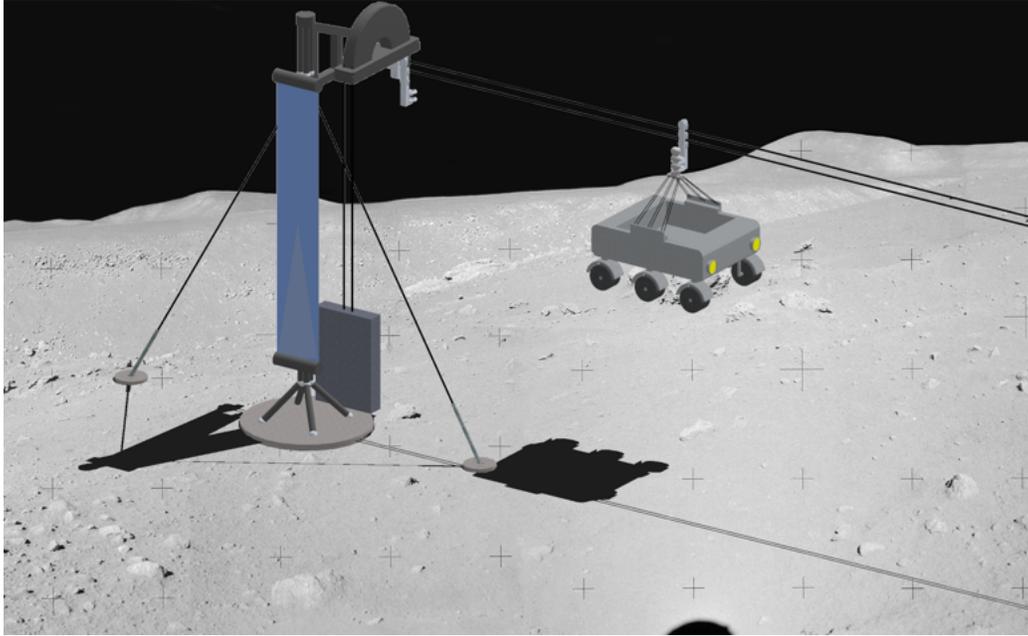


Figure 6: Artist's impression of a wheeled rover being transported by cable-based transportation for a portion of its trip to a final destination. Image credit NASA.

or landscape features. In addition to the transportation of wheeled vehicles part-way on their journeys (Figure 6), the end points i.e. the towers/pylons of the cable-based transportation could be themselves made mobile/re-deployable to add flexibility to the infrastructure.

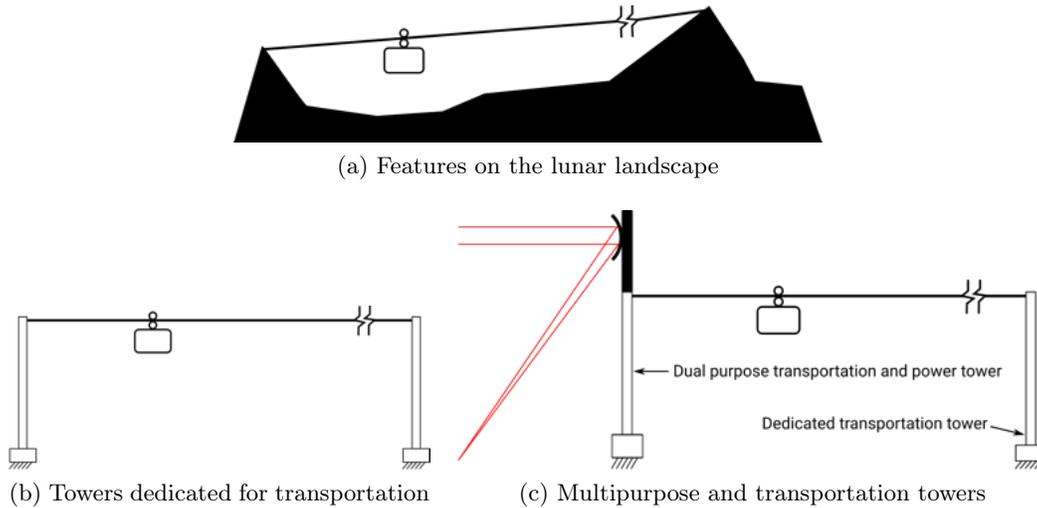
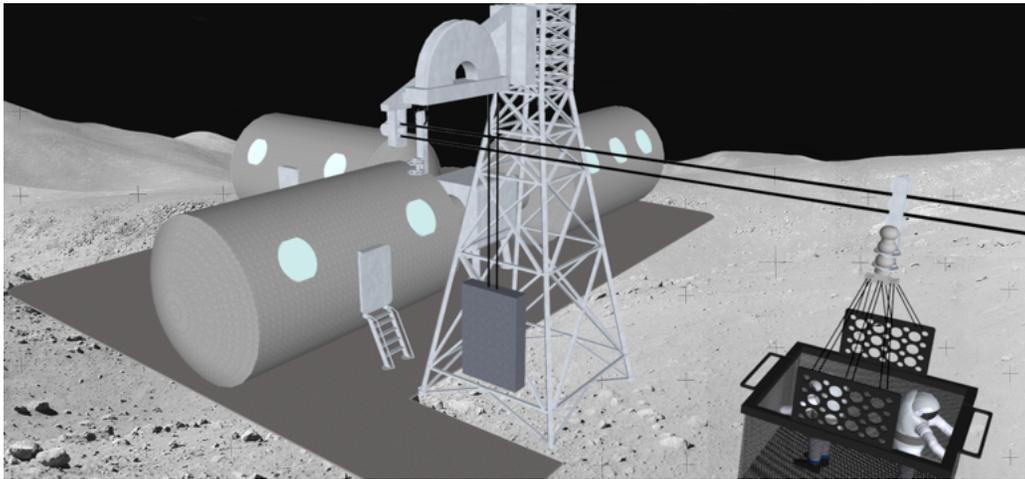


Figure 7: Examples of end points that could be used for cable-based transportation on the Moon. Image credit NASA.

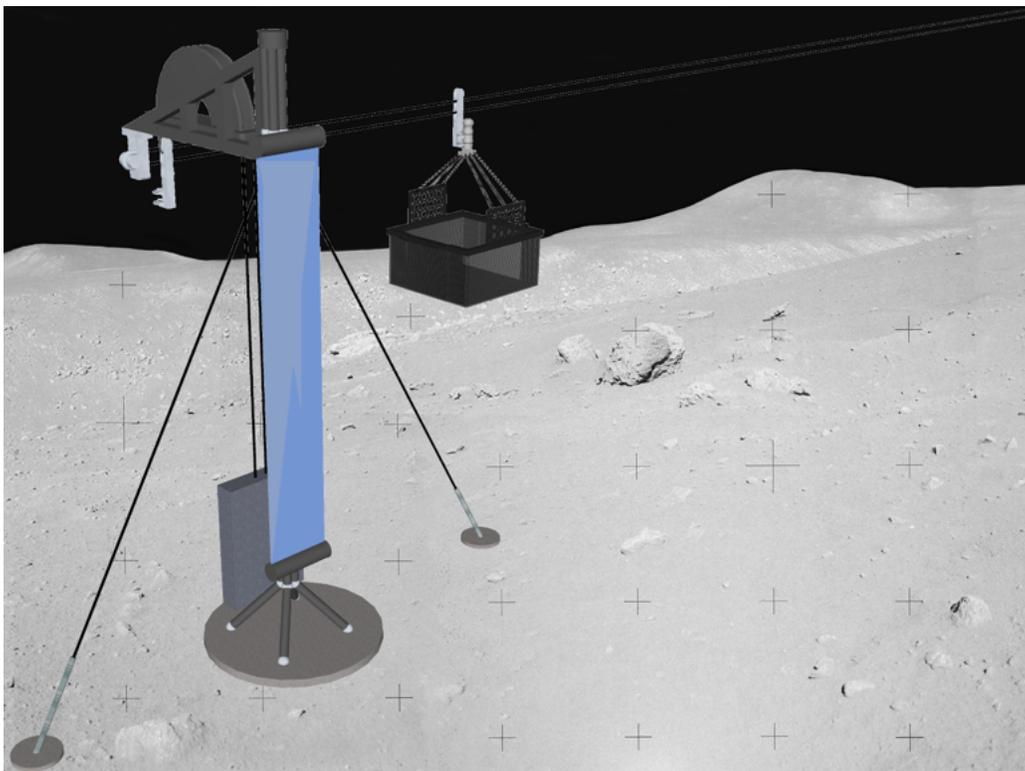
### 3 Implementation for Artemis

The recent development of a new class of super heavy-lift launch vehicles such as the Space Launch System and re-usable vehicles such as SpaceX's Falcon Heavy and Starship promises to vastly increase the mass and volume of material that can be launched into space. Already, the re-usability of SpaceX's Falcon rocket has enabled the deployment of a satellite constellation, Starlink, the size of which would not have been deemed feasible just under a decade ago. In spite of the increase in mass and volume that can be launched into Earth-orbit, getting mass onto the lunar surface is still going to be at a premium. Therefore, technology that is intended for use on the Moon, particularly earlier on in the development of lunar infrastructure, must be both mass and volume efficient. Cable-based transportation infrastructure fits well with these restrictions. The mass is mainly in the towers, which can be constructed from lightweight materials such as Earth-derived aluminum and carbon composites initially as shown in Figure 8, with potential for the use of materials obtained from lunar *In-situ* Resource Utilization (ISRU) as the infrastructure continues to build up. The towers can also be made deployable or ready to assemble on the lunar surface, increasing the launch volume efficiency. Towers can also serve multiple purposes such as power generation and/or transmission infrastructure. The transportation of cables can be very volume efficient and the use of carbon fiber and other materials in the construction of the cables, something that is being done terrestrially for new generation power lines and in the heavy equipment industry, could reduce the mass of these significantly.

Equally, the gondolas can be made from lightweight materials and using modular or collapsible construction approaches therefore making them more efficient to ferry to the lunar surface. Flexible or modular designs have high packaging efficiency. Strong and lightweight materials can be used to decrease mass. Designs that can be made on-site such as knitted or woven baskets can be customized to the requirements from an existing stock of fiber. Figure 9 shows renderings of some potentially deployable gondola designs. Drive mechanisms, motors, gears and other components will still need to be carried from Earth to the lunar surface but the scaling of cable-based transportation means that for any number of these transported to the Moon, there will be a large benefit in their use.

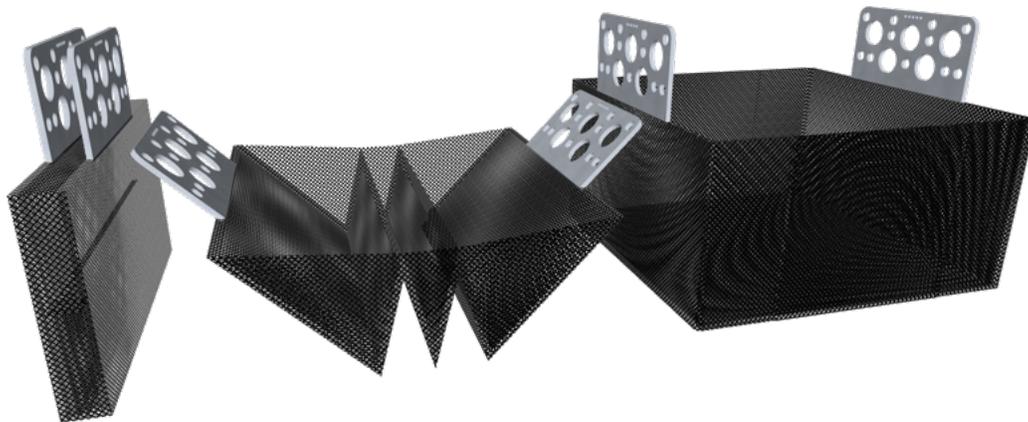


(a) Metallic cable tower

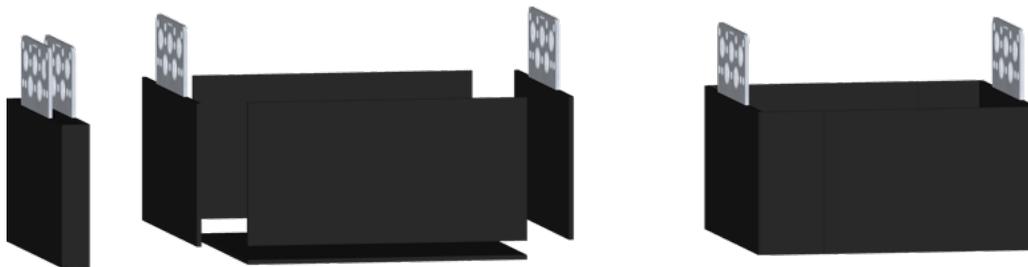


(b) Composite cable pylon with power generation solar panels

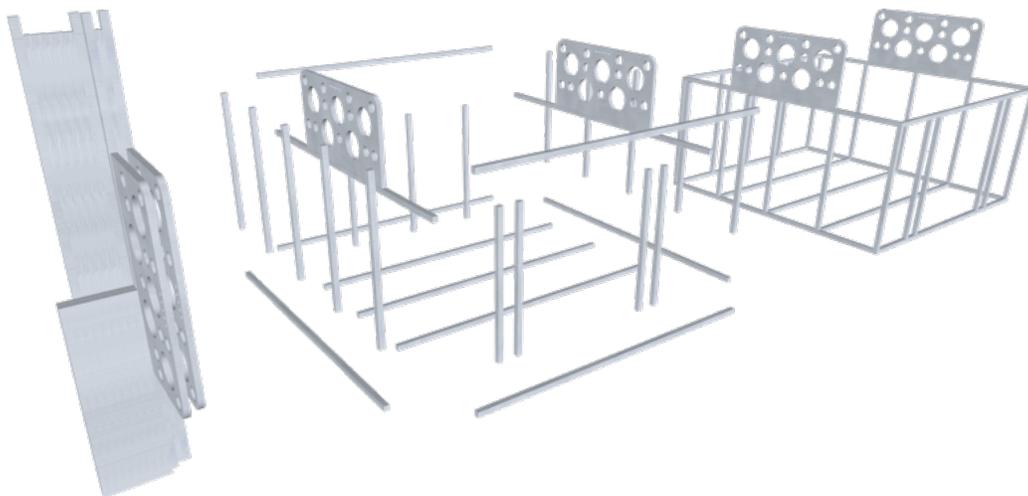
Figure 8: Artist's impression of towers for LuZip, lunar cable-based transportation. Image credit NASA.



(a) Textile based



(b) Composite panel based



(c) Metallic frame based

Figure 9: Artist's conception of gondolas that can be efficiently transported to the lunar surface and deployed or assembled on-site. Image credit NASA.

### 3.1 Materials Considerations

The following are some properties to be considered for the materials to be used to make the components for lunar cable-based transportation:

- Mechanical strength and modulus
- Density
- Survivability in the lunar environment including fatigue and thermal expansion/contraction
- Fatigue through the production, packaging, launch, deployment and utilization cycle
- Flexibility (for collapsible designs)
- Maintainability, repairability and modifiability
- Availability/cost
- Potential for *in situ* production

High performance wires and fibers can be used for the cables as well as the construction of gondolas and harnesses. Properties of some high performance fibers are given in Table 1. Breaking length (the maximum length of material can be hung under its own weight without breaking) =  $T/(\rho * g)$ , where  $T$  is tensile strength,  $\rho$  is density, and  $g$  is the gravitational acceleration constant. Some combinations of these materials could also be used, as would combinations involving materials not listed in the table. For example, a cable where basalt fiber provides structural support could have aluminum wires running through it for electrical conductivity if the cable car is electrically powered. Some materials, such as steel and carbon nanotube yarn may be able to provide both the structural and electrical functions.

Bulk metallic, polymeric and composite materials can be used for gondola panels and frames. Examples of these are given in Table 2. Metallic, composite and cementitious materials will also be needed for the tower construction.

In addition to the materials for the structural elements and the cables, there will be materials required for specialized subsystems such as drive motors, gears, hoists and other equipment. These mechanisms need to be protected from the dust by keeping them high off the surface as well as the use of protective enclosures.

Table 1: Properties of some high performance fiber and wire materials for potential use in cables, tower reinforcement and for woven and knitted gondolas and harnesses.

Material	Density (g/cm <sup>3</sup> )	Tensile strength (MPa)	Tensile modulus (GPa)	Specific strength (kN m/kg)	Breaking length in 0.165 g (km)	Ref.
Steel (316/316L stainless)	8.03	627	193	78	48	[20]
Kevlar 29	1.44	2920	70.5	2028	1253	[21]
Kevlar 49	1.44	3000	112.4	2083	1287	[21]
Dyneema DM20	0.97-0.98	3100	94	3163-3196	1954-1974	[22]
Dyneema SK75	0.97-0.98	3300-3900	109-132	3367-4021	2080-2484	[23]
Carbon fiber (Toray T300)	1.76	3530	230	2006	1239	[24]
Carbon fiber (Toray T1100G)	1.79	7000	324	3911	2416	[24]
CNT yarn (Miralon 4-ply)	0.8	1040	46.4	1300	803	[25]
Basalt fiber	2.63-2.80	4100-4840	93.1-110	1464-1840	905-1137	[26]
Glass fiber (S-2)	2.46-2.49	4590-4830	86-90	1866-1940	1153-1198	[27]
Glass fiber (E-Glass)	2.55-2.58	3450-3790	69-72	1353-1469	836-908	[27]

CNT (carbon nanotube)

Table 2: Properties of some bulk materials for tower and gondola construction

Material	Density (g/cm <sup>3</sup> )	Tensile strength (MPa)	Tensile modulus (GPa)	Specific strength (kN m/kg)	Ref.
Steel (304/304L stainless)	8.03	655	193	82	[28]
Aluminum (6061-T6)	2.7	310	68.9	115	[29]
PEEK (450G)	1.30	98.0*	4.0	75*	[30]
PEEK/40%carbon fiber composite	1.45	330	43	228	[31]
IM7/8552 carbon fiber composite**	1.58	2559	162	1620	[32]

PEEK (polyether ether ketone) - thermoplastic polymer

\*At yield

\*\*Unidirectional

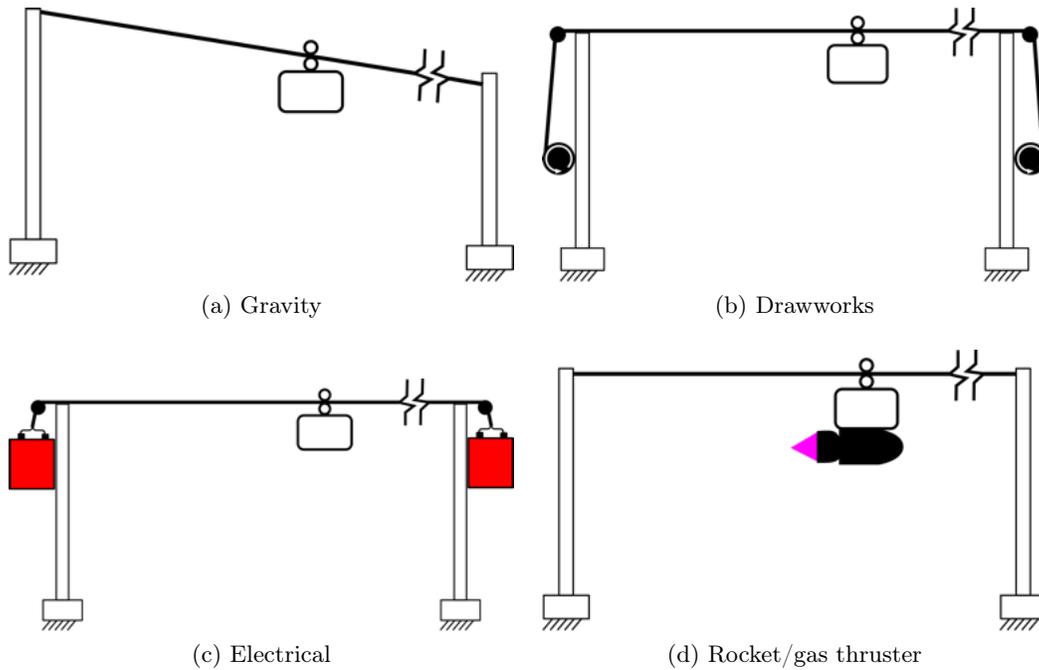


Figure 10: Potential propulsion/drive options for lunar cable-based transportation. Image credit NASA.

### 3.2 Propulsion/Drive Mechanisms

Some propulsion/drive mechanisms for cable-based transportation on the Moon are shown in Figure 10. The simplest implementations are gravity driven. These work provided there is a suitable height gradient in the desired direction of travel. A means of lifting the payloads to the starting height such as a winch or similar device is also required. Bullwheels and other mechanisms can also be incorporated to control the travel of the cables. Most terrestrial cable-based transportation is electrically driven. In this case, electrical power is delivered to drive mechanisms above the gondola and these enable the gondola to move along the cable. Motion of the gondola can also be achieved by placing the drive mechanisms at the ends and pulling it along its traverse with cables that can be reeled in and out. This drawworks mechanism is also typically used in the lifting of payloads. Rocket or gas thrust is also technically conceivable as a propulsion mechanism that would work in the lunar vacuum but would require consumables.

## 4 Path to the Moon

The case for using cable-based transportation as part of the infrastructure on the lunar surface has been described, following which some steps necessary to further explore the technology and make it a part of the mission architecture for Artemis

must also be addressed. Activities along the way to deployment on the Moon include:

1. Detailed identification of the operational requirements and use/deployment cases
2. Understanding the lunar terrain and operating environment - selecting notional sites for cable-based transportation infrastructure that would fit with the Artemis campaign objectives
3. Materials selections and testing, targeting specific implementations
4. Component mock up, fabrication and testing
5. Large scale concept demonstration and design challenges [16, 17]
6. Lunar demonstration missions for components and subsystems

All the above activities can contribute to readying the technology for practical deployment on the Moon. These would leverage what is already known about using cable-based transportation on Earth and tailor them for the lunar environment. Carefully executed, they could result in usable lunar infrastructure more quickly than other approaches, due to the relative simplicity of cable-based transportation.

## 5 Conclusions

The Artemis program is aimed at providing humanity with a foothold on terrestrial bodies in the Solar System outside the Earth. In order to achieve the objective of a sustainable presence on the Moon and a thriving lunar economy, the key distinguishing feature of the return to the Moon, transportation of goods and crew are going to be a vital element. In this work, cable-based transportation is presented as an option for implementation on the lunar surface. Cable-based transportation has the benefits of a small footprint, low mass and volume of the equipment needing to be delivered to the lunar surface. Perhaps most importantly it is a technology that has already been demonstrated on Earth to be able to bring access to a range of locations many of which would be hard to reach in other ways. Such a well understood, simple technology also offers a solution for keeping off the lunar dirt that can contribute to the future that Artemis envisages of a thriving human and machine presence on the Moon.

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