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Materials and design concepts for space-resilient structures

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A B S T R A C T

Space exploration and terraforming nearby planets have been fascinating concepts for the longest time. Nowadays, that technological advancements with regard to space exploration are thriving, it is only a matter of time before humans can start colonizing nearby moons and planets. This paper presents a state-of-the-art literature review on recent developments of "space-native" construction materials, and highlights evolutionary design concepts for "space-resilient" structures (i.e., colonies and habitats). This paper also details effects of harsh (and unique) space environments on various terrestrial and extraterrestrial construction materials, as well as on space infrastructure and structural systems. The feasibility of exploiting available space resources in terms of "in-situ resource utilization" and "harvesting of elements and compounds", as well as emergence of enabling technologies such as "cultured (lab-grown)" space construction materials are discussed. Towards the end of the present review, number of limitations and challenges facing Lunar and Martian exploration, and venues in-need for urgent research are identified and examined.

1. Introduction

Humans are explorers by nature. Our curiosity continues to grow as, since the lunch of Apollo 11 Mission in 1961, we managed not only to explore nearby moons and planets, but also number of galaxies in search of an Earth-like destination that would be suitable for human colonization. In concurrence to searching for a prospect plant (or moon), modern concepts such as "Terraforming" (Earth-shaping) of space bodies have emerged. Terraforming is defined as the process of deliberately modifying a space body's atmosphere in terms of temperature, topography, or ecology to engineer an environment similar to that of the Earth [1]. Unfortunately, terraforming of a typical-sized plant (such as the Moon or Mars) can take thousands of years; and without a significant scientific breakthrough, terraforming of space bodies may not be practically possible [1]. Hence, most of the current research efforts are mainly directed towards further exploring of nearby planets and moons.

Due to their proximity to Earth, number of studies have pointed out the possibility of human life on the Moon and more recently on Mars without the need for terraformation [1,2]. These studies also agree on the fact that in order to provide a safe environment to humans, habitats (bases) not only need to withstand extreme space environment, but also need to be properly fabricated; preferably using in-situ space resources. Interestingly, analysis on lunar and Maritain soils has demonstrated that they contain an abundance of substances and elements that could potentially be used to produce construction materials [3,4]. Thus, number of studies have emphasized the importance of using in-situ materials [3,5,6]. This emphasis is triggered by the fact that it can cost up to $20, 000 to transport one kilo-gram of materials from Earth to Moon; a cost that can exponentially scale in the case of Mars [5]. Although utilizing space-native raw materials seems promising and promotes development of independent and sustainable space habitats, however characterization, processing, and fabrication of such materials under microgravity as well as hard vacuum conditions continues to be challenging [7,8].

Therefore, parallel studies were carried out during the last 50 years to advance our state of knowledge, in terms of material science and structural design, to allow development of space-native construction materials and space-resilient habitats [9–12]. Some of these studies have led to the development of advanced and specifically tailored construction materials ranging from derivatives of classical composites and metals/alloys, to those inspired by nature (bio-inspired materials, comprising of Earth or space native raw elements and compounds), and/or designed to possess special features such as self-healing and sensing abilities, [13–15]. Although other types of materials are currently being developed, researchers seem to converge on the fact that among all available construction materials, composite materials (such as concrete) could be the most suitable material for fabrication of space structures since, unlike

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other construction materials, the performance of concrete under extreme conditions, i.e., radiation, elevated temperature, etc., has been well documented in terrestrial applications [3,16–18].

Whether human habitats are built using traditional, advanced, or space-native construction materials, these habitats, much like Earth-based structures, need to protect their occupants and provide them with a safe environment to live and function. Despite recent advancements in structural engineering, there is virtually no design or construction precedents for space habitats [19]. Given the extreme and harsh environmental conditions associated with the Moon and Mars, the design of safe space-resilient structures seem to be a unique challenge that requires in-depth investigation and interdisciplinary efforts. This is one of the main motivations behind this work.

This paper is also inspired by the National Aeronautics and Space Administration (NASA) recent announcement that Geodesy and Heat Transport (InSight) mission is scheduled to launch on May 2018, and for Mars landing on November 2018 [20]. This announcement also included a target deadline to send manned mission to Mars by 2030, and to start building future human habitats soon after. In essence, these announcements have started an inertia directed towards developing new materials, structural systems, and technologies to enable space exploration and colonialization within the next 10–15 years.

In support of these efforts, this paper presents a comprehensive survey that summaries past and most recent research findings, as well as identifies current limitations and technological needs associated with space colonization. More specifically, the present review addresses the effect of extreme and harsh space environments on properties of various construction materials. This review also explores feasibility of using available space resources to allow development of space construction materials and fabrication of structural components. Furthermore, structural–related design principles and number of concepts for "space-resilient" structural systems and infrastructure are highlighted. This review also highlights number of issues and challenges facing space exploration and venues in-need for urgent research.

2. Background on extraterrestrial exploration

Serious consideration was directed towards space exploration in the early 1900s due to the pioneering work of Tsjolkoysky [21] and Goddard [22]. Soon after that and during the Second World War (WWII), the Germans managed to launch the first rocket to ever reach the space (namely, V-2 rocket). After the end of WWII, the United States and the Soviet Union started their individual space programs. In 1957, the Soviets launched Sputnik 1, the first satellite, into space. Encouraged by the early Soviet success, the United States reorganized and expanded its space exploration efforts in 1958 with the commencement of NASA which began conducting space missions shortly after its establishment.

In April 12, 1961, Yuri Gagarin became the first human to orbit the Earth. Twenty-three days later, Alan Shepard Jr. became the first American to travel to space. After these successful missions, a series of major events took place. For example, the Soviets placed the first spacecraft that carried more than one person in orbit in 1964 and Russian cosmonaut Alexei Leonov became the first person to step outside a spacecraft in 1965. The space race reached its climax in 1969 when Neil Armstrong was the first man to land on the Moon. Since 1969, nearly twelve landings have been made on the Moon surface by the Soviets and the Americans, along with plentiful scientific operations.

In the mid-1990s, the discussion on space exploration was divided between those who wished to pursue Moon exploration and others who sought out shelter on Mars or nearby Earth-analog exoplanets. While it is clear that lesser energy, time, cost and technology are required for transportation to (and from) the Moon, it is of equal importance to note few major differences between Moon, Mars, and habitatable exoplanets i.e., Kepler-452b and Proxima- Centauri b (see Table 1). For example, one lunar day equals about twenty-seven days on Earth, while one sidereal day on Mars takes 24 h and 37 min [23]. Further, the gravity on Mars is double of that on the Moon, and Mars also has a better atmosphere which can provide better environment for shielding from space radiation. For brevity, the present paper does not address major differences between Moon, Mars, or exoplanets nor on discusses the alternative space bodies that are appropriate for human colonization, but rather directs interested readers to the following references [24–26].

2.1. Space environment

The outer space holds a multitude of environments and load actions that are primarily different than those on Earth such a high-energy charged particles, ultraviolet (UV) irradiation, meteoroids, orbital debris, etc. [30]. These actions can adversely affect behavior of construction materials and can also change fundamental aspects of loading and mechanics. In general, there are three main differences between Earth, Lunar and Martian environments. These differences pose critical challenges and are often grouped under 1) lack of atmosphere; 2) extreme radiation; and 3) differences in gravity.

For a start, the atmosphere of Earth is composed of a specific mixture of gases, primarily Oxygen (21%) and Nitrogen (78%), with very small amounts of Carbon Dioxide, Neon, etc. Unlike Earth, the Moon has a much smaller size (and correspondingly lower gravity) and technically does not have an atmosphere. On the other hand, the atmosphere of Mars is about 100 times thinner than the Earth, and mainly consists of Carbon Dioxide, Nitrogen and Argon [31]. This very thin atmosphere of the Moon and Mars forms a weak shield against meteorites and micrometeorites impact. Lindsey [32] noted that micrometeorites can reach a speed of 20–70 km/s. The impact effect of similar particles was studied by Toutanji et al. [33], wherein projectiles with a mass of 1.4×10^{-4} g were fired into representative specimens made of concrete at a speed of 5.9 km/s. The impact of such particles caused damages in the form of craters with 13 mm diameters. Such experiments, together with those carried out by Nealy et al. [34], demonstrate the devastating effects of meteorites impact, need for considerable protection measures from large–sized meteorites, and emphasize the use of durable and resilient construction materials.

The lack of atmosphere can cause other phenomena such as temperature fluctuations and low pressure. For example, temperature fluctuates on the Moon between −173 and 127 °C, while it remains particularly freezing on Mars at about −57 °C. The lack of atmosphere can also amplify adverse effects of vacuum. For a comparison, the hard vacuum of space has a magnitude ranging from 3×10^{-13} kPa on the Moon to 0.7 kPa on Mars (as compared to 101.3 kPa on Earth). Vacuum conditions can cause materials to outgas (releasing volatiles). Kanamori et al. [35] studied the long-term exposure of mortar to vacuum. Despite the fact that some vacuum-exposed mortar specimens achieved higher strength than

Table 1
Key differences between Earth, Moon, Mars, and other exoplanets [27–29].

Parameter	Earth	Moon	Mars	Kepler-452b	Proxima- Centauri b
Total Mass Compared to Earth (%)	–	1.2	10.7	190	80–110
Approximate Distance from Earth (km)	–	3.84×10^5	2.25×10^8	1.32×10^{16}	3.9×10^{13}
Day Period (hrs)	23.9	655.7	24.7	–	–
Revolution Period (days)	365.3	27.3	686.9	384.8	11.2
Average Surface Temperature (°C)	13	−30	−57	−8	−39
Atmospheric Pressure (kPa)	101.3	negligible	0.7	unknown	unknown

those cured with water, Kanamori et al. concluded that vacuum condition accelerated water loss.

On a different front, the main source of radiation in space arises from solar flares and galactic cosmic radiation, generally produced from distant supernova explosions [36]. Galactic cosmic radiation consists of rapidly moving heavy, positive ions with median velocity approaching 95% of the speed of light. Radiation can also occur due to electromagnetics (such as gamma rays) and other types of particulate radiation (i.e., high mass and energy and solar energetic particles).

2.2. Loading and mechanics

Another major difference between the Earth and other space bodies (Moon and Mars) is the type of actions (loadings) present on each body. On Earth, the primordial loads are gravitational and environmental live loads (such as wind, earthquakes, etc.), while on the Moon (and Mars to some extent), wind loads can be neglected due to the weak/thin atmosphere. With a magnitude of less than 2 on Richter scale, majority of Moon- and Martian-quakes produce insignificant energy and can be neglected [37].

In two separate studies, Clarke [38] and Benaroya et al. [2] suggested that expected design loads can be scaled to the corresponding gravity of Moon and Mars. For example, Benaroya et al. [2] suggested that a lunar structure can approximately has at least six times the weight-bearing capacity to that on Earth. Similarly, Clarke [38] demonstrated an insight into the structural mechanics of large (182 m diameter) radio telescopes intended for construction in West Virginia in the US. This researcher estimated that the mass of this structure (36,000 tons) could be reduced by 90% if designed on the lunar surface due to low gravity and lack of weather loads.

Chua et al. [39] and Benaroya et al. [2] also examined aspects of foundation design and noted that it is due to the wide range in lunar temperatures (which implies thermal cycling i.e., expansion and contraction of regolith), that foundations need to be placed below the depth of thermal cycling in order to appropriately control settlement. It should be noted that the load-bearing capacity of a typical soil is governed by its confining stress. For example, if the soil surrounding is heavier, due to higher gravity, then this confining stress would be larger enabling the soil to support higher load levels before collapsing. Hence, in low gravity conditions, a foundation can theoretically support higher levels of load. Thus, failure in space footing (or rigid structures in that matter) could solely occur due to excessive settlement rather than collapse as a result of exceeding load capacity.

3. Space resources

When considering exploring nearby moons and planets, the first habitations will certainly be those sent from Earth. Even though transportation costs could be reduced due to emerging technologies, these costs would probably remain considerably high for large habitations and most of all transportation process would be risky for frequent space travel. Throughout the years, number of concepts have been raised with the common purpose of reducing cost of space imports. These concepts highlighted the need for 1) direct use of in-situ raw materials, and 2) finding effective processing and treatment means for extracting elements and minerals in-situ materials to produce construction materials [40]. In this section, feasibility of exploiting available space resources and harvesting of elements and compounds is discussed.

3.1. In-situ resource utilization

Over the last few decades, there has been a number of successful exploration missions to the surfaces and sub-surfaces of the Moon and Mars. These missions were carried out using remote sensing techniques and through analyzing samples collected by NASA. The success of early space missions allowed proper assessment of Lunar and Martian in-situ resources and led to the inception of in-situ resource utilization. In-situ resource utilization (ISRU) is defined as an operation that harnesses 'in-situ' raw resources to produce products (or create services) that allow robotic and human exploration [41].

NASA reported that over 380 kg of soil samples and rocks were collected from previous Apollo and Luna missions. Analysis on NASA collected samples showed that lunar soil and rocks consisted of substantial amounts of alumina, calcium oxide and silicate; which makes the production of terrestrial cementitious materials possible [42–44]. Although soil samples have not been brought back from Mars yet, remote sensing carried out using Viking and Mariner-9 orbiters has confirmed availability of similar elements to those found on the Moon [45]. Comparisons of chemical contents between lunar basalt, Martian soil, Martian lava, and cement are shown in Table 2. As it can be seen in the table, all samples have high amounts of SiO_2, as well as FeO, ranging from approximately 37-45% and 11–21%, respectively, of the total sample weight.

Heiken [50] was one of the researchers that analyzed samples collected by NASA and reported that lunar regolith has an average grain size ranging from 0.04 to 0.27 mm. Similarly, Cesaretti et al. [51] reported gradation data for a lunar soil sample and showed that more than 50% of sample weight is consisted of well-graded grain-sizes less than 0.075 mm in diameter. Moreover, Happel [52] reported mechanical properties of Moon materials, such as cast regolith and lunar glass, showed to possess significant compressive and tensile strengths reaching approximately 538 and 34.5 MPa, respectively, which could be beneficial in various construction applications. Properties of these lunar materials are listed in Table 3.

Identification of space resources, and development of processing methods to fully utilize such resources, not only could reduce dependence on Earth, but could also aid in founding a financially sustainable exploration programs. It should be noted that several studies investigated various aspects of ISRU such as developing components, systems, and technologies to excavate (drill) into surface, process, transport, and store minerals and elements, etc. [42,53,54].

3.2. Harvesting elements, minerals, and materials during space travel

In lieu of in-situ resource utilization, harvesting of elements and compounds from nearby asteroids, moons and planets could also lead to earth-independency, as well as sustainable and economic development of space habitats. The concept of exploiting natural resources of smaller space bodies (particularly asteroids) has surfaced in 1903 and then re-emerged as a result of recent technological advancements that enables identifying possible mineral-rich asteroids and ability to successfully trace, capture, and transport such asteroids for harvesting purposes [21,55].

Table 2
Chemical content of lunar and Martian Samples (by percentage of total weight).

Constituent	Lunar Basalt[a]	Lunar Basalt[b]	Martian Sample[c]	Martian Lava[d]	Cement[e]
SiO_2	45.03	37.79	44.7	44.48	20.13
Al_2O_3	7.27	8.85	5.7	11.25	5.98
FeO	21.09	19.66	–	11.38	–
Fe_2O_3	–	–	18.2	3	2.35
MgO	16.45	8.44	8.3	17.32	1.19
CaO	8.01	10.74	5.6	9.54	64.01
K_2O	0.06	0.05	<0.3	0.4	0.77
TiO_2	2.54	12.97	0.9	–	0.37
SO_3	–	–	7.7	–	–
Cl	–	–	0.7	–	–

[a] Apollo 12 and.
[b] Apollo 17 (Greeley and Spudis [46]).
[c] Chryse Planitia (Toulmin et al. [47]).
[d] Calculated composition (McGetchin and Smyth [48]).
[e] From Khitab et al. [49].

Table 3
Properties of lunar construction materials [52].

Property	Cast Regolith	Lunar Glass Bars
Compressive Strength (MPa)	538	–
Tensile Strength (MPa)	34.5	–
Density (g/cm^3)	3	–
Modulus of Elasticity (GPa)	100	450
Thermal Exp. Coefficient	8×10^{-6}	–
Bending Strength (MPa)	–	100–125

In this promising concept, minerals can be mined from an asteroid or a moon near Earth or Mars (such as Phobos and Deimos) using spacecrafts and robots. Once minerals are mined, they can then be processed on the parent asteroid or, depending on distance from Earth, can be transported back to Earth. In a more convenient way, space shuttles can have a pre-defined flight route at which they can mine and harvest several asteroids/comets while on-route to final destination. Mined minerals can then be processed on space shuttles while being transported to their final destination.

In a futuristic version of this concept and similar to capturing space debris, small to medium-sized comets and asteroids can be robotically captured, and transported to a safe orbital zone around the Earth, Moon, Mars, or even to a large space "mining" workstation [56,57]. Brophy et al. [58] projected that a comet with 7 m in diameter and estimated mass between 250,000 and 1,000,000 kg can be harvested for valuable minerals and elements in the near future. Once a comet is identified and captured, minerals and materials can be harvested in variety of means. For example, materials can be scraped or grabbed using robotic tools and limps. In some cases, minerals could be mined using onsite "stationary" or attached to "non-stationary" shafts, where space bodies with high metal and loose contents could be collected via suction tubes or large magnets. Extraction of hydrated minerals and those rich in nickel and iron could be possible by means of heating and mounding, respectively. The use of additional geo-physio-chemical techniques could also be applied to collect and separate compounds and elements [59].

A potential material that can be harvested during space travel is spider silk. Protein fiber spun by spiders has superior mechanical properties, such as high strength-to-weight ratio (about five times that of steel fibers), resilience, and durability compared to other metallic and non-metallic materials [60]. With a tensile strength reaching 1 GPa, spider silk can be utilized in various structural components [61]. For example, spider silk products can be integrated as flexural and tensile reinforcement of concrete structural members, connections in metallic structures, and/or in developing advanced composites.

Hardy and Scheibel [62] have pointed out number of challenges associated with harvesting spider silk in large quantities and proposed the development of spider silk-like proteins biotechnologically. Although such technique accelerates production process for spider silk-like materials, it would still require sophisticated facilities. Thus, a practical method could be to harvest natural spider silk inside small-size moon-habitats, or inside spacecraft during lengthy travelling period. Such "harvesting-farms" can be effective in producing required silk in sufficient amounts for civil construction, if processed properly. An alternative in-space production of reinforcing-silk materials can be obtained from silkworms, which has less strength compared to that of spider silk, but still sufficient for several structural applications [61].

4. Properties of space construction materials

A noteworthy amount of research related to in-situ resource utilization and development of space-native construction materials has been carried out in the past forty years [10,14,33,52,53,63–65]. This section highlights properties of various construction materials suitable for space construction such as concrete, metals, alloys, composites, and advanced materials etc.

4.1. Concrete derivates

Concrete, due to its inherent resiliency and durable characteristics, is regarded as the material with the highest potential for use in space construction [66–69]. The suitability of concrete material, together with various concrete derivates, was examined throughout the past years. For example, Cullingford and Keller [68] discussed the viability of using ordinary concrete for lunar construction. Results from their experimental work indicated that properly designed concrete could be stable in vacuum conditions. In a parallel study, Swint and Schmidt [69] proposed design equations to optimize the mixture design of lunar concrete based on 80 different mixture combinations. Lin et al. [67] investigated the effect of lunar temperatures on precast lunar panels during construction, and also concluded that concrete is a suitable construction material under lunar environment.

In a notable study, NASA awarded 40 g of lunar soil to Lin et al. [10] to evaluate its performance, physical properties, and feasibility for use as aggregates in concrete. In the same study, small concrete cubes and slabs were made of aluminum cement, water, and lunar soil, and then tested under compression loading. Test results showed that it was possible to develop a concrete material with a compressive strength of about 75.7 MPa. Despite encouraging findings of aforementioned studies, a key limitation that continues to arise and hinders the use of concrete in space structures is the need for water, and hydration process, required to cure concrete. When chemically reacts with cement, water creates a binding product, i.e. cement paste that fills the space between fines and coarse aggregates. Thus, availability of water is vital to produce and cure concrete, and if water is not accessible, it must then be imported from Earth or produced on Moon or Mars.

Fortunately, recent exploration missions have eluded to the availability of water reservoirs on both the Moon and Mars [53,70]. However, the same studies also raised concerns regarding accessibility and quality of such water reservoirs. It is worth noting that water can be produced on Moon or Mars through lunar oxygen facilities that carry out ^{3}He mining operations. While few concepts on such facilities have been proposed, ^{3}He mining might not be realized for number of decades [71].

Thus, in order to produce non-hydraulic (i.e., waterless) concrete, other alternatives such as use of resins, epoxies, polymer matrices, or in-situ elements were recently investigated [63,65,72,73]. For example, Khitab [63] and Kumar [72] noted that epoxies can be successfully used as binders in concrete (rather than cement paste). The compressive strength of epoxy concrete can vary from 17 to 60 MPa depending on the amount and type of epoxy resin. In a separate study, Lee et al. [73] developed a mixture consisted of 10% polymer and 90% lunar simulant soil, and used it to produce polymeric concrete. In order to bind the polymer matrix with lunar soil, the developed mixture was exposed to a temperature of 230 °C. The compressive strength of this polymeric concrete reached 12.75 MPa (on average) within 5 h, and when fully cured, can be strong enough to construct infrastructure and landing pads on the Moon.

Another type of concrete derivative is that developed using geopolymers. Geopolymers are materials produced through reaction between an aluminosilicate precursor and alkaline solution [74]. Depending on the silicon to aluminum ratio in the concrete mix, different polymeric structures can be produced. In one study, Tucker et al. [75] showed how melting lunar regolith simulant at high temperature (~1600 °C), could be used in reinforcing concrete elements. According to Montes et al. [76], geopolymer binders can also be produced from regolith and such binders can reach a compressive strength ranging from 16.6 to 33.1 MPa, which makes the use of geopolymer concrete adequate for constructing infrastructures on the Moon and Mars. The same study also concluded that geopolymer concrete can provide sufficient radiation protection for a lengthy manned lunar missions. Lee et al. [73] presented results of solidification testing of preheated lunar concrete made of an artificial lunar soil bounded with thermoplastic polymer, and showed that the porosity of the solidified concrete is equivalent to that of an ordinary Portland concrete with a compressive strength of about 35 MPa. Conversely, Davis et al. [9] reported results of curing and testing of small cubes, made from lunar regolith based geopolymer cement, in a resembled lunar environment. Unfortunately, the outcome of these tests did not meet the minimum compressive strength (25–30 MPa) standards for concrete structures specified by the US Marine Corp.

An alternative to traditional "hydrulic" concrete, is the use of sulfur concrete (which does not require addition of water). The recent discovery of high concentration of mineral troilite (FeS) on the surface of Moon (and Mars) present an option to extract sulfur for use as a non-hydraulic concrete-derivate construction material [65]. The fundamental idea is to heat and melt sulfur at about 120–150 °C so that it becomes liquid. Then, melted sulfur is mixed with Lunar or Martian soil. Once this mixture is cooled down, the sulfur solidifies and creates sulfur concrete. A typical sulfur concrete comprises of 10–20% sulfur, 80–90% aggregate, and about 5% of plasticizers added to mitigate cracking of cooled sulfur. Sulfur concrete does not require hydration and gains strength in a short time as compared to hydraulic concrete [77].

Few studies investigated the viability of sulfur concrete as a construction material for space applications. One of these studies was carried out by Wan et al. [64], who reported mechanical properties of an equivalent Martian concrete under various loading conditions (see Table 4). As shown in this table, the compressive strength of lunar concrete samples ranges from 39 to 75.7 MPa and from 20 to 63 MPa for sulfur concrete. These values are comparable to concrete strengths used for structural design on Earth, and thus, suitable for building applications on the Moon [52,64].

Effects of freezing and thawing on the compressive strength of sulfur concrete have been investigated by Toutanji and Grugel [7]. They showed that thermal cycling can adversely affected the strength of sulfur concrete by about 20%. This study also reported that beams made of sulfur concrete but strengthened with regolith derived from glass fibers had up to 40% increase in flexural strength. Similarly, Grugel [78] investigated the integrity of sulfur concrete through testing small concrete cubes subjected to temperatures analogs to that of the Moon surface. Microscopic examination of the tested cubes displayed clear de-bonding between hardened sulfur and aggregate. This is due to the fact that sulfur shrinks when it cools down and solidifies, and this shrinkage develops cavities within hardened concrete, which as a result, severely weaken the microstructure of concrete material.

Khitab et al. [13] discussed other challenges associated with the use of sulfur concrete as a construction material on the Moon. For example, use of high levels of sulfur may lead to relatively poor durability in response to repeated thermal cycles, flammability, and heat susceptibility of sulfur concrete. Grugel and Toutanji [77] examined two types of sulfur concretes that were prepared and kept in vacuum for a period of two months. Outcome of their work showed that vacuum condition induced continuous mass loss due to the sublimation of sulfur. Osio-Norgaard and Ferraro [79] evaluated the permeability of sulfur-based concrete for lunar construction, and determined that it is more permeable than the ordinary Portland concrete. This higher permeability resulted due to absorption of melted sulfur by regolith during fabrication, which created specimens with large voids.

Table 4
Properties of lunar and Martian concert [65].

Property	Lunar Concrete	Martian Concrete
Compressive Strength (MPa)	39–75.7	20–63
Tensile Strength (MPa)	8.3	2.7–3.6
Density (kg/m^3)	2600	–
Modulus of Elasticity (GPa)	21.4	6.5–10
Thermal Exp. Coefficient	5.4×10^{-6}	–
Bending Strength (MPa)	–	1.65

4.2. Metals and alloys

While metals are not readily available on the surface of the Moon or Mars, a number of elements do exist, which could be mined and then used to produce metals and/or alloys. This observation is based on the work of Binder [80], Happel [52], and Fairen et al. [81] who analyzed samples of lunar regolith, as well as imagery from Martian surface. In their studies, these researchers indicated that aluminum (Al), magnesium (Mg), iron (Fe), and titanium (Ti) are commonly available among other elements including zirconium (Zr), chromium (Cr), vanadium (V), and manganese (Mn). A summary of mechanical properties of some of these elements, together with their fraction of existence, is listed in Table 5.

As can be seen in Table 5, both aluminum (Al) and magnesium (Mg) are attractive elements for space applications due to their relatively low density, reasonable mechanical properties, and low melting point (which can ease processing requirement of these elements). An advantage of using aluminum in space construction is that it can be thermally liquefied to bind lunar (or Martian) soil and form waterless-aluminum concrete [84]. It should be noted that aluminum can be found in the form of aluminum oxide (Al_2O_3) in significant amounts (approximately 15%) in lunar highland soils [85].

Magnesium also has physical characteristics that makes it suitable for various space construction, especially for electromagnetic shielding purposes. Besides its effectiveness in radiation shielding [86], magnesium has thirty times vibration damping effect of that of aluminum, a trait that makes magnesium more effective material for external shielding of lunar habitats against meteorite impacts [87]. According to McCallum et al. [88], large proportions of magnesium have been observed on the Moon in the form of olivine, i.e. magnesium iron silicate (Mg, Fe_2SiO_4), containing 32% of magnesium oxide (MgO).

Due to the availability of aluminum and magnesium on lunar surface, number of studies have investigated the use of these minerals for construction of space bases. For instance, Belvin et al. [89] reported that the Apollo space program used aluminum into development of a rigid unit that could be deployed as a space module. Mottaghi and Benaroya [90] investigated the response of an igloo-shaped space base entirely made of magnesium and covered with lunar regolith. The same researchers also investigated the structural performance of this base under simulated thermal and seismic loading similar to that to occur on the Moon and reported adequate behavior under such conditions.

Iron (Fe) is another element suitable for use in early development on the Moon and Mars due to the following main reasons: 1) its mechanical properties and usage in steel-based terrestrial construction is well known [91,92]; and 2) it can be produced by consuming a lesser amount of energy compared to other metals (e.g., according to Zhuk et al. [93], Aluminum production requires six times more energy than producing steel). Compared to iron, titanium (Ti) has significantly higher mechanical properties, but it is only available in very small quantities, mainly in mare basalts in the form of ilmenite ($FeTiO_3$) and can be extracted by electro-chemical processes [94]. It should be noted that titanium may not be appropriate for use in interior structural systems/components because it tends to readily react with oxygen.

The availability of the aforementioned minerals (listed in Table 5) has

Table 5
Properties of lunar and Martian derived elements.

Element	Tensile strength (MPa)[a]	Specific Gravity[a]	Young's Modulus (GPa)[a]	Melting Point (°C)[b]	Elongation[b]	wt. (%)[c]
Al	170	2.7	70	660	45	7.5
Mg	200	1.7	45	650	5	6.5
Fe	280	7.9	196	1535	45	4.5
Ti	2300	4.6	119	3287	18	1.5

[a] Blacic [82].
[b] Wataria [83].
[c] Binder [80].

led to investigating number of alloys for use in structural components and systems [95–97]. For instance, Yin [95] proposed the use of aluminum lithium (Al-Li/8090-T8771) and magnesium (ZCM711) alloys in a horizontal habitat with a cylindrical shape. Unlike magnesium alloy which loses its ductility at low temperature, aluminum lithium alloy has superior resistance to embrittlement (loss of ductility) at low temperature. Due to the nature of these alloys, Yin [95] urged that magnesium alloy is not fit for resisting tensile forces, and to be only used to support the cylindrical habitat under compression loading (i.e. foundation mat), while aluminum lithium alloy is used for the interior floor trusses framing as well as guy cables (i.e., wire ropes). Gionet [96] proposed a frame-membrane system made of 2014-T6 Aluminum, examined its performance under impact and thermal loads, and implied that such structure can successfully withstand lunar environment.

Titanium alloys are often used where aluminum alloys do not meet strength, corrosion resistance, and elevated temperature requirement. For example, titanium alloy (Ti6Al4V) can replace aluminum alloys due to its higher strength, and stiffness, as well as low thermal expansion [98]. Other types of alloys could also be used in construction of space habitats. For instance, Szilard [99] proposed the use of Beryllium alloys in design of prefabricated sphere supported lunar habitat. The properties of these aluminum, magnesium, titanium alloys, and beryllium alloys are listed in Table 6.

4.3. Advanced materials

Due to the harsh conditions of vacuum, conventional construction materials (such as steel) may not satisfy strength, serviceability, and safety requirements when used in structural members in space habitats nor be readily available (i.e. concrete). To overcome limitations related to conventional construction materials, researchers started investigating the use of advanced materials specifically designed for use in space construction [102–104]. While most of these advanced materials can be classified as composites (or polymer/polyimide derivates), others include those with memory shape effect, lab "cultured" materials, as well as self-sensing/self-healing materials. This section highlights main characteristics and properties of these materials and a summary of mechanical and thermal properties of some of these materials is shown in Table 7.

Composites were developed as a result of advancements in tailoring metallic and non-metallic materials which yielded improved characteristics such as high strength-to-weight ratio, dimensional stability, reduced tendency to outgassing, low thermal expansion, and near-zero thermal conductivity [102]. Due to their superior properties and improved characteristics, composite materials might have better performance when compared to conventional construction materials, especially under extreme conditions [104,109–111]. While some of these materials were originally designed for use in space shuttle components, their use could also be extended to structural (building) applications. The newly developed advanced composite materials are often grouped under, 1) organic matrix, 2) metal matrix, 3) ceramic matrix, 4) carbon fiber reinforced carbon (C/C) composites, and 5) polyimides [103,112,113].

Organic matrix composites, such as graphite/epoxy (Gr/E), can be integrated into structural truss elements, and cable support structures often used in construction of inflatable and truss-based habitats. The use of organic matrix composites in such components was experimentally investigated by Milkovich [114] and Adams et al. [115]. These studies highlighted the merit of using organic matrix composites in space applications but also demonstrated that the microstructure of these composites seems to be vulnerable to cracking under continuous exposure to thermal cycling and radiation in space environment.

Williamson [102] reviewed number of metal matrix composites and pointed out their inherent resistant to most of the harsh space condition. In his review, Williamson demonstrated how metal matrix composites could be designed to serve multi-functions components with structural, electrical, and thermal-control functions. Williamson [102] also reviewed the performance of silicon carbide particulate/whisker reinforced aluminum (SiC/AI) as well as graphite reinforced aluminum (Gr/AI) and pointed out that while the later has superior mechanical and thermal properties, SiC/AI composites offers comparable features at much lower cost. In another study, Bowles and Tenney [116] reported successful fabrication of truss elements that are 50 mm in diameter and 1800 mm long made from metal matrix composites. These truss elements were then used to build a 3-bay space truss system prototype that is 3 m long. Unfortunately, the integration of metal matrix composites into space structural applications is limited by their associated high costs of raw materials, fabrication, and inconclusive performance under long-term extreme conditions [117].

Ceramic matrix composites, on the other hand, are non-brittle refractory materials designed to withstand severe thermo-mechanical-corrosion conditions. These composites possess very high strength properties due to the use of small ceramic fiber reinforcement (with a diameter in the order of 10^{-6} m). Similar to ceramic matrix, carbon fiber reinforced carbon (C/C) composite is also a composite material that comprise of carbon fiber reinforcement embedded in a matrix of graphite. Both ceramic matrix composite as well as carbon fiber reinforced carbon (C/C) composite materials have been primarily developed for use in design and construction of space vehicles and satellites [118]. Despite their promising features, there is still limited research on both ceramic matrix and C/C composites in use of space habitats particularly for their scalability, damage tolerance, and reproducibility [119,120]. In general, the resiliency and multi-uniformity of the fiber reinforcement, C/C composite materials can be tailored for design of cladding systems for habitats, internal and/or external load bearing structural systems, as well as strengthening of locally damaged components (i.e. broken shields from micrometeoroids impact).

Number of studies undertook experimental tests to better understand the behavior of aforementioned composite materials under simulated conditions to that in space environment. In a notable study, Rawal et al. [104] carried out an extensive examination of number of laminate specimens made of carbon/thermoplastics (C/TP), carbon fiber reinforced carbon (C/C), carbon/glass (C/GI), graphite/aluminum (Gr/AI), and discontinuous (SiC/Al) have demonstrated that while these composites can undergo cracking after exposure to10,000 thermal cycles ranging between −100 °C and 65 °C, they could still maintain 92-75% of

Table 6
Properties of various metal alloys.

Property	2014-T6 Aluminum[a]	Aluminum Lithium 8090-T8771[b]	Magnesium ZCM711[b]	Titanium Alloy (Ti6Al4V)[c]	Beryllium Alloys[d]
Ultimate Strength (MPa)	–	441.28	275	900–950	290–324
Yield Strength (MPa)	410	344.75	185	800–920	207–241
Elongation (%)	–	0.5–2.0	12	5–18	2–3
Modulus of Elasticity (GPa)	72.5	80.67	45	104–113	–
Density (kg/m[c])	2800	2519	1795	4420	–
Thermal Exp. Coefficient	–	23×10^{-6}	27×10^{-6}	9.2×10^{-6}	–

[a] Gionet [96].
[b] Yin [95].
[c] Chu and Lu [100].
[d] Materion [101].

Table 7
Mechanical and Thermal Properties of advanced material suitable for space construction applications.

Material Property	Gr/E (P75/1962)[1]	Gr/TP (P75/PEEK)[2]	SiC/Al (SiCp/2124 Al)[3]	Gr/Al (P100/6061 Al)[4]	Gr/Mg (P100/AZ91C Mg)[4]	C/Gl (HMU/7070)[5]	C/C (P100/C)[6]	LaRC-SI[7]	LaRC-PETI-5[7]	Shape Memory Alloy (Nitinol)[8]	Shape Memory Polymer[9, 10]
Density (g.cm^3)	1.73	1.74	2.88	2.49	1.89	1.97	1.66	1.37	–	6–8	0.9–1.2
Ply Thickness (mm)	0.12	0.13	1.52	0.55	0.32	1.32	0.43	–	–	–	3
Tensile Strength$^{(x)}$ (MPa)	307.5	240.7	582.6	905.3	422.0	282.0	304.1	141	59.4	754–960	6–20
Tensile Strength$^{(y)}$ (MPa)	345.4	297.9	534.3	25.0	25.4	–	199.9	–	–	–	–
Comp. Strength$^{(x)}$ (MPa)	182.7	147.2	557.1	321.4	200.6	597.8	47.9	–	–	–	–
Comp. Strength$^{(y)}$ (MPa)	190.3	191.3	522.6	104.9	–	540.5	64.8	–	–	–	–
Tensile Strain$^{(x)}$	0.261	0.263	1.26	0.262	0.21	0.405	0.17	–	–	15.5	–
Tensile Strain$^{(y)}$	0.301	0.286	1.18	0.0707	–	–	0.15	–	–	–	–
Young's Modulus$^{(x)}$ (GPa)	104.8	91.7	114.7	342.8	175.4	80.7	223.4	4.00	3.82	75	1.0
Young's Modulus$^{(y)}$ (GPa)	104.8	96.5	117.2	35.4	28.3	–	140.0	–	–	–	–
Specific Heat (J/kg-K)	808.1	849.9	830.7	812.2	916.9	753.6	707.6	–	–	–	–
Thermal Conductivity$^{(x)}$ (W/m-K)	43.6	46.3	119.2	317.3	–	17.2	141.9	–	–	100	–
Thermal Conductivity$^{(y)}$ (W/m-K)	43.6	48.6	116.6	69.2	–	17.2	67.5	–	–	–	–
Toughness (kJ/m^3)	–	–	–	–	–	–	–	–	106	–	–
Extent of deformation (%)	–	–	–	–	–	–	–	–	–	<8	up to 800

[x]longitudinal direction; [y]transverse direction.
[1]continuously reinforced graphite/epoxy; [2]graphite/thermoplastic; [3]discontinuously reinforced aluminum-matrix composite; [4]unidirectional metal-matrix composites; [5]carbon/glass; [6]carbon/carbon, [7]Armanios and Reeder [105], [8]TiNi Alloy Company [106], [9]Gross [107], [10]Liu et al. [108].

their initial strength. It should be noted that Rawal and Misra [121] carried out similar tests on other composite materials such as Graphite/Thermoplastic (Im7/Peek) as well as discontinuous SiC/2124 A1 composites and results on these tests and noted that the effect of thermal cycling was more pronounced on the strength as compared to the stiffness properties. Rawal and Misra [121] noted that there lack of standardized test methods and procedures which continue to hinder integration of advanced composites into structural application for space exploration.

Other types of advanced materials include those developed at the Langley Research Center (LaRC) such as LaRC SI, LaRC TEEK, LaRC RP-50 Polyimides, LaRC PETI-5, among others [122]. These are engineered materials and comprise of high temperature-high performance polyimides. LaRC materials, with high glass transition temperature, possess superior thermal stability at ambient and inert atmosphere conditions. Table 7 lists properties of LaRC SI and LaRC PETI-5. It should be noted that little to no information currently exsits on the behavior of these materials as structural components.

Materials that can dynamically respond to external stimulus and have the ability to recover mechanically induced strains once heated or subjected to electric (or magnetic) field by virtue of a martensitic phase transformation are often referred to as shape memory materials [123]. These materials can be grouped under shape memory-alloys (SMA), ceramics (SMC), or polymers (SMP). In general, shape memory materials can return to their original shape when stimulated, i.e. heated above its transformation temperature, as this stimulation changes its crystal structure and causes it to return to its original shape. This phenomenon provides shape memory materials with a unique feature that allows self-deployment of mechanisms [124,125].

Schetky [125] reported that NASA has developed SMAs to facilitate joining of composite tube structural members. In these trails, the memory shape effect was triggered through heat generated from electric current. Kalra et al. [126] showed feasibility of integrating SMAs into intelligent and adaptive space structural framing for communication facilities. When compared to SMAs, shape memory polymers have a very low tensile strength, in the range of 2–5% of SMAs, but can still be used as low mass, and cheap self-deployable structures for space construction. In one study, Liang et al. [127] successfully managed to employ reinforcing fibres in order to enhance strength and stiffness properties of SMPs as to allow their use as load bearing structural components. In a more recent study, Darooka et al. [128] developed an inflatable truss frame fabricated using SMP with comparable performance to that terrestrial trusses. Lai et al. [129] and Reyes-Morel et al. [130] explained that the implementation of shape memory ceramics (as well as intermetallics) is still hindered by the fact that although ceramics exhibit a martensitic transformation, these materials still fail by cracking at low levels of strain (of about ~2%).

An alternative concept that can be used to significantly reduce transportation cost and maximize use of construction materials is the development of innovative and emerging technologies to grow raw crystals or construction materials. In this concept, small pieces of bio-like materials could be lunched to space. These materials will be in an "inactive" state during space travel, and once arrived at their destination would start to grow into pre-engineered structures (habitats). This is a futuristic concept that could revolutionize space travel and exploration [131].

Graphene shows promise is produced in mass, affordable quantities. Graphene, when supplemented with Piezoelectric substances, has self-healing properties that can detect physical damage in structural systems, shields, etc. [132]. Richter et al. [133] proposed the use of geosynthetics materials (polymeric products) as soil reinforcement to stabilize lunar or Martian soil for foundation support. The same study also noted that advancements in geosynthetics are needed to properly address degradation of plastics under vacuum and radiation environment.

While the discussion presented in this section shows the premise of various materials for use in construction of space habitats, one should note that the integration of such materials is an involved and hectic process. According to Gaddis [134], integrating new materials into space application typically requires up to 20 years of tests and experimentations which could cost over \$400M to accumulate enough data documenting material behavior under extreme space conditions. Gaddis [134] highlighted that integration of construction materials does not imply selecting those with superior mechanical, thermal, shielding, etc. properties but such materials need also to be readily available, affordable, scalable, durable, and resilient.

5. Processing of space construction materials

Interest in materials processing in space began to evolve in the late 1950s with the primary motivation being the scientific and commercial utilization of the effects of space environments to develop materials that allow design and construction of spacecrafts [135]. This turned out to be a challenging research problem due to the unique space environment and absence of gravitational effects. This section highlights main processing methods associated with space construction materials and a more complete review on various other methods, together with, history of space processing of materials in space can be found elsewhere [135–137].

5.1. Solar and laser sintering

Heating a porous material, often in the form of powder, up to a temperature below its melting point is referred to as sintering [138,139]. Using sunlight (or laser) as a source of energy and lunar (or Marian regolith) as raw materials, sintering can be employed for constructing objects and even structures in dry settings. In this process, energy rays are directed and focused through lens/mirrors onto a small volume of bedded granular material which is then heated to its melting point. The grains are then embedded onto the surface either by crystallization of the whole melted grain or by using micro melt grain welding. This enables the particles of the porous material to bond together to form a solid with a reduced volume of porosity [139].

Number of studies have investigated the feasibility of solar and laser sintering for processing of space construction materials. For example, Meurisse et al. [140] investigated the prospective of manufacturing lunar brick using solar energy. In a similar process, lunar bricks of dimensions of $200 \times 100 \times 30$ mm can be fabricated, in 5 h, through 0.1 mm successive layers of moondust at 1000 °C. Other researchers investigated the potential of using concentrated solar energy to produce lunar glass composite structures [141]. Krishna Balla et al. [142] showed that low-energy laser sintering, of about 2.12 J/mm^2, can be used to fabricate nanocrystalline and/or amorphous microstructures from lunar regolith. Such materials would be suitable for use in load bearing structures, and assemblies for radiation shielding.

Solar sintering can be considered as a dominant technology on the Moon. This is due to the fact that lack of atmosphere allows higher degree of sunlight to reach the Moon (and Mars) surface. Still, solar sintering has few limitations such as: 1) specific arrangement of large number of mirrors and lens is needed to enable development of high source of energy, 2) solar sintering equipment requires continuous maintenance to clean mirrors and lenses, 3) need for proper shielding of mirrors and lens from meteorites impact.

Laser sintering also suffers from number of limitations including, 1) a small portion of material can be thermally treated at a time, 2) this process could induce thermal transient stresses as well as residual stresses due to the development of high thermal gradients when processing materials, and 3) laser absorption is directly proportional to electrical resistivity of materials, and since regolith is a poor conductor, regolith can retain large amount of laser energy before starting to sinter.

5.2. Microwave sintering

In lieu of solar and laser sintering, volumetric heating by absorbing and coupling a microwave field, is another method of sintering and is commonly referred to as microwave sintering [143]. In microwave sintering, electromagnetic energy is converted into thermal energy through using ultra-high frequency microwaves (2.45 GHz) and/or extra-high frequency microwaves (in the range of 100 and 500 GHz). It should be stressed that microwave sintering may better suit processing of ceramics and semi-metals like nitrides and carbides, but can also be applied to powdered metals [144]. When compared to solar sintering, Hintze and Quintana [145] showed that microwave sintering could penetrate up to 13.4 mm lunar simulant materials, as oppose to 6 mm of the same material as reported by Allan et al. [146].

Meek et al. [147] demonstrated how ultra-high frequency microwaving can be utilized to produce terrestrial brick-like materials using basalt and an ilmenite-rich rock. They also illustrated how microwave sintering can be used in fabrication of large constructions/facilities such as pavement network, etc. In a separate study, Meek et al. [148] used microwave sintering to heat three different lunar simulants similar to that collected in three Apollo missions (11, 15, and 16) to a variety of temperatures. The measured compressive strength and hardness of processed materials varied between 0.84 and 20.9 MPa and 96–705 kg/mm^3, respectively. Allen et al. [149] proposed design for a microwave furnace capable of producing lunar bricks. In a later study, Allen [150] was able to produce uniform bricks measuring $7.9 \times 5.5 \times 3.6$ by heating two lunar simulants between 0.5 and 3 h at temperatures between 1000 and 1250 °C.

The benefits of microwave processing comprise of, 1) cost-effectiveness (in terms of both time and energy resources), and 2) improved properties and quality control of processed material. One of the main challenges associated with microwave sintering is the fact that although applying microwave energy through low frequencies may better penetrate materials, when compared to applying high frequency microwaves, the applied energy is often weakly absorbed due to the insulating-like properties of regolith. It is then expected that regolith would not adequately sinter without the use of considerable energy, especially at low temperatures [151]. Other challenges include efficiently (and equally) transferring microwave energy to processed material.

5.3. Other processing methods/techniques

While the aforementioned sintering-based processing methods seem promising, the open literature includes number of concepts that enable processing of various in-situ or harvested materials that could be used for construction of space habitats and facilities. Some of these processing techniques were specifically developed to enable production of space-native concrete and metals. For example, the possibility of producing lunar concrete using Dry-Mix/Steam-Injection (DMSI) procedure was investigated by Lin et al. [152]. In this procedure, once dry cement particles get exposed to high temperature steam, not only heat transfers from water steam to cement, but portion of this steam is forced (injected) into cement particles via micropores. At the same time hot water steam partially condenses to form a wet coating on the surface of cement particles. Energy accumulated from both activation and condensation effects enhances hydration process. These researchers demonstrated how integration of solar energy to power DMSI can produce 50 mm thick concrete cubes with a high compressive strength of 69 MPa.

Wilhelm and Curbach [153] investigated the use of an Enhanced Dry-Mix/Steam-Injected (E-DMSI) method to produce lunar concrete. Their study concluded that the proposed method is successful in producing concrete with an equal compressive strength, and in a shorter hardening time, as compared to traditional concrete. The use of rapid setting cement as a binder to reduce moisture loss under vacuum conditions was studied by Hatanaka and Ishida [154]. Outcome of their experiments showed that due to the rapid setting time of the proposed mix, this concrete achieves high compressive strength and be casted without sealed formwork. In the area of processing metals and alloys, Carswell et al. [155] designed two unique material processing furnaces that can operate under microgravity conditions. These furnaced are referred to as Quench Module Insert (QMI) and Diffusion Module Insert (DMI). These furnaces are capable of reaching temperatures between 400 and 1600 °C and have operational life of 8000 h. The QMI will be used to perform directional solidification of metallic and alloys by imposing extremely high thermal gradients, while the DMI can be used for crystal growing experiments in metals and semiconductors. Other processing methods have been summarized in Table 8 and a detailed review on these methods can be found elsewhere [156,157].

6. Design and construction considerations for space structures

Analysis and design principles for gravity loadings as well as for dynamic loadings (i.e. wind and seismic effects) on Earth have been properly investigated and documented over the last few decades. Various building codes and standards have been also commissioned to ensure the safety and serviceability of structures under Earth-like conditions and these codes are constantly being updated to include the latest advancement with regard to material properties, design philosophies, observations from failure etc. [158]. In fact, design (and analysis) of typical structures have become standardized and automated through the use of computing workstations. Thus, structural designers and engineers have a substantial body of literature available to assist them in the design and construction of conventional (terrestrial) structures.

On the other hand, structural design of extremely large, resilient structures, preferably made of space materials, to be fabricated and installed on the Moon or Mars is not well-understood, let alone be properly investigated [159]. Although there are number of striking differences between space habitats and Earth structures, in essence and just like conventional buildings, the most critical aspect of space habitats is the safety and well-being of crew members; together with providing psychologically stable and ergonomically supporting environment.

To fulfill these requirements, and in order to minimize the effects of harsh space environment such as radiation, extreme temperature etc. on humans (and infrastructure), space habitats are required to be shielded or preferably concealed into the sub-surface of the Moon or Mars. While the most popular approach of shielding is through covering the habitat with thick layers of surface regolith, this approach leads to number of challenges that not only complicate construction, maintenance, and inspection procedures, but could also increase the difficulty of ingress (or egress) in case of emergencies.

Since gravity levels on the Moon and Mars are approximately 1/6 and 1/3 that of Earth, space habitats will be able to resist dead loads of at least three to six times the mass of an equivalent structure on Earth. Due to this massive reduction in dead loads, spans in space structures can be increased and structural members could be designed to be much slender and/or made of relatively low strength materials. This would lead to significant savings in construction materials, erection time, and overall resources. On a side note, construction equipment can also be downsized, which may offer additional savings in transportation and energy costs as well as operating requirements.

Overall, structural systems would be similar to that used on Earth, but with modifications to allow for easier and quicker installation. For example, joints and complicated detailing need be minimized (and when possible, avoided) to ensure easy assemblage, erection, accelerate the construction process, and minimize the need for maintenance and post-installation inspection. Manufacturing and construction process should also accommodate independent quality-control of construction materials and installed structural components/systems (framing). Space structural systems may utilize self-healing materials and self-diagnostics (sensing) structures. This can be essential to monitor structural "health" performance and any need for maintenance/upgrades. Considering the harsh surrounding environment, space habitats (and colonies) are required to implement higher levels of intelligence, redundancy, safety, reliability, and resiliency.

While the aforementioned discussion has been directed towards structural and design aspects of space structures, other aspects such as optimized interior space, capability to treat and recycle waste efficiently, continued functionality without power disturbance, ability to be self-independent of Earth in terms of supplies (including i.e. oxygen, water, food) are of equal importance. For example, space utilization of facilities needs to be maximized for both crew and equipment. From interior design point of view, human habitation encourages bringing natural light and views into the inside of the habitat, since long-term occupancy in windowless quarters is undesirable. This could be achieved through addition of built-in windows/porches or providing artificial sunlight as well as communication/interactive features. Detailed discussion on many of these aspects and features can be found elsewhere [160–163].

Table 8
Methods for space processing of materials.

Processing method	Definition/Suitability
Electrostatic	To separate mineral grains (i.e. in lunar soil) by charging them with static electricity. Since minerals have different tendency to electrostatic attractions, they can absorb different amounts of electric charge depending upon their composition. Then, charged grains can be separated by passing them through an electric field.
Electrophoresis	Similar to the electrostatic separation method, minerals are electrically stimulated through passing into a charged tank filled with a fluid. Due to variation in molecular nature of minerals, each mineral type will accumulate a different net electric charge and migrate to a certain position corresponding to their charge (i.e. across the height of charged tank) forming a plane of material.
Electrolysis	In this method, minerals can be melted and put into electrodes using high current. Once a voltage is applied, metals get attracted to the negative electrode and oxygen attaches to the positive electrode.
Smelting	Minerals can be heated to very high temperatures, and then melted to liquid form to separate silicon and oxygen.
Solar Oven Distillation	Unlike smelting, solar distillation releases the material in gaseous form. Solar distillation aims to boil off materials in a refractory ceramic-based container or using containerless processing under low gravity. As different materials liquify or boil off at different temperatures, once an element boils off, the temperature can be raised, and the next element will be collected.
Magnetic	For asteroids rich in free metal granules and surface of Moon (and Mars) formed by meteorite impact.
Chemical Processing	Collected soil (or minerals) can be processed to extract elements through chain of reactions from chemical compounds. This method emphasizes the use of "re-agents" (chemical agents with high recyclability), especially if such chemical compounds are not readily available on the Moon or Mars.

7. Structural concepts

Since the early days of space exploration, several researchers started to outline concepts for space base structures [30,164–166]. Although these concepts span a time period of over 50 years, they seem to recognize number of commonalities such as 1) the surface of Moon, and Mars to some extent, lays beneath a very weak atmosphere, and thus their surface is vulnerable to galactic and solar radiation as well as to meteorites impact; and 2) any built structure needs to be highly redundant, internally-pressurized, and adjusted for lack of gravity.

Numerous studies, including those commissioned by NASA, agree that construction on the Moon (or Mars) need to be light and flexible, and could undergo an evolutionary process encompassing several generations of habitats [167–169]. The first generation of space structures represents simple, pre-assembled structures (or outposts), which can be entirely imported from Earth. These structures are characterized by rapid deployment, ability to house small crews (2–6 personnel), and function for short mission times; usually 30–45 days [26,170].

The second generation of space habitats is of hybrid nature, as these structures primarily combine components imported from Earth with those fabricated using indigenous materials and/or space processed construction materials. These bases can support larger crews, and for longer mission durations (1–3 years). The second-generation bases act as transposing period where planning, research, and training can take place to lay out the foundation for full-scale colonization of the Moon or Mars. These bases could be expendables and might transition to full scale colonies [26,171].

The third generation of structures is to be constructed with substantial amounts of in-situ materials on the Moon or Mars or harvested from near space bodies [26]. This generation of structures represents large-scale colonies that are completely self-sufficient, can house large number of people indefinitely, can be used for space commercialization/tourism, as well as act as bases to further space exploration of nearby plants.

This section highlights some of the proposed concepts for second and third-generation structures. It should be noted that many of these concepts were derived from well-articulated assumptions in lieu of number of uncertainties. In general, space habitats (and basses) can be grouped under two main types; stationary or mobile. These types are further categorized into those installed in the orbit of the Moon or Mars, those built on-surface, and those built sub-surface of space bodies. For brevity, this review focuses on space bases built above and below surface of the Moon and Mars.

7.1. Terrestrial-like bases

From a structural engineering point of view, our most experiences are accumulated from designing structures with terrestrial-based “rigid” structural framing. This type of structures, often provides high degree of robustness, redundancy, and puncture resistance. Rigid structures can be designed to accommodate majority of load actions without the need for a secondary (or supplementary) load bearing system.

Number of studies have developed concepts for rigid-type concrete bases as a result of the successful investigation of the American Concrete Institute (ACI) SP-125 committee aimed at exploring possibilities related to concrete for space construction [66,172]. As such, much of the proposed rigid structures were made of space-derived conventional, precast, and prestressed conventional or sulfur concrete as most of concrete raw materials are derivable from lunar resources. In one such study, Lin [3] designed and analyzed a hypothetical cylindrical structure (64 m in diameter) under lunar environment conditions (i.e., vacuum, lunar gravity, and temperature, etc.) and noted the potential of concrete material. In a following study, Lin et al. [66] proposed a preliminary design of a three-story prestressed precast concrete lunar structure (with a diameter and height of 36.6 and 22 m, respectively), constructed from in-situ Moon materials. The proposed structure was designed with an interior work area of 3066 m^2, and can support a 36.6 m diameter dish-shaped solar energy collector on its roof. Chow and Lin [173] also proposed the use of lunar concrete to construct precast thin shell structures on the Moon, while Bell et al. [170] proposed the use of basalt (derived from lunar regolith) as a base material for construction of a lunar base with a diameter of 10–15 m and height of 6–12 m. Other researchers went into full details regarding geometrical dimensions, load combination, detailing, etc., of their proposed bases and facilities, which can be found elsewhere [174,175]. It should be noted that European Space Agency (ESA) recently investigated the use of 3D printed rigid structures [140].

While terrestrial-based bases seem to be a good fit for space construction, the major issue with the use of rigid structures is that they require complex construction and design process, which is also associated with higher mass, material utilization, and transportation volume. Rigid bases also suffer from number of limitations, such as cracking/rupture in case of meteorite impact as well as development of differential settlements, etc. Thus, innovative solutions need to be attained in order to preserve structural integrity (as well as air tightness). One proposed solution is the use of a rigid base with foundation that floats [66].

7.2. Inflatable bases

Unlike rigid terrestrial-based bases, inflatable structures for space habitats promotes a practical solution while reducing the construction process and associated costs [25]. Inflatable structures are often fully preassembled and folded to fit into a space shuttle compartment due to the highest packing coefficient for inflatable forms. Once the space shuttle reaches its destination, the deflated structure is deployed, unfolded and inflated via mechanical or automated process (see Fig. 1). In inflatable structures, high-strength fabrics are used to form an efficient support system to carry the applied external (such as regolith) and various internal loads (i.e. live load, pressure etc.) in the structure. The main advantages of inflatable bases are that they can hold large volumes, and are easy to install and transport [128].

Some of the proposed concepts involving the use of spherical inflatable bases was suggested by Roberts [176]. In this concept, the inflatable base is made of redundant structural system in which a spherical inflated envelope, with a secondary structural metal cage that supports the structural framing (i.e. floors, walls), can hold up the inflatable envelope in case of pressure loss. Roberts [176] detailed design of an inflatable structure made of a composite material (e.g., Kevlar). This base can have a total mass of 2200 kg, and provide a space up to 40 m^3 with a deflating safety factor of 5. In order to shield the base from radiation, a thick layer of regolith in the form of 3 m of overburden and sandbags was proposed to cover the inflatable habitat.

Vanderbilt et al. [177] proposed the use of a pillow or box-shaped structure consisting of different inflatable sub-structures combined using fiber composites with high tensile strength properties, envisioned to achieve high redundancy levels. In another concept, Chow and Lin [165] proposed the use of double-skin inflatable membrane filled with structural foam. In this concept, construction requires leveling the surface on the Moon (or Mars), and then spreading the uninflated structure on top of the surface. Once the torus-shaped substructure is inflated, the foam is injected into the inflatable module.

Kondyurin et al. [178] argued that using inflatable habitat in high vacuum environment is only convenient if the habitat is made of durable materials. These researchers proposed the use of inflatable bases that turn rigid upon inflation via chemical reaction in the material of the constructed walls. They refer to this process as “rigidization” in which a composite material can transform from liquid to solid during reaction of polymerization.

While inflatable structures offer number of advantages, they still rise

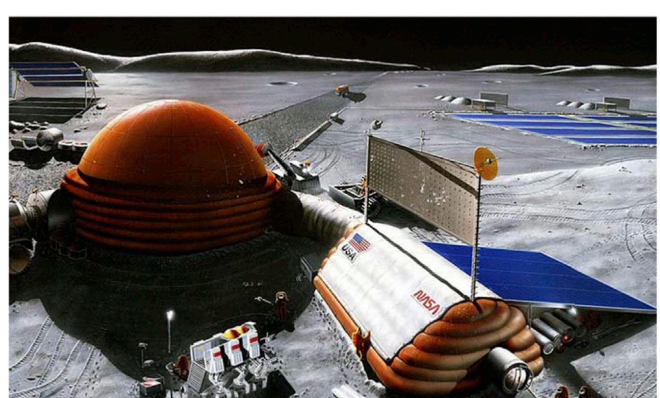


Fig. 1. Inflatable lunar base (Courtesy of NASA).

number of concerns including their response to dynamic loads, airlock operation, as well as maintenance and inspection. Another major concern is the threat of deflation which can be addressed through resilient design that incorporate "fail-safe" measures. When it comes to structure transportation, fabrication and construction need to avoid damage to the membranes and fabric. Perhaps one of the main disadvantages is the fact that composite materials may not be produced from in-situ resources. Although number of studies advocated the use of multi-layered or composite membranes, due to their resistance to radiation and abrasion, a key point to remember is that membrane fabrics, such as those used on Earth, may not meet all requirements for extreme construction [179,180]. It should be also noted that use of lunar fiberglass is being investigated which, if successful, could be a viable solution to this problem [75].

7.3. Cable bases

Number of researches including Otto [181], Buchhold [182], Leonard [183] and Eichold [184] have advocated the use of cable bases as an alternative to rigid and inflatable bases structures. Cable structures have been extensively used on Earth (i.e. roof structures, stadiums, etc.) and could provide adequate platform for space bases. Cable structures mainly comprise of tension-based structural framing systems that often include cable reinforced fabrics (in one direction or in multiple dimensions i.e. nets) and/or combination of cables and stiffened trusses (see Fig. 2). These systems have been shown to be capable of carrying the applied loads through axial internal tension forces with high efficiency.

Eichold [185] proposed a concept of a cable-based structure inserted into a surface crater that uses natural features of the Moon to reduce excavation and volume of shielding needed. The cover of this cable structures can be comprised of inflatable membranes, or thin walled metal plates. In the case of metal plates, sheets can be imported from Earth, made from surface space resources, or recycled from space shuttle parts. In some concepts proposed by Land [163], structures can be made from flat (or low arched) and pressurized enclosures connected with transverse cable mesh. More details on the feasibility of this concept from long-term human factor perspective were discussed by Eichold [185], Ruess et al. [25], as well as Cohen [185].

7.4. Expandable bases

An expandable lunar habitat was proposed by Mangan [186] and Gruber [187] that could also be extended to serve on Mars. This concept comprises of geometrically configured three-dimensional trusses or radial frame elements (i.e. tetrahedral, hexahedral etc.) that can be utilized as both, building blocks and a platform for future expansion of a base. Gruber et al. proposed a similar concept to that shown in Fig. 3.

King et al. [188] envisioned the use of portions from a space shuttle external tank for an elementary habitat by integrating some modifications such as setting up living quarters, life-support systems, and environmental control systems, and are to take place in low Earth orbit. Then, the modified tank-base can be launched to the Moon or Mars for a soft landing. These modified shuttles would land in the vicinity of each other, thus expanding the lunar or Martian base overtime.

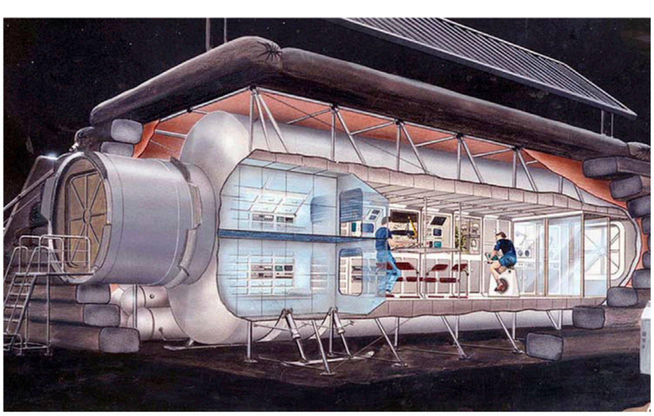


Fig. 2. Structural system comprising of cables and trusses (Courtesy of NASA).

In order to enable innovative expandable structures, Hartl et al. [189] explored the design of reconfigurable space habitat assembled from programmable 2-D planar self-folding shape memory alloys materials. In the same study, Hartl et al. [189] advocated the use of origami, a Japanese ancient art of paper folding, to develop modern and smart deployable space structures. Through use of adaptive materials (i.e., those that convert various forms of energy, such as heat into mechanical work), these researchers highlighted the possibility of optimizing and achieving various structural shapes that can be suitable for use as self-folding space habitats. Origami-designed habitats are capable of folding (and unfolding) without being kinematically manipulated via external actions (forces). This implies that large-sized bases could be folded on Earth into very small size packages, transported to the Moon or Mars, and then unfolded in space without the need for external forces.

7.5. Spacecraft landers

With recent advancement in technology, success of SpaceX program and reusable rockets, as well as that projected to occur in the near future, it would be possible to build larger space shuttles/rockets with large payloads [5]. Furthermore, we might be able to transport full-sized or pre-fabricated structures. In a futuristic concept, space rockets which could be of 50–70 m high, will not be only used as transportation ships but to also connect into habitats and expand colonies [190].

7.6. Underground bases

Although one might think that constructing underground bases might require large resources to excavate and build a space habitat, however, this may not be the case. In fact, space habitats could be easily installed within underground caves or "lava tubes" commonly available in the Moon and Mars. On Earth, these lava tubes which are formed from volcanic activities, can be 30 m in diameters [191]. However, due to the low gravity on the Moon and Mars, lava tubes could grow to a few kilo-meters. According to Orlandi et al. [191], lava tubes can house protected habitats large enough for small compounds on the Moon and Mars. Constructing a human habitat (or colony) inside of a lava tube can be accomplished employing light inflatable system, since such a structural system does not have to support shielding systems. In fact, an inflatable (and protected) base could be set up, within 24 h, if inflated with compressed air [191].

Unfortunately, underground habitats can only be constructed in specific locations with appropriate sized lava tubes. The appropriate selection of a tube located at a relatively deep location (at depth of 10–20 m) can provide long-term shelter against different kinds of radiation, meteoroid impact, outgassing of construction materials, and extreme temperature cycles. In lieu of providing radiation protection, lava tubes might also contain frozen water deposits which would facilitate developing independent habitats. Table 9 lists details on candidate lava tubes that can house Lunar and Martian habitats.

At this stage, enough information may not be available regarding mechanics, possibility, and probability of collapsing tubes. Further, lighting, accessibility, and architectural problems of a base inside a lava tube need a sustaining solution for different site conditions [193]. Moreover, human psychology, and other human factors in underground habitats are other important issues that need further research.

7.7. Cognitive and autonomous bases

The aforementioned concepts detail the implementation of "passive" structures in which the habitats are assumed to have a fixed

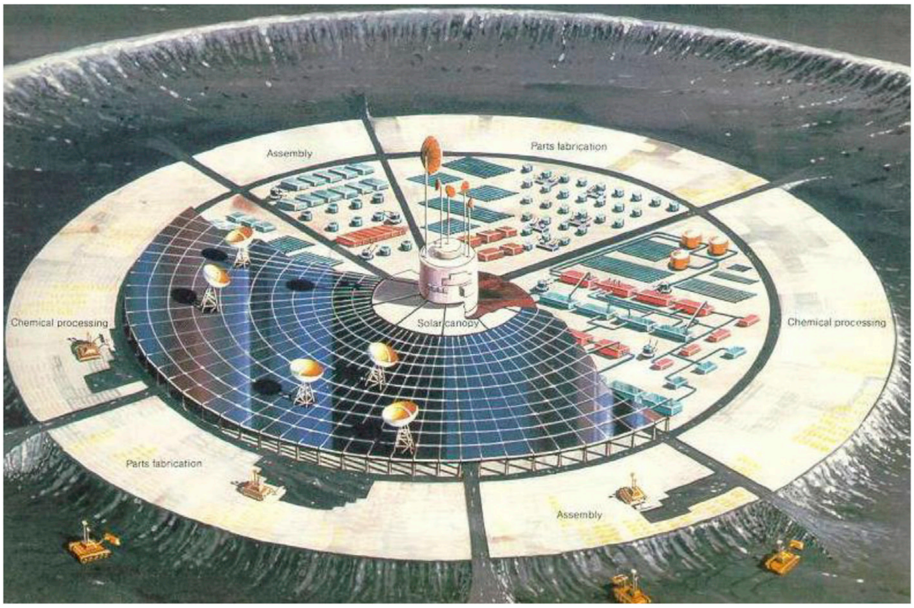


Fig. 3. Expandable base (Courtesy of NASA).

Table 9
Lava tube candidates.

Planet	Name	Latitude	Longitude	Area (km[b])	Roof thickness (m)
Moon[a]	A1	22° 00′ N	30° 30′ W	1.1	110
	B1	22° 00′ N	29° 00′ W	0.39	110
	B2	22° 00′ N	29° 00′ W	0.61	276
	B5	22° 00′ N	29° 00′ W	0.36	56
Mars[b]	Albor Tholus	19° 00′	210° 00′	1.94×10^4	-
	Uranius Tholus	26° 00′	97° 00′	0.38×10^4	-
	Biblis Patera	2° 00′	124° 00′	13.1×10^4	-

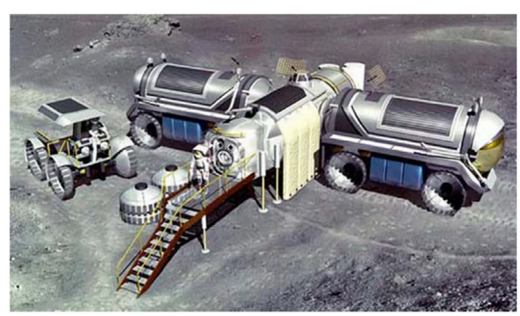
[a] Greeley and Spudis [46].
[b] Coombs and Hawke [192].

configuration and antagonistic nature. In a recent study, Naser and Kodur [194] proposed the concept of enabling cognitive and autonomous abilities in structures to achieve resilient performance in extreme events. This concept could be extended to space habitats. Such space bases can trace structural performance (i.e. health) in extreme environments (such as radiation leakage or meteorite impact). Since they are made of dynamic components and integrated with cognitive abilities, these structures can autonomously reconfigure their internal structure to adapt and mitigate to wide range of stressful conditions. Such bases have the ability to perform pre-determined safety measures such as, isolating damaged regions, detaching faulty components, notify crew members of anticipated damage levels, etc.

7.8. Mobile bases

Traditional concepts of space bases (and habitats), as those discussed above, revolve around scenarios where components of bases are fabricated or landed on the Moon or Mars, and then assembled to form a stationary habitat. Recently, some studies have demonstrated the benefits of operating a mobile or "roving" habitat [195,196]. Such bases could improve the exploration range as compared to stationary bases. The concept of a mobile base addresses number of key challenges associated with conventional "static" structures. For example, the use of mobile bases could be superior for short-to-medium duration reconnaissance missions. Weaver and Duke [197] proposed a mobile base concept in which the base is formed by a group of several independent rovers that travel together as individual units (e.g., wagon style), as shown in Fig. 4a, and join to form a temporary base at a specified site. Since each rover is an independent unit, this system has high redundancy.

In general, the objective of a mobile base is to ensure the use of landed resources by moving them to support crew in carrying out exploration "reconnaissance" mission. Mobile rovers can also be used to transport inflatable bases across surface of Moon or Mars. These hybrid bases can be suitable for semi-long missions were laboratory and communication equipment need to be set-up. An illustration of such base is shown in



(a) Mobile base comprising of rovers

(b) Hybrid mobile base comprising of a rover and inflatable components

Fig. 4. Mobile base on surface of Moon or Mars (Courtesy of NASA).

Fig. 4b. A similar concept could also be used in underground habitats. In this case, inflatable bases can be completely deflated and moved on to nearby lava tubes. In cases of need for expansion or in the aftermath of an extreme event, a space habitat can be salvaged by deflating undamaged segments of a compound base. This promotes a new concept refer to as "semi-portable" habitats.

Schreiner et al. [196] proposed a conceptual design for a portable (mobile) habitat. This system is intended to enable small crews (of two members) to explore the lunar surface using unpressurized rover. This portable base allows the crew members to remove their space suits for an 8-h rest period. Hence, crew members may be able to stay away from a stationary lunar base to conduct surface exploration before returning to base. Schreiner et al. [196] provided preliminary designs to this inflatable base including life support system and environmental control, as well as shielding system. In order to optimize packaging and transporting the inflatable habitat, these researchers applied folding principles from origami technique.

8. Research and future needs

Space is an extreme environment that is not favorable to human life nor robotics, to some extent. Similar to humans, robots (including machines) can be impacted by lack of gravity, variation in propulsive forces, radiation levels, extreme temperatures, etc. As a result, exploration of planetary bodies is limited by current available technologies which can partially mitigate the adverse effects of space on humans (and equipment). The fact of the matter is that current robotic and human systems are still slow and immature for large scale exploration missions. In order to enable Earth-like stay in space, developing technologies that ensure survival in extreme environments though improved construction materials, accommodate human performance, and enable faster space travel with larger payloads are essential. These challenges if not addressed properly, could result in significant risk, cost, and delay of subsequent manned missions. Some of the main concerns and needs for constructing safe, adequate, and cost-effective space structures are summarized in this section.

8.1. Additive printing

Research and advancements in additive printing technologies are rapidly rising due to their potential in improving manufacturing and construction of structures as well as other complex assemblies. Additive printing relies on the accumulation process of construction materials such as concrete and composites to achieve quick construction (see Fig. 5). Many aspects of additive printing, i.e. automation, ability to perform in harsh spatial environments, exploiting in-situ resources, etc., seem to fulfil the needs of construction of space habitats [51].

Unfortunately, limited research has been carried out on the application of additive printing in space environment and/or for construction of space habitats. In one study, Ceccanti et al. [198] evaluated the feasibility and practicality of 3D printing technology of regolith concrete to build human habitation on the Moon. In this study, physical properties and granulometry of lunar regolith were assessed in vacuum environment and were found to work properly with the proposed "D_SHAPE" printing technology. Outcome of this work indicated that a small wheeled robotic 3D printer (1–2 m wide) could be able to cast walls with thickness that would provide protection from radiation and micrometeoroids impact.

In a separate study, Cesaretti et al. [51] showed that current optimization efforts on wall elements have led to development of 3D printed "closed foam" walls. Closed foam walls are those made of foam patterns (without interconnected pores). Such walls might have unique advantageous over conventional "solid" walls especially when considering meteorite impact, bending resistance, and overall robustness. Further, closed foams promote the use of loose regolith within the pores, which act as a secondary shielding system that can prevent piercing of the outer shell of habitat.

Despite the promising preliminary results of additive printing technology in space applications, development of large-scale 3D printers; with the ability to carry out mineralogical analysis; and assessment of mechanical (e.g., compression and flexural strengths) and thermo-mechanical (e.g., thermal expansion coefficient) properties of the manufactured concrete structure in vacuum is not fully explored yet. It is envisioned that composites used in space shuttles can be used as "ink" (or raw materials) for such 3D printers to build habitats made of composite (along with in-situ raw materials).

8.2. Robo-engineers, and autonomous construction equipment

Considering the harsh conditions of the Moon and Mars, it would be practical to develop robotic, fully autonomous construction, and engineering systems (equipment). These construction systems need to have the ability to survey, improve/update structural designs and make construction-related decisions in real-time. The use on robots for construction missions on the Moon, and Mars for that matter, is of great importance in terms of reducing the risks of harsh space environment on humans. This can guarantee safety to crew members, and can also maximize fabrication speed, accuracy, and consistency.

Several studies investigated the possibility of sending robots for space construction missions on the Moon, and discussed challenges associated with such attractive approach [199–203]. In the recent work of Hatanaka and Perino [200], an automatic operation was proposed using extendable robotic arms to construct concrete radiation shielding prior to crew arrival. Similarly, Benaroya [26] discussed the use of a suspended platform with a robotic limp that can perform excavating functions for habitat construction. The use of tele-operating in remote-controlling mining equipment and robots on the Moon from the Earth (or the International Space Station) is another practical and low risk solution. Nevertheless, such tele-operating process might suffer from transmission time delay between 4 and 10 s [202].

Overall, robots and autonomous construction vehicles need to be made of resilient materials and possess cognition and intelligence as to take immediate actions without relying on human operators. It can be seen that development of such fully functional robots can be a tedious task, thus there is a necessity for technological developments in the field of robotic engineering and artificial intelligence to be used in harsh and dangerous lunar environments.

8.3. Property characterization of modern construction materials

Due to significant research and development efforts, a number of new materials are finding applications in terrestrial constructions such as ultra-high performance concrete, high strength alloys, and composites. While there exists a good amount of information on the behavior of such materials at ambient (Earth-like) conditions, the performance of such materials when exposed to vacuum, radiation, and space environment is still not fully explored yet. This absence of information is due to the limited research facilities, testing equipment (sensors), expertise, and trained personnel etc. needed to carry out sophisticated experiments.

As a result, there is a lack of fundamental understanding on the behavior of modern construction materials as well as information with regard to deriving appropriate constitutive models for integration of such materials into space construction application. It is therefore a necessity to design and to carry out systematic research efforts to better understand (and document) the behavior of modern construction materials once subjected to the harsh environment of space. The outcome of such research not only will improve current state of structural design, but also might attract new opportunities for space construction industry as well as continue improvements in material sciences (i.e. material processing). Moreover, property characterization will help in improving state of numerical modelling techniques which can modernize structural engineering practice, specifically for space-like conditions [204–207].

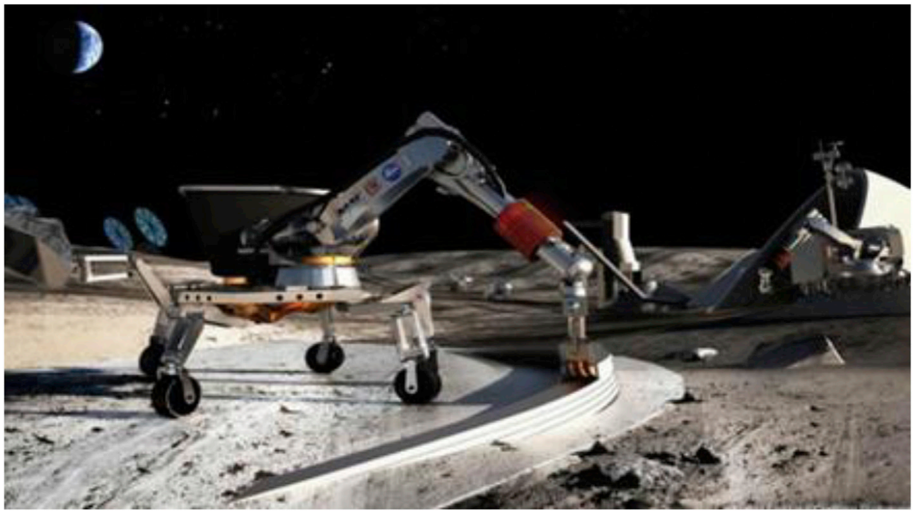


Fig. 5. Concept of a space robotic printer (Courtesy of Center for Rapid Automated Fabrication Technologies (CRAFT) at University of Southern California).

8.4. Development efforts for space exploration

The various sections of this review have demonstrated how the design, development, and fabrication of lunar and Martian bases can be a challenging task. This challenge does not only rise from current technological limitations regarding material development, material processing, and structural design, but also from other aspects such as those associated with logistics including appropriate selection of base site, power supply for base and extra-vehicular equipment, life support, communication tool and equipment etc. One needs to remember that development of space bases, and colonies, also requires advances in fields other than engineering such as physics, chemistry, medicine, agriculture, economy, politics, and management. Details on research needs on some of these areas were not covered here for brevity but can be found elsewhere [208–210].

9. Summary and conclusions

Space exploration and colonization of nearby planets and moons could be regarded as one of the major milestones in human history. In order to achieve such a milestone, multidisciplinary researchers, with complementary expertise, need to collaborate to overcome many of the current limitations and challenges associated with material development, structural design, robotics, etc. Overall, the outcome of this review can be summarized in the following points:

- The harsh and unique space environment can cause adverse effects on various terrestrial and extraterrestrial construction materials, as well as on structural systems and space infrastructure. Such effects are to be taken into account when designing space habitats.
- Due to its inherent resiliency, and durable characteristics, together with promising efficient production using in-situ raw resources, concrete material along with its derivates are regarded with the highest potential for use in space construction.
- Space habitats can be grouped under two main types: stationary and mobile. These habitats could be installed in the orbit of the Moon or Mars, built on-surface, or within lave tubes.
- Realization of space exploration and functioning space habitats cannot be fulfilled without overcoming current limitations and challenges facing extraterrestrial exploration such as those associated with material development, processing technologies, robotics etc.

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“Human colonization on other planets is no longer science fiction. It can be science fact. The human race has existed as a separate species for about 2 million years. Civilization began about 10,000 years ago, and the rate of development has been steadily increasing. If humanity is to continue for another million years, our future lies in boldly going where no one else has gone before,” Stephen Hawking (1942–2018).

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