applied sciences

MDPI

Review

A Survey on Extraterrestrial Habitation Structures with a Focus on Energy-Saving 3D Printing Techniques

Mitra Khalilidermani and Dariusz Knez *

Department of Drilling and Geoengineering, AGH University of Krakow, 30-059 Krakow, Poland; mitra@agh.edu.pl

* Correspondence: knez@agh.edu.pl

Abstract: In the past two decades, various space agencies have shown great enthusiasm for constructing habitable structures on lunar and Martian surfaces. Consequently, several extraterrestrial structures have been proposed by different researchers. Nevertheless, only a small number of those structures are energy-efficient and cost-effective. In this research, a comprehensive review of the proposed extraterrestrial structures has been conducted. The objective is to evaluate different habitat construction techniques from technical, economic, and energy-consumption perspectives. To carry this out, different proposed structures are elaborated, and their advantages and limitations are discussed. The primary focus is on the 3D printing technique, which has demonstrated significant potential in automated manufacturing tasks. From the conducted research, it was found that the combination of 3D-printed components along with an internal breathable inflatable module is the most promising technique for habitat development on the Moon and Mars. Moreover, the microwave sintering method was identified as the most energy-saving and reliable approach for melting the on-site regolith for use in the 3D printing process. This survey has applied a multidisciplinary approach to evaluate the most energy-saving planetary construction techniques that are economically crucial for different private or government-funded space agencies.

Keywords: space exploration; extraterrestrial habitat; 3D printing; regolith; inflatable structure; regolith sintering; space transportation cost; lunar outpost; Martian outpost; Artemis mission

check for updates

Citation: Khalilidermani, M.; Knez, D. A Survey on Extraterrestrial Habitation Structures with a Focus on Energy-Saving 3D Printing Techniques. *Appl. Sci.* **2023**, *13*, 12913. https://doi.org/10.3390/app132312913

Academic Editor: Asterios Bakolas

Received: 10 October 2023
Revised: 15 November 2023
Accepted: 29 November 2023
Published: 2 December 2023

1. Introduction

The Earth's dwindling resources, together with climate change issues, have spread the notion of space civilizations. Future space habitation is envisioned to be the circumvention of mankind's sustainability in the solar system. This is why large space agencies in the US and European Union are presently tracing the construction of permanent extraterrestrial habitats on the Moon and Mars [1]. From the safety viewpoint, a long-duration stay that provides immunity in planetary environments needs resilient structures [2], sheltering human inhabitants (or astronauts) so that they can discover the atmosphere, lithosphere, biosphere, and even hydrosphere of their surroundings. On a positive note, recent evidence of water presence on lunar and Martian surfaces has given fresh impetus for rendering off-Earth life a reality [3–5].

Currently, there are several space missions dedicated to advancing the concept of planetary habitation. One prominent example is the National Aeronautics and Space Administration (NASA)'s Mars Exploration Program, which includes the ongoing Perseverance rover mission. Perseverance, launched in 2020, aims to explore the geology of Mars, search for signs of ancient microbial life, and collect samples for potential return to Earth [6]. The mission also includes the Ingenuity helicopter, which successfully demonstrated powered flight on another planet. Another notable endeavor is the Artemis program, led by NASA in collaboration with international partners [7]. Artemis seeks to return humans to the Moon and establish sustainable lunar habitats, utilizing the Lunar

Gateway as a staging point for crewed missions. Moreover, the Artemis program aims to accomplish the significant milestone of sending the first woman to the Moon. These missions, among others, represent significant milestones in the human journey towards planetary habitation, pushing the boundaries of human knowledge and capabilities in our quest to expand beyond Earth.

From the perspective of engineering challenges, it appears that three main categories of uncertainties have postponed the rapid development of habitable outposts on remote planets: unfavorable extra-terrestrial physics, risky characteristics of the regolith soils, and uncertain construction techniques. In the following paragraphs, these three factors are described.

The potential of habitability on a specific planet is substantially intertwined with its dominating physics rules [8]. Gravity, ambient temperature, atmospheric pressure, magnetic field, surface radiation, and seismic events are the most influential factors with respect to the suitability of human habitation on a specific planet. Such physics-based factors are very mankind-friendly on Earth; however, on distant planets, physics rules can be challenging for human life, either completely or partially. Years of space exploration missions have revealed that two promising planets, the Moon and Mars, may someday be occupied by human generations if physics requirements are addressed by technology. Since an adequate understanding of lunar and Martian physics is essential for developing reliable habitats, a dedicated broad description is provided in Section 2.1 to elucidate the effect of such physics-based challenges on outpost development.

Lunar and Martian outposts can be entirely constructed regardless of whether they are on the planet's surface or underground. Alternatively, the outpost can also be constructed using a combination of both surficial and subsurface modules. The most frequent propositions have been surficial outposts, which are less complex than underground ones. Lunar and Martian surfaces are covered by a fine-grained abrasive soil known as regolith [9]. Some characteristics of the regolith can positively contribute to the development of a prospective human outpost, while at the same time, they may impede the construction process with formidable obstacles. For instance, the regolith's cohesionlessness facilitates the excavation operation conducted by construction robots, thereby requiring less energy for regolith removal and haulage. On the contrary, lunar and Martian dust storms perpetually disperse such cohesionless regolith particles in the atmosphere, thereby covering the robots' cameras and lenses and, even worse, penetrating their working units [10]. The latter issue can entirely or partially hamper robots from the construction process.

To revert to underground outposts, it can be said that although the excavation of any foundation, channel, trench, and tunnel can be easily carried out in loose regolith, the instability of the roof of such structures is highly problematic. Most importantly, temperature fluctuations frequently change the physical properties of soils [11,12]. This may lead to potential failure in the underground walls of the outpost.

Extraterrestrial outpost designs were initially proposed three decades ago. Nowak et al. proposed inflatable structures made of lightweight composites to build lunar habitats [13]. Aside from lightness, these inflatable structures could easily be compacted during transportation from the Earth to the Moon. Moreover, the outpost's erection could be carried out using low amounts of energy, and this is carried out by construction robots. Benaroya and Ettouney suggested the utilization of a 3D flat truss for the development of lunar bases (Figure 1 (left)) [14]. The members of the truss were made of light aluminum. Furthermore, the truss was installed on a naturally available lunar valley. To protect the outpost from the outer harsh environmental conditions, the roof of the truss was covered by the local regolith. Shortly thereafter, Benaroya put forward the idea of using tensegrity assemblies for space habitats [15]. Tensegrity structures includes a series of interlocking cables and bars capable of forming an intertwined structure (Figure 1 (Right)).

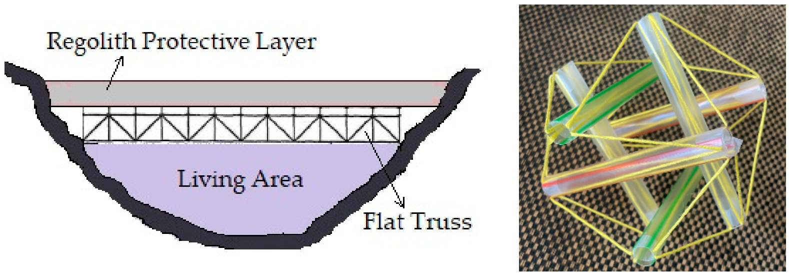

Figure 1. Early proposed structures for extraterrestrial habitat construction: flat truss (**Left**); tensegrity (**right**) [16].

In the middle of the 2000s, the concept of deployable modules was suggested for the establishment of extraterrestrial outposts [17]. The deployable structures encompass size-variable components, which can be stowed during Earth-to-space transportation, and then, they can be expanded to a desirable size and shape. For example, two typical deployable structures include the umbrella and TV antenna. In the same years, the idea of arch structures was also offered by [18,19]. In these propositions, the main structural module was a semicircular arch made of light aluminum together with a regolith-based roof for sheltering human habitants against hostile environmental conditions (Figure 2).

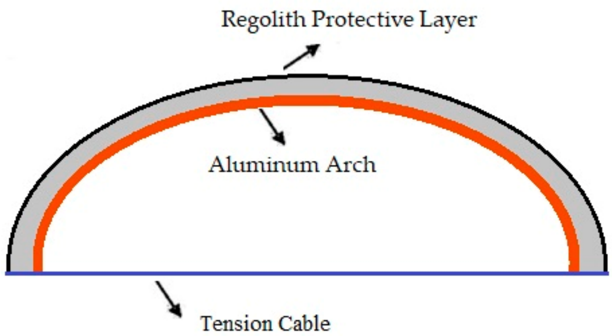

Figure 2. A schematic of arch structure protected by the regolith shield layer.

In subsequent years, the next-generation technology of 3D-printed structures started to absorb the attention of extraterrestrial researchers and engineers [20,21]. This is why gigantic space agencies such as NASA and ESA have dedicated extensive funds to the feasibility studies of 3D printing applications in extraterrestrial habitat construction [20,21]. In general, in this automated manufacturing technique, with cutting-edge 3D printing machines erected on advanced rovers, local regolith can be sintered (molten) up to a certain temperature, and then, it is combined with an additive such as aluminum powder to make a low-porosity material with much more strength than the in situ regolith. In Section 2.2, the aggregate ability of the in situ regolith is discussed. The artificially produced material can then be utilized in the fabrication of desirable building components, such as bricks, domes, etc.

The main advantage of the 3D printing technique is that the local regolith is directly used in the construction process, thereby leading to a reduction in the cost of interplanetary transportation. It should be noted that 3D printing technology can also be utilized in conjunction with other techniques, such as inflatable modules and arc structures [18,19,22–26]. Nevertheless, this fabrication technique has some limitations for large-scale implementation on lunar and Martian surfaces [20–22]. In Section 2.3, a comprehensive description of the previously proposed construction techniques in off-Earth environments is presented. Moreover, in Section 2.4, the different aspects of 3D printing technology in extraterrestrial outpost construction are described.

The extraterrestrial outpost construction is a multidisciplinary field in which a vast range of science branches, i.e., robotics, electronics, mechanics, geotechnics, geomechanics, physics, etc., are brought together. With the daily exponential growth in technology, there is always a necessity to collate and integrate the latest progressions, inventions, and investigations related to habitat development on remote planets. The main objective of this research is to provide an inclusive survey that is beneficial for different researchers involved in these diverse scientific branches. Furthermore, the authors have strived to further concentrate on the 3D printing technique as encouraging technology for the future development of human habitation on remote planets.

2. Materials and Methods

In this chapter, firstly, from the standpoint of outpost construction, different physics-based challenges in lunar and Martian environments are recounted. Then, the applicability of regolith in the outpost development process is assessed. Afterwards, a concise glance is thrown at the most intriguing construction techniques for habitat construction on Moon and Mars surfaces. Finally, the important aspects of 3D-printing applications in outpost construction are inclusively elaborated.

2.1. Physics-Based Challenges

As it was already mentioned, there are several physics-based challenges restricting the outpost development on the Moon and Mars. These challenges comprise microgravity, cryogenic temperature, the non-existence of adequate atmospheric pressure, a lack of magnetic fields, extreme surface radiations, and micrometeoroid impacts. Figure 3 shows these challenges. Any conceptual lunar or Martian outpost must meet the specifications related to these challenges. In the case of access to inclusive data related to these challenges, artificial intelligence approaches can be used to analyze the effect of these challenges on extraterrestrial outpost construction [27].

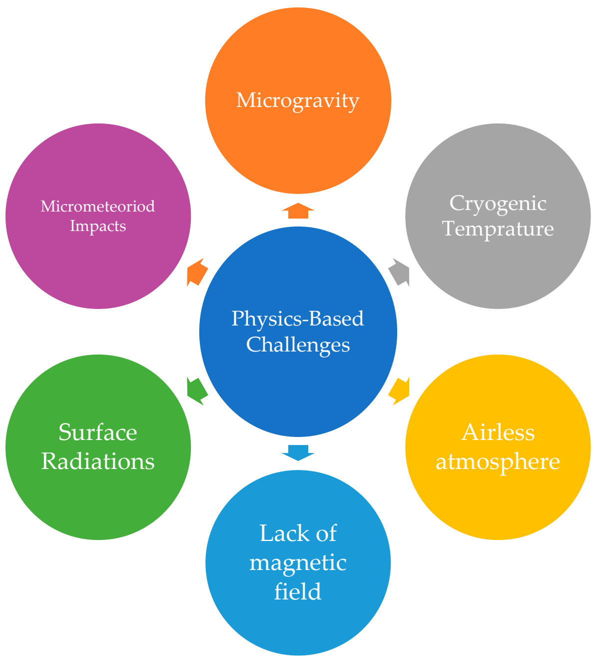

Figure 3. Primary physics-based challenges in the construction of lunar and Martian outposts.

The Earth's diameter is relatively two times Mars's diameter and four times the Moon's diameter [28]. Moreover, gravitational acceleration on the lunar and Martian surface is, respectively, equal to 1.62 m/s^2 and 3.71 m/s^2; these values are significantly less than 9.81 m/s^2 on the Earth [28]. This phenomenon is known as microgravity imposing many limitations on habitation development. Because of microgravity, a human habitat may undergo instability problems [29]. Consequently, to address this challenge, there is a need for a foundation that fastens the habitat to the regolith beneath; however, the lunar and

Martian regolith is very cohesionless (order of a few kPa) [9]; therefore, to reach a depth with stiff regolith, drilling tools capable of penetrating into the lower depths must be deployed. As a result, there will be a need to apply much greater forces to drill the lunar and Martian regolith [30,31]. Therefore, the first challenge is the microgravity-derived instability of the habitat, which calls for stronger, weightier, and bulkier drilling machinery.

The atmospheric temperature on the Moon's poles amounts to −230 °C, and on Mars's poles, it reaches −140 °C [10]. Such cryogenic conditions create a diverse spectrum of challenges in the development of extra-terrestrial outposts [32,33]. To address this issue, a vital action is the thermal insulation of the interior parts of the outpost from harsh exterior atmospheric conditions. To carry this out, appropriate insulators must be transported and deployed, thereby increasing transportation costs. Furthermore, cryogenic temperatures induce thermal stresses within the materials [34,35]. Therefore, adequate resistance to cryogenic temperatures is another criterion for the selection of construction materials [20]. This matter precludes countless raw materials from being adopted in lunar and Martian outpost construction.

While on Earth, the atmospheric pressure (at room temperature) is around 100 kPa, the tenuous Martian atmosphere has a very low pressure equal to 0.6 kPa [36]. Even worse, the atmospheric pressure on the lunar surface falls between 4 kPa–10 kPa (during days) and 7 kPa–10 kPa (during nights). The lack of atmospheric pressure on Martian and lunar surfaces exacerbates the conditions for outpost development. Most importantly, the shortage of atmospheric pressure curtails the applications of fluids in the construction process [20]. Thus, many terrestrial-based fuels, hydraulic oils, additives, binders, etc., are only applicable under stringent specifications. Furthermore, the non-existence of atmospheric pressure makes the Moon and Mars susceptible to micrometeoroid collisions and solar/cosmic radiation [37]. This obstacle calls for the adoption of a protective layer on the outpost. To meet this issue, a number of researchers have proposed the construction of underground structures, such as the expansion of lava tubes and tunnel construction using tunnel boring machines (TBMs) [38–40].

On a certain planet, the magnetic field stems from its core conditions, i.e., the core composition, lack or presence of plate tectonics, and water repartition [41]. On Earth, the magnetic field protects human life from solar and galactic radiation [42]. In other words, Earth's magnetic field constitutes a magnetic shield (magnetosphere) that spans several tens of thousands of kilometres from the Earth's surface towards space [42] and prevents charged particles from stripping away the upper atmosphere, i.e., most importantly, the Ozone layer [43]. Nevertheless, Mars, the Moon, and even Venus suffer from their magnetic fields in order to protect their surfaces from solar winds, cosmic rays, and micrometeoroid impacts [20,28]. On Mars, the photos captured by the Curiosity rover have confirmed the early presence of water streams, forming a delta area in the craters. From this observation, the former existence of the Martian magnetic field was deduced [44]. Lundin et al. have ascribed the water loss and obliteration of the Martian atmosphere (life) to such dramatic reductions in the Martian core's magnetic field [44].

Surface radiation in lunar and Martian environments is far more extreme than Earth's [45]. Solar winds, solar flares, and cosmic rays are three major spectra of radiation that reach the Moon and Mars's surfaces [46]. Of all these radiation types, solar winds are further hazardous for the outpost's inhabitants. From the site-selection standpoint, the location of the outpost must be chosen in regard to the minimum degree of such solar winds. On the Moon's surface, a typical lunar day relatively lasts 28 Earth days [47]. In the lunar polar regions in which the water-bearing regolith has already been reported [8,20], the solar wind reaches the surface with a roughly horizontal angle [20]. Hence, the construction of an outpost in such locations effectively curtails the solar wind. In addition, for further a reduction in incoming solar wind, the outpost can be covered by a protective regolith layer [20]. The thickness of the regolith layer can range from 1.5 m to 2 m [20]. Furthermore, some membranes, such as lightweight polyimides, which are very suitable for extraterrestrial inflatable structures, can hinder solar radiation [48]. Polyimide also has good transparency, and it can be utilized as outpost windows, permitting sunlight to shine into the outpost [48].

Seismic events on lunar and Martian surfaces mainly originated from two sources: meteoroid impacts and lunar/Martian ground motions (quacks) [49]. In this paragraph, we only describe the effects of meteoroid impacts on lunar/Martian outpost development because the topic of ground motions on the Moon and Mars is too broad to be elaborated in detail here. Due to the non-existence of magnetic and atmospheric barriers, potential meteoroids strike lunar and Martian surfaces at high speeds.

A wealth of information pertinent to the weight, size, speed, and location of the lunar meteoroids was obtained during the years of 1970–1977 via a series of seismometers emplaced on the Moon's surface [50]. According to those data, the most frequent meteoroids reaching the lunar surface have a mass of less than 0.5 kg [50]. On the other hand, collisions of meteoroids heavier than 1 ton are very scarce [51]. The average velocity of the striking meteoroids amounts to 22.5 km/s (to compare to this speed, a bullet is released from a rifle at a speed that is approximately equal to 2 km/s) [52]. During each year, more than 4000 impactors with an average weight of 1 kg may hit the Moon's surface. Furthermore, from the site-selection viewpoint, it can be said that the collision locations of bigger impactors are not regularly distributed on the Moon's surface although they demonstrate clustering [53]. Hence, it is of paramount significance to consider the possibility of meteoroids collisions with the outpost's structure.

Before the 2000s, researchers chiefly proposed Kevlar composites in their conceptual structures because of their protection against meteoroid impacts and their lightness and high tensile strength. Cesaretti et al. suggested the usage of a special type of 3D-printed regolith-based foam to disperse meteoroid energy in the case of collision with an outpost [20]. Moreover, the development of underground structures also has been offered by a number of investigators to keep the outpost away from the probable impactors [38–40]. Similarly, hybrid structures that contain both surficial and underground units may experience less impact relative to likely meteoroid collisions [38–40].

2.2. Aggregate Ability of the Regolith

On the Moon, there are two morphological landforms, including highland regions and the flat Maria. The highland and mare terrains form nearly 83% and 17% of the Moon's surface, respectively. The mare regions are black in colour and basaltic in composition [54,55]. On the other side, the highland regions comprise the felspathic formations described as anorthosite, which is again an igneous rock. Similarly to the Moon, Martian soils/rocks have basaltic genes interestingly. Due to the never-ending bombardment of lunar and Martian surfaces by small and large meteoroids, upper rocks have been extensively smashed into a silt-size powdered soil called regolith.

The utilization of in situ resources (ISRUs) has acquired considerable attention amongst the space community. The on-site production of water, oxygen, hydrogen, helium 3, titanium, sulfur, and other precious elements from the lunar and Martian surfaces can be carried out via the direct processing of in situ regolith. Such invaluable elements will benefit human presence on the Moon and Mars's surfaces. This is a revolutionary breakthrough promoting the utilization of local aggregates instead of transported terrestrial materials.

There are some industrial techniques by which new substances can be created from the in situ regolith (or igneous (basaltic) rocks) present on Mars and Moon. In this section, the potential applications of these on-site resources are discussed from the outpost's development perspective.

The lunar and Martian regolith can be deployed for outpost development in two possible forms: raw and synthesized. In the raw form, regolith is utilized in the construction process while its natural composition and intact shape remain unchanged. For instance, raw regolith can be stored in some special bags, and then, they are accumulated on all sides of the outpost [56]. On the Moon, the collision of small-size particles with the lunar surface ceaselessly occurs since no atmosphere and magnetic field exist [57]. The regolith bags serve as a shielding layer, protecting the outpost from particles, solar radiation, intensive temperature fluctuations, and possible meteoroid impacts. Another identical application of raw regolith is to directly deposit regolith on the structure and then covering such a regolith with membranes that are anchored to the ground [13,14,58–60]. The direction of the anchor is a key parameter in the stability of the structure [61].

The second more important application of the in situ regolith is using it in a synthesized form. In this case, the indigenous regolith is combined with other substances to constitute new, altered materials with far more compressive strength. To carry this out, the first simple way is blending an amount of regolith with additives or binders to create new mortars. The additives can be directly taken from the Earth to space, or alternatively, they may be produced via advanced techniques at the construction site. As an illustration, NASA has already assessed the combination of epoxy ICI Fiberite 934 binder with the Martian regolith to curtail surface radiation [62]. Via a combination of additives with the in situ regolith, the new materials will have further structural strength and can be molded into diverse shapes, such as bricks, blocks, voussoir, etc. This is the basis of the 3D-printed modules utilized in 3D printing technology applied for outpost construction [63].

In the 3D printing technique, the regolith is firstly sintered, and then, a special binder is added to the regolith to make a substance with lower porosity and higher strength. For sintering the regolith, a number of methods are applicable: laser sintering, solar sintering, and microwave sintering [64]. Regarding laser and solar sintering, it can be said that the complexity, high energy consumption, and environmental challenges restrict the large-scale usability of such methods [22,65–67]. Microwave sintering appears to be more promising since it can melt the regolith to a much further depth compared to the laser and solar sintering methods [21,64]. A broad description of these three sintering techniques is provided in Section 2.4.

The sintered regolith can be used for diverse purposes. Mottaghi and Benaroya proposed an igloo-shaped outpost that was installed on a flat foundation made of sintered regolith [56]. Another application of the in situ regolith can be the production of extraterrestrial concrete. Meyers and Toutanji stated that sulfur concrete has adequate strength and durability for use in outpost construction [68]. Furthermore, Khoshnevis and Zhang utilized a 3D printing technique called contour crafting (CC) for the construction of outposts made of sulfur concrete and sintered regolith [21]. They proposed that the sintered regolith firstly can be molded in the shape of brick-like modules, and then, a layer of sulfur concrete is spread over them. They expressed that the compressive strength of such admixture amounts to 55.16 MPa, which is quite considerable for the construction of structural modules, such as foundation pads, sidewalls, and other structural modules. In addition, for the reinforcement of sulfur concrete, regolith-based glass fibers and rebars can be added to the admixture.

2.3. Outpost Construction Techniques

The previous sections concentrated on physics-based challenges and regolith aggregate ability in extraterrestrial habitat development. In this section, the focus changes to a condensed overview on outpost construction techniques proposed by different researchers. The objective of this section is to assess different construction techniques from a generic viewpoint. As already mentioned, the main proposed outpost designs included the flat truss, tensegrity structures, inflatable modules, deployable structures, arch components, and 3D-printed modules.

Table 1 summarizes the major construction techniques suggested for outpost development on lunar, Martian, and cislunar environments in a chronological order. For each construction technique, the material's type is mentioned. To test the applicability and reliability of each outpost, the applied analysis methods have also been presented. Moreover, in the table, the term "underground" refers to the outposts with a natural roof of regolith, such as tunnels or expanded lava tubes. The structures in which the outpost partially lies in a natural valley, or in an artificial trench, are considered as hybrid structures.

Table 1. Chronological order of major proposed extra-terrestrial outpost designs.

Reference	Year	S, U, H *	Construction Technique	Material Type	Analysis Method
[14]	1992	H	Flat truss	Lightweight Truss and regolith cover	Static
[13]	1992	S	Inflatable	Kevlar 49 and regolith cover	Static and numerical
[15]	1993	S	Tensegrity	Unmentioned	Unmentioned
[58]	1993	S	Inflatable	Kevlar 49 and regolith cover	Static and numerical
[59]	1994	H	Flat truss	Composite Truss and regolith cover	Static
[69]	1995	H	Flat truss	Aluminum Truss and regolith cover	Static, Dynamic, and numerical A
[60]	1996	S	Inflatable	Kevlar and regolith cover	Static and numerical
[70]	1999	S	Inflatable	Kevlar	Static
[71]	2000	S	Inflatable	Kevlar	Static and numerical
[72]	2004	S	Inflatable	Kevlar	Static
[73]	2004	S	Inflatable	Kevlar	Static
[74]	2006	S	Inflatable	Kevlar	Static
[17]	2006	S	Deployable	laminates of AS4 Carbon PEEK	Dynamic and numerical
[75]	2006	variable	Deployable and inflatable	Variable (review paper)	Not applicable
[18]	2006	H	Arch	Aluminum	Numerical A
[19]	2006	H	Arch	Aluminum	Numerical A
[23]	2006	S	Truss and inflatable	Truss made of aluminum; inflatable structure made of Kevlar	Numerical A
[24]	2008	S	Truss and inflatable	Truss made of aluminum; inflatable structure made of Kevlar	Dynamic
[68]	2007	S	Arch	Regolith-based sulfur concrete	Static and thermal
[76]	2010	S	Arch	Regolith-derived voussoir dome	Static
[21]	2012	S	3D printing	Sintered regolith and sulfur concrete	Not applicable
[25]	2013	S	Truss and inflatable	Truss made of aluminum; inflatable structure made of Kevlar	Numerical
[20]	2014	S	3D Printing and inflatable	Regolith	Numerical
[38]	2017	U	Tunnel	Precast lining	Numerical
[77]	2018	S	Deployable	Mylar	Numerical, empirical approaches
[39]	2018	U	Lunar/Martian lava tubes	-	Static and numerical
[78]	2018	S	Inflatable	ETFE membrane/Kevlar network	Numerical
[79]	2019	S	3D Printing	Sintered regolith	Destructive mechanical tests

* (U = underground; S = surficial; H = hybrid).

The first conceptual structure was an inflatable structure proposed by Nowak et al. in 1992 [13]. Inflatable structures are constructed from lightweight composites that are very cost-effective for Earth-to-space transportation. Their interior is filled with pressurized air, which is necessary for breathing and the integrity of the outpost shape. Inflatable structures can be developed using shapes such as cylinders, spheres, domes, cubes, or combinations of them. Figure 4 depicts an inflatable module tested by ESA for habitat construction on remote planets [80].

Figure 4. An inflatable module tested by ESA for extraterrestrial outpost construction [80].

Inflatable structures provide high tensional and compressional strength values, which are the most crucial properties in extraterrestrial structural design. It can be said that from 1992 until now, the most proposed structures are based on inflatable structures. In most, the material of the inflatable structure has comprised Kevlar (reinforced carbon composite) membranes [13,58,60,73,74,78]. Yet, the popularity of inflatable structures has exponentially continued to grow amongst outpost designers and architects. Moreover, 3D-printed outposts need an inflatable module to form an internal breathable environment [20]. Figure 5 (Left) shows interconnected structural modules made of inflatable modules and a 3D-printed protective regolith layer. Not only for lunar and Martian outpost construction, but regolith has also been proposed for building habitats on the International Space Station [70,71] and in low Earth orbit [72]. Figure 5 (Right) depicts the TransHab designation proposed by Kennedy [70].

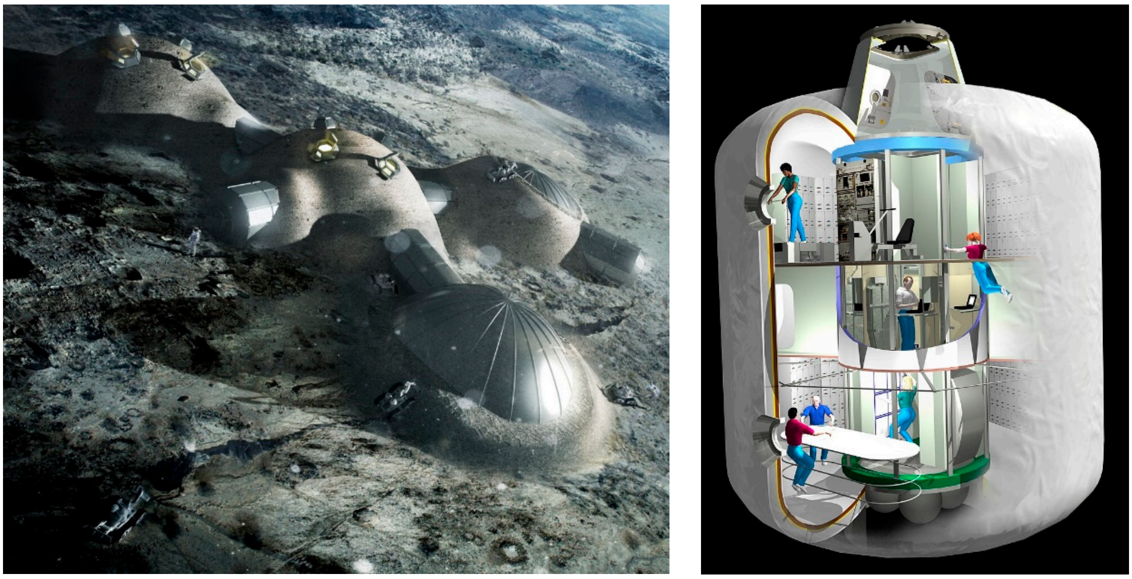

Figure 5. A lunar/Martian outpost made of inflatable structures and 3D-printed protective layers (**left**) [2]. The schematic representation of the TransHab inflatable module developed by NASA in the late 1990s for astronauts' accommodation in the International Space Station (**right**) [81].

Also, in 1992, Benaroya and Ettouney proposed a lunar outpost composed of a 3D flat truss that could be installed on the top of a natural valley (see Figure 1) [14]. After the installment of the truss, a layer of in situ regolith was then spread on the roof of the truss to shield the habitat from intensive temperature fluctuations, outside radiation, and possible micrometeoroid impacts. During the subsequent years, some researchers suggested similar 3D flat structures for lunar bases [23,24,59,69]. The material of truss members was chiefly aluminum or light composites, such as Kevlar. In practice, it can be said that the idea of the proposed flat truss gained less attention since other forms of technology emerged in the next two decades. Apart from the 3D truss, Benaroya also proposed several conceptual layouts of tensegrity structures for lunar outposts [15]. Tensegrity structures encompass a combination of cables and bars within an intertwined net so that the whole structure renders a stable system (see Figure 1). The idea of tensegrity-based structures did not acquire relative attention in subsequent years.

From 2006 to 2010, two novel methods, including deployable structures and arch components, were proposed for outpost development on the lunar and Martian surfaces (see Figure 2). Deployable structures encompass size-variable components and, hence, can be compactly stowed during transportation from Earth to space [16]. These structures are presently used in space missions; for instance, the spaceship's antenna and solar panels are types of deployable structures. Nevertheless, only a few engineers have suggested extraterrestrial deployable outposts [6,17]. Tinker et al. conducted an inclusive review on the possible deployable and inflatable structures in extraterrestrial environments [75].

Regarding arch structures, they involved a fabricated semicircular arch made of aluminum, which could provide a shelter for its inhabitants [18,19]. A protective regolith layer was also suggested to be deposited on the arch to protect it against harsh external environmental conditions. Since a creative utilization of on-site materials significantly cuts project costs [82,83], some researchers began to investigate the manufacture of arches using lunar/Martian regolith. Meyers and Toutanji stated that sulfur-based concrete made of lunar/Martian regolith can be utilized for arch construction as it exhibits a high extent of strength and durability [68]. To fabricate such sulfur-based concrete, the regolith was heated, and then, it was allowed to be steadily cooled. Furthermore, Faierson et al. studied an admixture of lunar regolith simulants with aluminum powder for the fabrication of a regolith-based voussoir dome during a geothemite reaction [76]. Figure 6 shows the different stages of such an outpost. They deduced that the combination of these materials generates high-strength units that make reliable dome-shaped structures on the lunar surface.

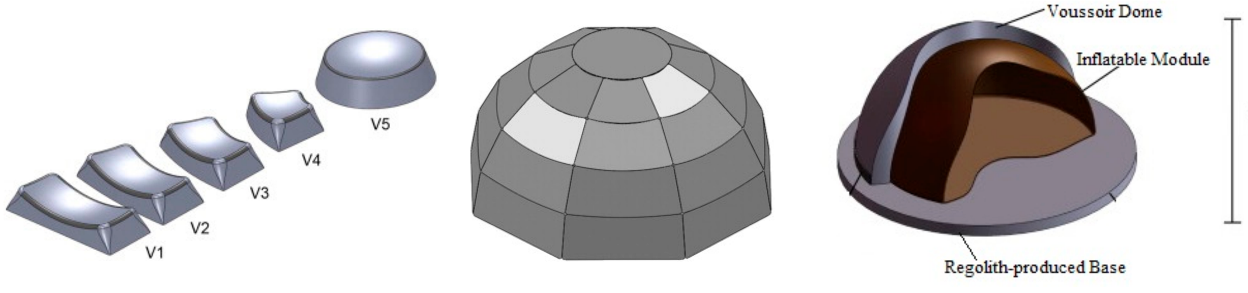

Figure 6. Different stages of the fabrication of a regolith-based voussoir dome [76].

From 2010 onwards, with the emergence of 3D printing technology, architects contemplated developing 3D-printed structures on lunar and Martian surfaces [84]. The main advantage of this construction technique is the direct utilization of the in situ regolith as feedstock in the construction process [22]. In this technique, the in situ regolith is gradually sintered until its temperature reaches its melting point; then, a binding fluid is added to the mixture to compose a consolidated substance with lower density and higher strength. Since this technique is currently used by NASA and ESA to build extraterrestrial outposts, this review paper dedicates an inclusive section to 3D printing technology. In the subsequent section, an attempt was made to review the important aspects of 3D printing technique applications in outpost construction.

2.4. Three-Dimensional Printing Technology Applications in Outpost Construction

Any extraterrestrial outpost must satisfy two requirements: The first requirement is to provide a breathable environment (room) for inhabitants. Such a room contains breathable air with a pressure equal to the Earth's surface pressure (approximately equal to 100 kPa). In the planetary environment, this can be carried out using an inflatable module made of a light, resistant composite, such as ethylene-tetrafluoroethylene copolymer (ETFE). The inflatable structure is simply transported from the Earth to the remote planet; then, it will be filled with the breathable air under appropriate pressure. The second requirement is to shelter the inflatable module from outer environmental radiation, meteorites, temperature variations, etc. To address this requirement, 3D printing technology that is capable of manufacturing regolith-based building blocks can be utilized. Different 3D printing techniques can be used in extraterrestrial outpost construction [20].

At present, there are three applicable 3D printing techniques for printing building components on remote planets. These techniques are the Monolite machine (or the D-shape technology), contour crafting (CC), and the freeform construction technique [20]. These techniques were initially developed during the 1990s as full-scale manufacturing processes [85–87]. These three techniques are presently utilized in the manufacture of 3D components in terrestrial construction projects. Figure 7 shows a schematic representation of 3D printing processes, which is relatively similar for all three techniques. The differences between these three methods are derived from the applied materials and deposition methods. The main difference among these methods is how they work with materials. D-shape technology selectively activates or solidifies materials within a layer that has already been placed, similarly to a printer choosing specific areas to solidify. The other methods, on the other hand, use a process in which building materials are pushed out (extruded) together with a binder or catalyst. This mixture is similar to concrete and is used to build up the structure layer by layer [20].

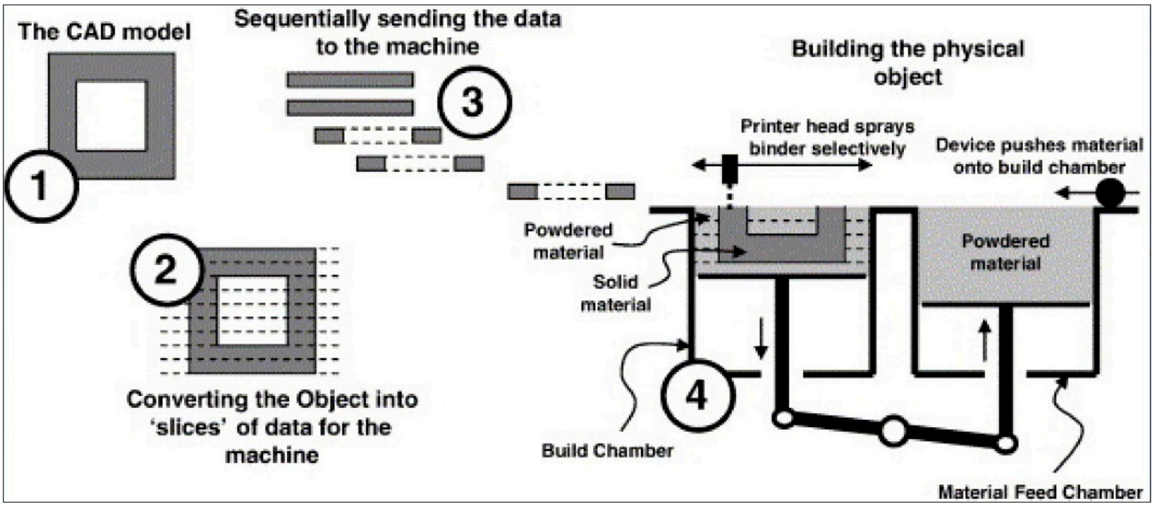

Figure 7. A schematic of the 3D printing process [87].

Each of these techniques needs a raw material (regolith) and a binder liquid for the manufacturing process. The binder can be entirely or partially produced on Earth. The ratio of the liquid binder to the raw regolith is crucial as it has a direct relationship with transportation costs.

So far, some large-scale projects pertinent to the application of 3D printing techniques in outpost construction have been conducted. The main examples are the works carried out by Khoshnevis and Zhang (2012) [21], Cesaretti et al. (2014) [20], and NASA's 3D-Printed

Habitat Challenge Competition (2019) [79]. In what follows, the above-mentioned projects and their achievements are briefly described.

In a feasibility study supported by NASA, Khoshnevis and Zhang utilized the CC technique to construct a lunar outpost [21]. In this research study, a dome-shape habitat composed of sulfur concrete and sintered regolith was constructed (Figure 8). Sulfur concrete can be produced by mixing pure sulfur and regolith [68]. Pure sulfur can be obtained via the decomposition of troilite minerals (FeS) found in lunar/Martian regolith [21], thereby dramatically reducing transportation costs. The researchers reported that the dome-shape structure constructed using the CC technique had a compressive strength close to 55 MPa, which is highly considerable. For comparison, the compressive strength of common terrestrial concrete varies from 17 MPa to 28 MPa [88].

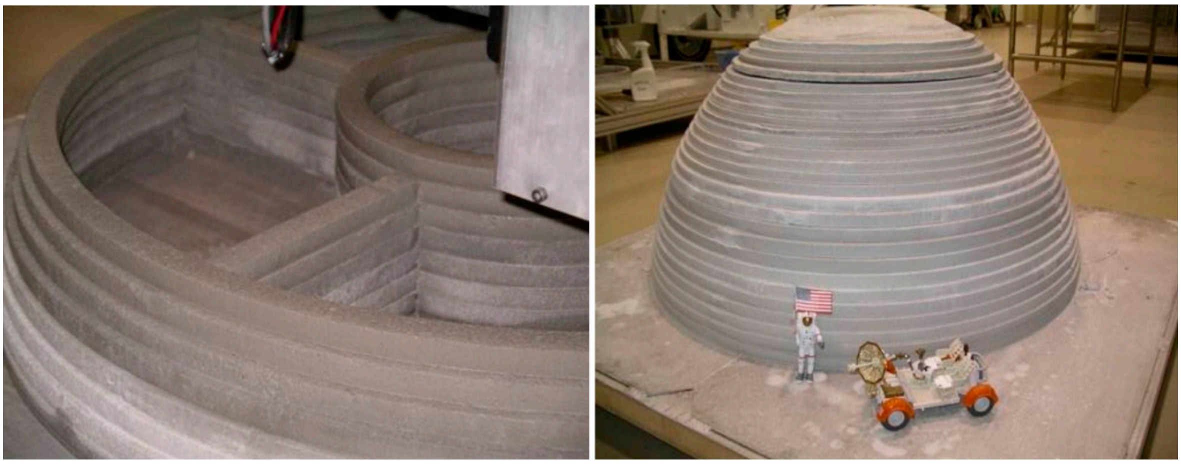

Figure 8. The dome-shaped lunar habitat manufactured using contour crafting 3D printing technology [9].

In another feasibility study founded by the ESA, Cesaretti et al. used D-shape technology to fabricate regolith-based components for outpost construction on the lunar surface [20]. The outpost's structure included an inflatable module protected by 3D-printed components (Figure 9 (left)). The diameter, length, and volume of the inflatable module were 2.5 m, 8 m, and 40 m^3, respectively. The printing machine was a large plotter capable of spraying the liquid binder on the regolith (Figure 9 (right)). To print each building component, firstly, the corresponding 3D CAD file was given to the machine. Then, the 3D body of the component was dissected by some horizontal planes to create 2D sections. Finally, each 2D section was sent to the plotter to print the section. This process continued until the whole body of the component was printed.

In Cesaretti et al.'s study, the location of the lunar outpost was proposed on the Moon's south pole, where the presence of water was already reported by different researchers [3–5,89–91]. As already mentioned, Cesaretti et al. expressed that the thickness of each printed component can be selected between 1.5 m and 2 m to curtail solar winds. Moreover, they stated that the thickness of printed components must at least be 0.8 m to protect the outpost from meteorite impacts. The main challenge in Cesaretti et al.'s outpost was the potential for evaporation or the binder liquid becoming frozen when it was sprayed on the regolith layer in vacuum and cryogenic temperature conditions. To evaluate this challenge, some experiments were conducted in the laboratory setting under vacuum and very low temperature conditions. It was found that the impact of cryogenic temperature on the liquid binder is more critical than the vacuum condition. However, it was concluded that the binder liquid survives if some necessary specifications are considered. In addition, a preliminary estimation of the transportation cost showed that for the construction of the 40 m^3 volume outpost, the interplanetary transportation of 3.8 tons of liquid binder together with 1.5 tons of inflatable module is needed. The transportation cost per kg is variable for different planets and space mission purposes; however, an average estimate can be EUR 200,000 per kg. Hence, the transportation of the whole 5.3 tons of materials from the Earth to the Moon costs at least EUR 1060 billion.

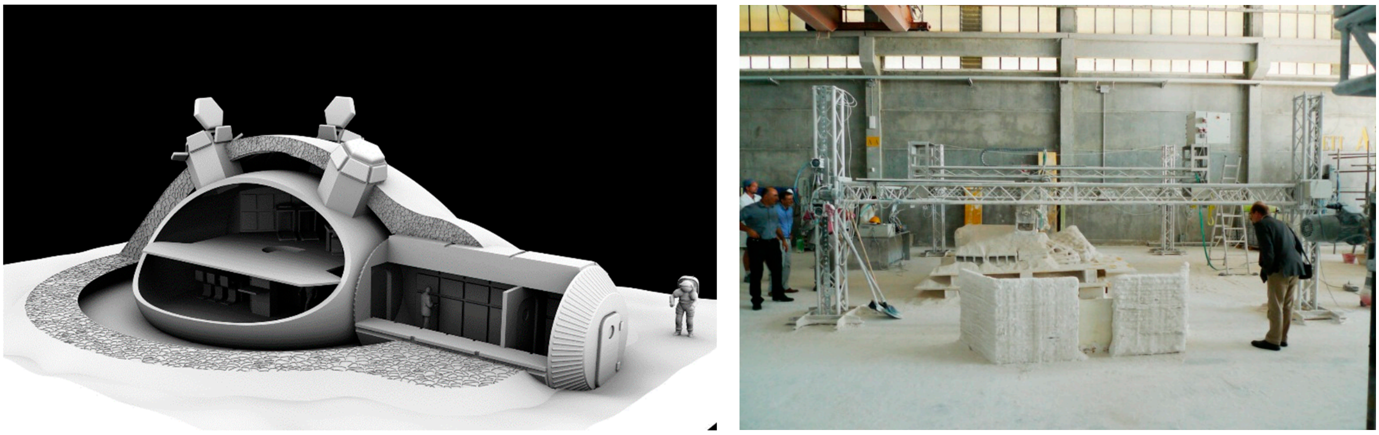

Figure 9. The design of the habitat constructed using D-shape technology and internal inflatable structure (**left**). The 3D printing machine (**right**) [2].

In NASA's 3D-Printed Habitat Challenge Competition project [79], two teams, including the AI Space Factory and Penn State University, competed to construct a habitable 3D-printed outpost on Mars. The competition's objective was to develop an autonomous printer that required minimal human intervention and fulfilled rigorous structural tests. The scale of the printed outpost was one-third of the main proposed design. The victorious team would be awarded a prize of USD 500,000 [79].

The AI Space Factory's team constructed a 15-by-8-foot egg-shaped structure (Figure 10a), known as MARSHA (Mars Habitat), using a recyclable composite comprising basaltic fibers and a bioplastic derived from plant starch. The material, heated to approximately 176 °C, was extruded and quickly cooled, and it transformed into a durable and reusable substance within five minutes. Meanwhile, Penn State's team employed river-sand-based cement to build their structure. This cement had the advantage of setting faster than conventional concrete, resulting in a stronger material. Within 120 min, the cement would solidify and prevent any deformation. The completed structure resembled two interconnected igloos, each featuring a cone-shaped roof (Figure 10b). However, the team encountered a setback when they discovered that the conveyor belt responsible for transporting cement powder had reversed, leading to the extrusion of only water by the printer [79].

To assess the structures' integrity, a series of tests were conducted. Firstly, colored smoke was blown into the structures to reveal any cracks or flaws. Secondly, judges dropped three weighted balls from a height of 4.5 m onto the structures: a 7.25 kg ball, a 9.07 kg ball, and a 11.80 kg ball. The last test was a compression test performed to check the resistance of both structures (Figure 10c,d). Finally, the AI space Factory won the competition, and currently, both teams are continuing their improvements of their proposed outpost design [79].

Apart from the type of 3D printing technique, the regolith sintering method also has a critical role in the success of the applied 3D printing process. As mentioned earlier, three methods, including laser sintering, solar sintering, and microwave sintering, can be utilized to sinter the regolith. These sintering methods use different types of energy sources, i.e., high-powered laser, solar concentrator, and microwave. The efficiency of these sintering methods was compared from different angles, such as the consumed energy, required time, heat penetration depth, the complexity of operations, regolith properties, and outpost location [64,66,92–95]. According to these studies, the following results were obtained:

- The laser sintering method needs an extremely high amount of energy for heating a small volume of regolith. Furthermore, the long time and high-temperature gradient during the printing operation can make the process problematic.
- Regarding solar sintering, although the energy source is easily available and unlimited, the dependence of the energy supplement relative to the project's performance and location can be a significant challenge. For example, solar energy is not considerably available on the Moon's poles.
- Microwave sintering requires an amount of energy that is nearly 33–44 times less than the laser sintering method [96].
- The heat penetration depth is also another challenge that should be considered. The heat penetration depth in the regolith is greater when using the microwave sintering method compared to the solar sintering method [97].
- The complexity of operations is another issue that is mostly critical in the solar sintering method. For example, the position maintenance of the focal spot, cleaning the lenses and mirrors from the dust, etc., are some of these challenges [97,98].
- Regolith properties can also affect the performance of sintering methods. For instance, the efficiency of the solar sintering method is dependent on the regolith's optical properties [99]. On the contrary, it is believed that the complexity of the regolith's morphology may enhance microwave sintering efficiency [100]. The reason for this is regolith densification due to the presence of high portions of glass and ilmenite ($FeTiO_3$) within the regolith's composition [101].

Figure 10. The 3D-printed outpost structures by the AI Space Factory team (**a**) and PENN State team (**b**). The performance of the outpost structures under compression tests (**c**,**d**) [79].

Based on the above-mentioned requirements, capabilities, and limitations, the microwave sintering method seems to be the most reliable option. Nevertheless, despite all its advantages, some challenges have not been addressed yet. For instance, at low frequencies, the heat penetration depth is greater, but less energy will be absorbed when sintering the regolith. In addition, in this method, energy absorption depends chiefly on the regolith's properties, such as the regolith's composition, grain size, density, temperature, moisture, and dielectric properties. Generally, self-insulation [98,102], weak absorption at low frequencies, and thermal runaway are the most significant challenges of the microwave sintering method.

Regardless of the 3D printing technique and regolith sintering method, it should be noted that the implementation of 3D printing operations in remote planets needs extra considerations. Based on the conducted research, the following considerations are necessary to take into account:

- Some activities, such as collecting raw regolith and feeding it into the 3D printing machine, are integral parts of the construction process. Therefore, a proactive approach is needed to mitigate the dust, which can create formidable obstacles during the printing process [22].
- The duration of the outpost's construction will be remarkably long if only one printing machine is used for the entire project [103]. As a consequence, the temperature variations, dust, and other harsh environmental factors may negatively impact the 3D printing process. Thus, considering the importance of the number of the 3D printing machines during the outpost construction process is recommended.
- For the evaluation of the performance of the 3D printing system, the diversity of the chemical and mineralogical properties of regolith should also be examined [104,105]. Since the original samples of the in situ regolith are limited, regolith simulants are used in terrestrial experiments; however, the size, shape, and composition of those simulants are not completely matched with the in situ regolith [106]. The lack of np-Fe^0 in the simulant is another difference [107]. Furthermore, the original sample of the regolith is taken from just one specific point, and even if the simulant is made completely similar to the real sample, it still cannot represent the entire surface of the construction site [105,108].
- To reduce the sintering time, the problem of low gravity should be addressed since it influences regolith densification. If the material is well compacted, not only will sintering times be minimized but the density and strength of the fabricated component also increase [109].

3. Results and Discussion

In the previous sections, a detailed review of extraterrestrial physics-based challenges, regolith aggregate ability, and the potential techniques for constructing extraterrestrial outposts on the Moon and Mars was presented. In this section, a discussion of the main challenge pertinent to planetary habitat development is provided.

Amongst physics-based challenges, the cryogenic temperature appears to be the most pressing problem for the development of extraterrestrial outposts. For instance, regarding the location of the outpost on the lunar surface, it may be said that the Shackleton crater, situated in the southern pole, is appropriate for outpost construction. In this region, the sun never sets, and it shines at a relative horizontal angle relative to the crater's surface [20]. Thus, minor solar radiation reaches the outpost. Nevertheless, the main problem will be the cryogenic temperature derived from the polar nature of the region. Therefore, ultra-resistance to cryogenic temperatures must be regarded as a key criterion in the selection of materials and 3D-printed modules.

The regolith found on the Moon and Mars can be applied in both raw and synthesized forms. The raw regolith can be used as a shield layer to protect the outposts from meteoroid impacts, solar radiation [110], and temperature fluctuations. It can also be directly deposited on the outpost and covered with membranes for guaranteeing the stability of the walls. In this case, the geomechanical properties of the regolith are highly influential with respect to the wall's stability [10,111]. On the other hand, the synthesized regolith can be combined with additives or binders to create new materials with increased compressive strength.

The physical and geotechnical properties of the raw regolith are also very seminal in the 3D printing process. During the manufacturing process, the regolith must be collected by rovers and is fed into the printing machine; hence, the subsequent factors must be considered. Firstly, collecting surficial lunar regolith needs more robotic energy than Martian regolith. In fact, from the Moon's surface level to the depth of 30 cm, the regolith's bulk density increases from 1.30 g/cm^3 to 1.69 g/cm^3 [112,113]. By contrast, on Mars, the regolith's bulk density builds up from 1.30 g/cm^3 (at surface) to 1.34 g/cm^3 (at depth = 30 cm) [114]. And more than this, the geotechnical properties of the Martian regolith are much closer to the lunar mare regions rather than the lunar highlands. The reason is that in a similar way to the Martian environment, the lunar mare regions have been impacted less by the meteoroids compared to the lunar highlands. Thus, the construction of a prospective outpost in mare regions requires less robotic energy as the regolith's bulk density is closer to the Martian regolith. The second consideration is related to the slope stability of the regolith's slopes; as the gravity of the Moon is less than Mars, the regolith's slopes remain stable, with sharper angles between their toe and the horizon. This matter also has a direct impact on the thickness (and volume) of the regolith required to be deposited on the outpost. The third consideration is pertinent to the effect of temperature fluctuations on the water volume contained in the regolith. The stress cycles derived from temperature fluctuations perpetually alter the physico-mechanical characteristics of soils [115–117]. Since hydro-mechanical coupling between the solid skeleton of the regolith and its frozen water continually shifts [118], the effect of temperature on poroelastic parameters must be also taken into account.

The inflatable modules are the most appropriate options for providing the breathable environment inside the habitat while 3D printing technology can be used for manufacturing the outer building components. The inflatable modules provide numerous benefits in the construction process. First of all, they can be easily designed and manufactured in various structural forms, including stowed, telescoping, cylindrical, hemispherical, etc. The second advantage is their high strength in tension conditions since the inner pressure inside the inflatable module induces large tensile stresses within the structure. The third benefit is their light weight and low occupied volume, which lead to lower transportation costs, lower energy consumption by construction robots/rovers, and increased execution flexibility. Last but not least, the inflatable structures prevent breathable air from leakage. This characteristic almost renders the inflatable structures indispensable in any future outpost structure combined with 3D-printed components.

Using 3D printing technology, the creation of large human outposts on lunar and Martian surfaces seems to be much more conceivable as it does not need a substantial transportation of raw materials to space. However, in lunar and Martian settings, inorganic binders are not available and must be taken from the Earth to space. This imposes substantial monetary and energy costs on the project. Some investigations have revealed that the Martian regolith possesses clay and gypsum minerals [119–121], and in the case of water extraction on the Martian surface, new materials, which function in a similar way to Earth-based concrete/cement, can be produced. Hence, further exploration operations, such as exploratory boreholes and sample collection from the lunar/Martian surface, are suggested to realize a fully ISRU outpost construction. To study the deeper layers of regolith, the implementation of drilling operations by rovers are inevitable [122,123]. The surface layer of the Moon and Mars can also be further studied using indirect techniques, such as geophysical methods and distant remote sensing [124,125].

The choice of a suitable 3D printing method hinges on three pivotal factors: firstly, the environmental condition; secondly, the expenses related to providing raw materials; and thirdly, the energy requirements essential for executing the project within the extraterrestrial setting. However, it is noteworthy to mention that all these three factors are intertwined.

Based on the conducted research, the authors posit that microgravity and cryogenic temperature are the most critical environmental challenges for the 3D printing process on remote planets. Due to microgravity, hauling regolith to feed the 3D printing machine is a difficult task. Additionally, the regolith may not be effectively consolidated and prepared for the sintering process. The less regolith densification there is, the more energy and time needed for the sintering and printing process. Regarding the cryogenic temperature of lunar and Martian environments, it can be said that this issue especially affects the binders' state. In other words, the cryogenic temperature makes the binder freeze or evaporate, thereby hindering the 3D printing process. Furthermore, the cryogenic temperature restricts the range of Earth-based materials that can be used in extraterrestrial habitat construction. Apart from microgravity and cryogenic temperature, other environmental challenges, such as low atmospheric pressure, lack of a magnetic field, surface radiation, and micrometeoroid impacts, are important. However, based on previous investigations, these issues can be solved by taking specific actions [20].

The energy efficiency of 3D printing processes principally relies on manufacturing technology, required raw materials, regolith sintering method, and dominant environmental challenges. Manufacturing technology determines the required raw materials; the complexity of the 3D printing process; and the size, weight, and number of printing machines. Moreover, the regolith sintering method is an essential factor in achieving a successful, energy-saving 3D printing process. The microwave sintering method requires 33–44 times less energy than the laser sintering method [96]. It is also more efficient than the solar sintering method, which depends on the outpost's location, regolith optical properties, the position maintenance of the focal spots, and dust removal from the printing machines' lenses [96]. Hence, a precise trade-off between the available manufacturing technology and regolith sintering methods must be realized to select the reliable 3D printing technique with optimal energy and time required for the fabrication process.

To test the reliability of extra-terrestrial outposts, as well as the experimental and numerical investigations on meteoroid impacts [126], evaluating the outpost's response to the moonquakes and marsquakes is also recommended. Moonquakes and marsquakes can have significant implications for lunar and Martian outposts [127,128]. Understanding the frequency, intensity, and patterns of these seismic activities is crucial for designing any robust and resilient infrastructure. Moonquakes, although generally mild, can still pose a risk to surface structures and equipment [127]. Lunar habitats and resource extraction facilities must be engineered to withstand the occasional shaking and vibrations. Similarly, Martian outposts need to account for the potential impact of marsquakes. These seismic events can vary in magnitude and duration, potentially affecting the stability of structures, underground habitats, and life support systems [128]. Engineers and designers working on Martian outposts must develop seismic-resistant technologies and construction methods to ensure the safety and longevity of habitats and infrastructure.

4. Conclusions

In this research, an inclusive review was carried out to assess the different structures proposed for outpost construction on celestial bodies, especially on the Moon and Mars. The chronological overview of the proposed structures showcased the evolution of construction techniques and materials. In fact, from the early concepts of inflatable structures and flat trusses to more recent advancements in 3D printing, researchers have continued to explore innovative approaches to ensure the viability and sustainability of future extraterrestrial habitats.

Based on the conducted investigation, six physics-based challenges were identified as the most critical obstacles to the development of lunar and Martian outposts. These challenges are microgravity, cryogenic temperature, vacuum condition, lack of magnetic field, intense surface radiations, and micrometeoroid impacts. While all of these challenges constrain planetary infrastructure development, the cryogenic temperature seems to be the most restricting factor. Cryogenic temperatures induce thermal stresses on the habitat's structural elements, thereby leading to potential fatigue and failure in the building modules. This limitation also precludes various materials from being applied in the construction process. Moreover, cryogenic temperatures lead to the freezing or evaporation of any fluid, such as the binder liquid utilized in 3D printing processes. Additionally, a vast amount of energy is required to keep the habitat warm for astronauts and habitants. All these issues require substantial energy consumption and material transportation costs from the Earth to space. Hence, for future works, further investigating the impact of cryogenic temperature on the manufacturing process of 3D printing operations is recommended.

Overall, the utilization of regolith and the advancement of 3D printing technology have opened up new possibilities for constructing outposts on Moon, Mars, and other extraterrestrial environments. These techniques offer potential energy savings by utilizing local resources. It can be stated that current 3D printing technology has the capability to create early structures with the necessary strength and durability for long-term human habitation. However, to extend habitats for a larger number of inhabitants, fully ISRU operations with more powerful rovers and 3D printing machines are required.

It was also concluded that a safe, reliable outpost is constructible if the 3D-printed components are utilized in conjunction with an internal breathable inflatable module. In this case, more than 60% of the total interplanetary transportation cost will be related to binder liquid transport. Hence, investigating binders that can be produced on site is recommended. If this is carried out, a dramatic saving in energy and costs can be acquired. To summarize, although current 3D printing technology seems to be robust for developing off-Earth outposts, there is still a need for more investigation with respect to its progression, leading to saving more transportation costs and energy.

Author Contributions: Conceptualization, data curation, writing—review and editing, writing—original draft preparation, visualization, and methodology: M.K. and D.K.; formal analysis, software, investigation, and resources: M.K.; validation, supervision, and project Administration: D.K. All authors have read and agreed to the published version of the manuscript.

Funding: This project was supported by the AGH University of Krakow, Poland, subsidy 16.16.190.779.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank Mohammad Zamani Ahmad Mahmoudi, student at the AGH university of Krakow, for his support during the conduction of this research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. A Future of Lunar Habitats: Designing for Life on the Moon. 2020. Available online: https://lifestyle.livemint.com/smart-living/innovation/future-of-lunar-habitats-designing-for-life-on-the-moon-111634486770359.html (accessed on 20 February 2022).
2. Building a Lunar Base with 3D Printing. Available online: https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Building_a_lunar_base_with_3D_printing (accessed on 31 January 2013).
3. Pieters, C.M.; Goswami, J.N.; Clark, R.N.; Annadurai, M.; Boardman, J.; Buratti, B.; Combe, J.P.; Dyar, M.D.; Green, R.; Head, J.W.; et al. Character and spatial distribution of OH/H_2O on the surface of the Moon seen by M3 on Chandrayaan-1. *Science* **2009**, *326*, 568–572. [CrossRef] [PubMed]
4. Colaprete, A.; Schultz, P.; Heldmann, J.; Wooden, D.; Shirley, M.; Ennico, K.; Hermalyn, B.; Marshall, W.; Ricco, A.; Elphic, R.C.; et al. Detection of water in the LCROSS ejecta plume. *Science* **2010**, *330*, 463–468. [CrossRef]
5. Martín-Torres, F.J.; Zorzano, M.P.; Valentín-Serrano, P.; Harri, A.M.; Genzer, M.; Kemppinen, O.; Rivera-Valentin, E.G.; Jun, I.; Wray, J.; Bo Madsen, M.; et al. Transient liquid water and water activity at Gale crater on Mars. *Nat. Geosci.* **2015**, *8*, 357–361. [CrossRef]
6. Mars Perseverance. 2020. Available online: https://www.eoportal.org/other-space-activities/mars-perseverance-2020#more-about-the-campaign (accessed on 21 June 2019).
7. Artemis Program Mars Perseverance. Available online: https://www.eoportal.org/other-space-activities/artemis-program (accessed on 15 July 2019).

8. Seweryn, K.; Skocki, K.; Banaszkiewicz, M.; Grygorczuk, J.; Kolano, M.; Kuciński, T.; Mazurek, J.; Morawski, M.; Białek, A.; Rickman, H.; et al. Determining the geotechnical properties of planetary regolith using low velocity penetrometers. *Planet. Space Sci.* **2014**, *99*, 70–83. [CrossRef]
9. Kalapodis, N.; Kampas, G.; Ktenidou, O. A review towards the design of extraterrestrial structures: From regolith to human outposts. *Acta Astronaut.* **2020**, *175*, 540–569. [CrossRef]
10. Knez, D.; Zamani, M.A.M. A Review of the Geomechanics Aspects in Space Exploration. *Energies* **2021**, *14*, 7522. [CrossRef]
11. Rajaoalison, H.; Knez, D.; Zlotkowski, A. Changes of Dynamic Mechanical Properties of Brine-Saturated Istebna Sandstone under Action of Temperature and Stress. *Przemysł Chem.* **2019**, *98*, 801–804.
12. Knez, D.; Rajaoalison, H. Discrepancy between Measured Dynamic Poroelastic Parameters and Predicted Values from Wyllie's Equation for Water-Saturated Istebna Sandstone. *Acta Geophys.* **2021**, *69*, 673–680. [CrossRef]
13. Nowak, P.S.; Sadeh, W.Z.; Morroni, L.A. Geometric Modeling of Inflatable Structures for Lunar Base. *J. Aerosp. Eng.* **1992**, *5*, 311–322. [CrossRef]
14. Benaroya, H.; Ettouney, M. Framework for Evaluation of Lunar Base Structural Concepts. *J. Aerosp. Eng.* **1992**, *5*, 187–198. [CrossRef]
15. Benaroya, H. Tensile-integrity structures for the Moon. *Appl. Mech. Rev.* **1993**, *46*, 326–335. [CrossRef]
16. Tensegrity. Available online: https://en.wikipedia.org/wiki/Tensegrity (accessed on 6 November 2023).
17. Ng, T.T. Numerical Simulations of a Deployable Structure. In Proceedings of the Earth & Space 2006: Engineering, Construction, and Operations in Challenging Environment, League City, TX, USA, 5–8 March 2006. [CrossRef]
18. Ruess, F.; Schaenzlin, J.; Benaroya, H. Structural design of a lunar habitat. *J. Aerosp. Eng.* **2006**, *19*, 133–157. [CrossRef]
19. Benaroya, H. Structures for manned habitation. In Proceedings of the Earth & Space 2006: Engineering, Construction, and Operations in Challenging Environment, League City, TX, USA, 5–8 March 2006. [CrossRef]
20. Cesaretti, G.; Dini, E.; De Kestelier, X.; Colla, V.; Pambaguian, L. Building components for an outpost on the Lunar soil by means of a novel 3D printing technology. *Acta Astronaut.* **2014**, *93*, 430–450. [CrossRef]
21. Khoshnevis, B.; Zhang, J. Extraterrestrial construction using contour crafting. In Proceedings of the International Solid Freeform Fabrication Symposium. University of Texas at Austin, Austin, TX, USA, 14–16 August 2012. [CrossRef]
22. Lim, S.; Prabhu, V.L.; Anand, M.; Taylor, L.A. Extra-terrestrial construction processes—Advancements, opportunities and challenges. *Adv. Space Res.* **2017**, *60*, 1413–1429. [CrossRef]
23. Malla, R.B.; Chaudhuri, D. Analysis of a 3D frame—Membrane structure for lunar base. In Proceedings of the Engineering, Construction, and Operations in Challenging Environment, League City, TX, USA, 5–8 March 2006. [CrossRef]
24. Malla, R.B.; Chaudhuri, D. Dynamic analysis of a 3-D frame-membrane lunar structure subjected to impact. In Proceedings of the Earth & Space 2008: Engineering, Science, Construction, and Operations in Challenging Environments, Long Beach, CA, USA, 26 April 2008. [CrossRef]
25. Malla, R.B.; Gionet, T.G. Dynamic response of a pressurized frame-membrane lunar structure with regolith cover subjected to impact load. *J. Aerosp. Eng.* **2013**, *26*, 855–873. [CrossRef]
26. De Kestelier, X.; Dini, E.; Cesaretti, G.; Colla, V.; Pambaguian, L. Lunar Outpost Design for ESA. Available online: https://spacearchitect.org/portfolio-item/lunar-outpost-design-for-esa/ (accessed on 20 February 2012).
27. Mostafaei, K.; Zamani, M.A.M.; Knez, D. Risk Management Prediction of Mining and Industrial Projects by Support Vector Machine. *Resour. Policy* **2022**, *78*, 102819. [CrossRef]
28. Williams, D.R. Planetary Fact Sheet-Metric. Available online: https://nssdc.gsfc.nasa.gov/planetary/factsheet/ (accessed on 11 February 2023).
29. Schock, B.A.; Caleb Hing, C.L. A Civil Engineering Approach to Development of the Built Martian Environment. In *Earth and Space*; ASCE Publishing: Reston, VA, USA, 2014; pp. 313–327. [CrossRef]
30. Khalilidermani, M.; Knez, D. A Survey of Application of Mechanical Specific Energy in Petroleum and Space Drilling. *Energies* **2022**, *15*, 3162. [CrossRef]
31. Knez, D.; Khalilidermani, M. A Review of Different Aspects of Off-Earth Drilling. *Energies* **2021**, *14*, 7351. [CrossRef]
32. Koscher, E. Here's what Future Mars and Lunar Space Colonies Could Look Like. Available online: https://www.nbcnews.com/mach/science/here-s-what-future-mars-lunar-space-colonies-could-look-ncna889341 (accessed on 7 July 2018).
33. Williams, M.S. The Science of Becoming "Interplanetary": How Can Humans Live on Mars? Available online: https://interestingengineering.com/science/becoming-interplanetary-how-can-humans-live-on-mars (accessed on 11 January 2022).
34. Hollingham, R. The Epic Quest to Build a Permanent Moon Base. Available online: https://www.bbc.com/future/article/20230317-the-epic-quest-to-build-a-permanent-moon-base (accessed on 20 March 2023).
35. Knez, D.; Mazur, S. Simulation of Fracture Conductivity Changes due to Proppant Composition and Stress Cycles. *Inżynieria Miner.* **2019**, *21*, 231–234.
36. Jakosky, B.M.; Phillips, R.J. Mars' volatile and climate history. *Nature* **2001**, *412*, 237–244. [CrossRef]
37. Benaroya, H. Lunar Habitats: A Brief Overview of Issues and Concepts. *Reach* **2017**, *7*, 14–33. [CrossRef]
38. Sheshpari, M.; Fujii, Y.; Tani, Y. Underground structures in Mars excavated by tunneling methods for sheltering humans. *Tunn. Undergr. Space Technol.* **2017**, *64*, 61–73. [CrossRef]

39. Theinat, A.K.; Modiriasari, A.; Bobet, A.; Melosh, H.J.; Dyke, S.; Ramirez, J.; Maghareh, A.; Gomez, D. Geometry and Structural Stability of Lunar Lava Tubes. In Proceedings of the 2018 AIAA SPACE and Astronautics Forum and Exposition, Orlando, FL, USA, 15 September 2018; p. 5185. [CrossRef]
40. Theinat, A.K.; Modiriasari, A.; Bobet, A.; Melosh, H.J.; Dyke, S.J.; Ramirez, J.; Maghareh, A.; Gomez, D. Lunar lava tubes: Morphology to structural stability. *Icarus* **2020**, *338*, 113442. [CrossRef]
41. Lammer, H.; Bredehöft, J.H.; Coustenis, A.; Khodachenko, M.L.; Kaltenegger, L.; Grasset, O.; Prieur, D.; Raulin, F.; Ehrenfreund, P.; Yamauchi, M.; et al. What makes a planet habitable? *Astron. Astrophys. Rev.* **2009**, *17*, 181–249. [CrossRef]
42. Magnetospheres. Available online: https://science.nasa.gov/heliophysics/focus-areas/magnetosphere-ionosphere/ (accessed on 11 August 2023).
43. A Guide to the Magnetosphere. Available online: https://earthhow.com/magnetosphere/#:~:text=The%2520main%2520role%2520of%2520the,aurora%2520borealis%252C%2520and%2520space%2520weather (accessed on 28 September 2023).
44. Lundin, R.; Lammer, H.; Ribas, I. Planetary magnetic fields and solar forcing: Implications for atmospheric evolution. *Space Sci. Rev.* **2007**, *129*, 245–278. [CrossRef]
45. Reitz, G.; Berger, T.; Matthiae, D. Radiation Exposure in the Moon Environment. *Planet. Space Sci.* **2012**, *74*, 78–83. [CrossRef]
46. Parnell, T.A.; Watts, J.W., Jr.; Armstrong, T.W. Radiation Effects and Protection for Moon and Mars Missions. In Proceedings of the Space 98, Albuquerque, NM, USA, 26–30 April 1998. [CrossRef]
47. Celebrating International Moon Day While Paving the Way for Lunar Habitation. Available online: https://www.airbus.com/en/newsroom/stories/2023-07-celebrating-international-moon-day-while-paving-the-way-for-lunar (accessed on 20 July 2023).
48. Moore, H.J.; McGee, J. Optimization of thin film solar concentrators using non-linear deflection modeling. In Proceedings of the 19th AIAA Applied Aerodynamics Conference, Anaheim, CA, USA, 11–14 June 2001. [CrossRef]
49. Nakamura, Y.; Dorman, J.; Duennebier, F.; Ewing, M.; Lammlein, D.; Latham, G. High-frequency lunar teleseismic events. In Proceedings of the 5th Lunar Science Conference, Houston, TX, USA, 18–22 March 1974; Pergamon Press, Inc.: New York, NY, USA, 1974; Volume 3, pp. 2883–2890.
50. Duennebier, F.; Sutton, G.H. Meteoroid impacts recorded by the short-period component of Apollo 14 Lunar passive seismic station. *J. Geophys. Res.* **1974**, *79*, 4365–4374. [CrossRef]
51. Lognonné, P.; Banerdt, W.B.; Giardini, D.; Pike, W.T.; Christensen, U.; Laudet, P.; De Raucourt, S.; Zweifel, P.; Calcutt, S.; Bierwirth, M.; et al. SEIS: Insight's seismic experiment for internal structure of Mars. *Space Sci. Rev.* **2019**, *215*, 12. [CrossRef]
52. Duennebier, F.; Dorman, J.; Lammlein, D.; Latham, G.; Nakamura, Y. Meteoroid Flux from Passive Seismic Experiment Data. In *Lunar Science Conference, 6th, Houston, TX, USA, 17–21 March 1975, Proceedings. (A78-46668 21-91)*; Pergamon Press, Inc.: New York, NY, USA, 1975; Volume 2, pp. 2417–2426.
53. Duennebier, F.K.; Nakamura, Y.; Latham, G.V.; Dorman, H.J. Meteoroid Storms Detected on the Moon. *Science* **1976**, *192*, 1000–1002. [CrossRef]
54. Wilhelms, D.E.; John, F.; Trask, N.J. *The Geologic History of the Moon*; USGS: Reston, VA, USA, 1987. [CrossRef]
55. Head, J.W., III; Wilson, L. Lunar mare volcanism: Stratigraphy, eruption conditions, and the evolution of secondary crusts. *Geochim. Cosmochim. Acta* **1992**, *56*, 2155–2175. [CrossRef]
56. Mottaghi, S.; Benaroya, H. Design of a lunar surface structure. II: Seismic structural analysis. *J. Aerosp. Eng.* **2015**, *28*, 04014053. [CrossRef]
57. Lucey, P.; Korotev, R.L.; Gillis, J.J.; Taylor, L.A.; Lawrence, D.; Campbell, B.A.; Elphic, R.; Feldman, B.; Hood, L.L.; Hunten, D.; et al. Understanding the lunar surface and space-Moon interactions. *Rev. Mineral. Geochem.* **2006**, *60*, 83–219. [CrossRef]
58. Sadeh, W.; Criswell, M. Inflatable structures for a Lunar base. In Proceedings of the Space Programs and Technologies Conference and Exhibit, Huntsville, AL, USA, 21 September 1993. [CrossRef]
59. Jolly, S.D.; Happel, J.; Sture, S. Design and construction of a shielded Lunar outpost. *J. Aerosp. Eng.* **1994**, *7*, 417–434. [CrossRef]
60. Abarbanel, J.E.; Bateman, T.A.; Criswell, M.E.; Sadeh, W.Z. A Framing System for a Lunar/Martian Inflatable Structure. In Proceedings of the Engineering, Construction, and Operations in Space V, Albuquerque, NM, UAS, 26 April 1996. [CrossRef]
61. Knez, D. Stress State Analysis in Aspect of Wellbore Drilling Direction. *Arch. Min. Sci.* **2014**, *59*, 71–76. [CrossRef]
62. Kim, M.Y.; Thibault, S.A.; Simonsen, L.C.; Wilson, J.W. *Comparison of Martian Meteorites and Martian Regolith as Shield Materials for Galactic Cosmic Rays*; NASA Langley Research Center: Hampton, VA, USA, 1998.
63. Khoshnevis, B.; Carlson, A.; Thangavelu, M. *ISRU-Based Robotic Construction Technologies for Lunar and Martian Infrastructures*; NIAC Phase II Final Report; University of Southern California: Los Angeles, CA, USA, 2017.
64. Mueller, R.P.; Howe, S.; Kochmann, D.; Ali, H.; Andersen, C.; Burgoyne, H.; Chambers, W.; Clinton, R.; De Kestellier, X.; Ebelt, K.; et al. Automated Additive Construction (AAC) for Earth and Space Using in Situ Resources. In Proceedings of the 15th Biennial International Conference on Engineering, Science, Construction, and Operations in Challenging Environments, Orlando, FL, USA, 11–15 April 2016.
65. Balla, V.K.; Roberson, L.B.; O'Connor, G.W.; Trigwell, S.; Bose, S.; Bandyopadhyay, A. First demonstration on direct laser fabrication of lunar regolith parts. *Rapid Prototyp. J.* **2012**, *18*, 451–457. [CrossRef]
66. Meurisse, A.; Makaya, A.; Willsch, C.; Sperl, M. Solar 3D printing of lunar regolith. Solar 3D Printing of Lunar Regolith. *Acta Astronaut.* **2018**, *152*, 800–810. [CrossRef]
67. Goulas, A.; Binner, J.G.; Engstrøm, D.S.; Harris, R.A.; Friel, R.J. Mechanical behaviour of additively manufactured lunar regolith simulant components. *J. Mater. Des. Appl.* **2018**, *233*, 1629–1644. [CrossRef]

68. Meyers, C.; Toutanji, H. Analysis of Lunar-Habitat Structure Using Waterless Concrete and Tension Glass Fibers. *J. Aerosp. Eng.* **2007**, *20*, 220–226. [CrossRef]
69. Malla, R.B.; Adib-Jahromi, H.R.; Accorsi, M.L. Simplified design method for braced double-skinned structure in lunar application. *J. Aerosp. Eng.* **1995**, *8*, 189–195. [CrossRef]
70. Kennedy, K.J. ISS TransHab: Architecture Description. In Proceedings of the International Conference on Environmental Systems, Denver, CO, USA, 12 July 1999. [CrossRef]
71. Harris, P.; Kennedy, K. Wound Construction of Inflatable Space Structures. In Proceedings of the Seventh International Conference and Exposition on Engineering, Construction, Operations, and Business in Space, Albuquerque, NM, USA, 27 February–2 March 2000. [CrossRef]
72. Borin, A.; Fiscelli, M. An inflatable living concept. In Proceedings of the Ninth Biennial Conference on Engineering, Construction, and Operations in Challenging Environments, League City, TX, USA, 7–10 March 2004. [CrossRef]
73. Criswell, M.E.; Carlson, J.S. Concepts for the design and construction of a modular inflatable habitat. In Proceedings of the Ninth Biennial Conference on Engineering, Construction, and Operations in Challenging Environments, League City, TX, USA, 7–10 March 2004. [CrossRef]
74. Adams, C.M.; Petrov, G. The Surface Endoskeletal Inflatable Module (SEIM). In Proceedings of the Earth & Space 2006: Engineering, Construction, and Operations in Challenging Environment, League City, TX, USA, 5–8 March 2006. [CrossRef]
75. Tinker, M.; Hull, P.V.; SanSoucie, M.P.; Roldan, A. Inflatable and Deployable Structures for Surface Habitat Concepts Utilizing In-Situ Resources. In Proceedings of the Engineering, Construction, and Operations in Challenging Environment, League City, TX, USA, 5–8 March 2006. [CrossRef]
76. Faierson, E.J.; Logan, K.V.; Stewart, B.K.; Hunt, M.P. Demonstration of concept for fabrication of lunar physical assets utilizing lunar regolith simulant and a geothermite reaction. *Acta Astronaut.* **2010**, *67*, 38–45. [CrossRef]
77. Huang, W.; Zang, Y.; Wang, W.; Zhang, C.; Binienda, W. Advanced Materials and Designs for Hydraulic, Earth, and Aerospace Structures. In Proceedings of the Earth and Space 2018, Cleveland, OH, USA, 9–12 April 2018. [CrossRef]
78. Brandt-Olsen, C.; Coward, A.; Horswill, D. Mars Science City–Designing a future habitat in space. In Proceedings of the IASS Annual Symposia, IASS 2018 Boston Symposium: Extraplanetary Architecture; International Association for Shell and Spatial Structures (IASS): Madrid, Spain, 2018; pp. 1–8.
79. Staedter, T. AI Space Factory Wins NASA's 3D-Printed Extra-Terrestrial Habitats Challenge. Available online: https://spectrum.ieee.org/3d-printers-could-build-future-homes-on-mars (accessed on 7 May 2019).
80. Available online: https://www.esa.int/TEC/Structures/SEMMHH8J50F_2.html (accessed on 4 January 2013).
81. Available online: https://en.wikipedia.org/wiki/TransHab (accessed on 23 May 2023).
82. Knez, D.; Calicki, A. Looking For a New Source of Natural Proppants in Poland. *Bull. Pol. Acad. Sci. Tech. Sci.* **2018**, *66*, 3–8. [CrossRef]
83. Knez, D.; Wiśniowski, R.; Owusu, W.A. Turning Filling Material into Proppant for Coalbed Methane in Poland-Crush test results. *Energies* **2019**, *12*, 1820. [CrossRef]
84. Jablonski, A.; Showalter, D.J. Exploration and Utilization of Extraterrestrial Bodies. In Proceedings of the 15th Biennial ASCE Conference on Engineering, Science, Construction, and Operations in Challenging Environments, Orlando, FL, USA, 11–15 April 2016. [CrossRef]
85. Pham, D.; Dimov, S.S. *Rapid Manufacturing: The Technologies and Applications of Rapid Prototyping and Rapid Tooling*; Springer: New York, NY, USA, 2011.
86. Hopkinson, N.; Dickens, P. Emerging rapid manufacturing processes. In *Rapid Manufacturing: An Industrial Revolution for the Digital Age*; John Wiley & Sons Ltd.: Chichester, UK, 2006; pp. 55–80.
87. Buswell, R.A.; Soar, R.C.; Gibb, A.G.; Thorpe, A. Freeform construction: Mega-scale rapid manufacturing for construction. *Autom. Constr.* **2007**, *16*, 224–231. [CrossRef]
88. What Is the Standard Strength of Concrete? Available online: https://www.bigdreadymix.com/what-is-the-standard-strength-of-concrete/#:~:text=Usually%252C%2520the%2520compressive%2520strength%2520of,10%252C000%2520psi%2520(70%2520MPa) (accessed on 20 March 2023).
89. Bannova, O.; Bell, L. Radiation shielding design strategies for lunar minimal functionality habitability element. *Acta Astronaut.* **2010**, *67*, 1103–1109. [CrossRef]
90. Gladstone, G.R.; Hurley, D.M.; Retherford, K.D.; Feldman, P.D.; Pryor, W.R.; Chaufray, J.Y.; Versteeg, M.; Greathouse, T.K.; Steffl, A.J.; Throop, H.; et al. LRO-LAMP observations of the LCROSS impact plume. *Science* **2010**, *330*, 472–476. [CrossRef] [PubMed]
91. Khalilidermani, M.; Knez, D.; Zamani, M.A.M. Empirical Correlations between the Hydraulic Properties Obtained from the Geoelectrical Methods and Water Well Data of Arak Aquifer. *Energies* **2021**, *14*, 5415. [CrossRef]
92. Hafner, T.A. Microwave Sinter System for Lunar Regolith Studies. Master's Thesis, Luleå University of Technology, Kiruna, Sweden, 2015.
93. Lim, S.; Anand, M. In-Situ Resource Utilisation (ISRU) derived extra-terrestrial construction processes using sintering-based additive manufacturing techniques—Focusing on a lunar surface environment. In Proceedings of the European Lunar Symposium, Frascati, Italy, 13–14 May 2015.

94. Lim, S.; Anand, M.; Rousek, T. Estimation of energy and material use of sintering-based construction for a lunar outpost—with the example of SinterHab module design. In Proceedings of the 46th Lunar and Planetary Science Conference (LPSC), Session 817, Woodlands, TX, USA, 16–20 March 2015.
95. Srivastava, V.; Lim, S.; Anand, M. Microwave processing of lunar soil for supporting longer-term surface exploration on the Moon. *Space Policy* **2016**, *37*, 92–96. [CrossRef]
96. Taylor, L.A.; Meek, T.T. Microwave sintering of lunar soil: Properties, theory, and practice. *J. Aerosp. Eng.* **2005**, *18*, 188–196. [CrossRef]
97. Allen, C.C.; Graf, J.C.; McKay, D.S. Sintering bricks on the Moon. In *Proceeding of the Engineering, Construction, and Operations in Space IV*; American Society of Civil Engineers: Reston, VA, USA, 1994.
98. Allan, S.; Merritt, B.; Griffin, B.; Hintze, P.; Shulman, H. High temperature microwave dielectric properties and processing of JSC-1AC Lunar simulant. *J. Aerosp. Eng.* **2013**, *26*, 874–881. [CrossRef]
99. Hintze, P.E.; Quintana, S. Building a Lunar or Martian launch pad with in situ materials: Recent laboratory and field studies. *J. Aerosp. Eng.* **2013**, *26*, 134–142. [CrossRef]
100. Kingery, W.D.; Bowen, H.K.; Uhlmann, D.R. *Introduction to Ceramics*; John Wiley & Sons: New York, NY, USA, 1976.
101. Zhou, P.; Zhao, Z.; Wei, G.; Huo, H. Mineral Content Estimation of Lunar Soil of Lunar Highland and Lunar Mare Based on Diagnostic Spectral Characteristic and Partial Least Squares Method. *Appl. Sci.* **2022**, *12*, 1197. [CrossRef]
102. Kenkre, V.M.; Skala, L.; Weiser, M.W.; Katz, J.D. Theory of microwave interactions in ceramic materials: The phenomenon of thermal runaway. *J. Mater. Sci* **1991**, *26*, 2483–2489. [CrossRef]
103. Doule, O.; Detsis, E.; Ebrahimi, A. A Lunar base with astronomical observatory. In Proceedings of the 41st International Conference on Environmental Systems (ICES), AIAA, Portland, OR, USA, 17–21 July 2011. [CrossRef]
104. Anand, M.; Crawford, I.A.; Balat-Pichelin, M.; Abanades, S.; van Westrenen, W.; Pe'raudeau, G.; Jaumann, R.; Seboldt, W. A brief review of chemical and mineralogical resources on the Moon and likely initial in situ resource utilization (ISRU) applications. *Planet. Space Sci.* **2012**, *74*, 42–48. [CrossRef]
105. Taylor, L.A.; Pieters, C.M.; Britt, D. Evaluations of lunar regolith simulants. *Planet. Space Sci* **2016**, *126*, 1–7. [CrossRef]
106. McKay, D.S.; Heiken, G.; Basu, A.; Blanford, G.; Simon, S.; Reedy, R.; French, B.M.; Papike, J. *Lunar Sourcebook: A User's Guild to the Moon*; Cambridge University Press: Cambridge, UK, 1991.
107. Taylor, L.A. Generation of Native Fe in Lunar Soil. In Proceedings of the Space' 88 Conference, Albuquerque, NM, USA, 29–31 August 1988.
108. Taylor, L.A.; Liu, Y. Important considerations for lunar soil simulants. In Proceedings of the Earth and Space 2010: Engineering, Science, Construction, and Operations in Challenging Environments, Honolulu, Hawaii; American Society of Civil Engineers (ASCE): Reston, VA, USA, 2010. [CrossRef]
109. Pletka, B.J. Processing of lunar basalt materials. In *Resources of Near Earth Space*; University of Arizona Press Tucson: London, UK, 1993.
110. Akisheva, Y.; Gourinat, Y. Utilisation of Moon Regolith for Radiation Protection and Thermal Insulation in Permanent Lunar Habitats. *Appl. Sci.* **2021**, *11*, 3853. [CrossRef]
111. Zamani, M.A.M.; Knez, D. A new mechanical-hydrodynamic safety factor index for sand production prediction. *Energies* **2021**, *14*, 3130. [CrossRef]
112. Zhang, X.; Zhang, G.; Gao, M.; Wen, Y.; Wang, Y. Design of Man-Machine Synergic Lunar Coring Device and Its Coring Dynamic Analysis. *Appl. Sci.* **2023**, *13*, 7961. [CrossRef]
113. Carrier III, W.D.; Olhoeft, G.R.; Mendell, W. Physical Properties of the Lunar Surface. In *Lunar Sourcebook*; Cambridge University Press: Cambridge, UK, 1991; pp. 475–594. ISBN 0521334446.
114. Vrettos, C.; Becker, A.; Merz, K.; Witte, L. Penetration tests in a mold on regolith quasi-analogues at different relative densities. In Proceedings of the Earth and Space 2014, St. Louis, MO, USA, 27–29 October 2014; pp. 10–15. [CrossRef]
115. Knez, D.; Zamani, M.A.M. Empirical Formula for Dynamic Biot Coefficient of Sandstone Samples from South-West of Poland. *Energies* **2021**, *14*, 5514. [CrossRef]
116. Zamani, M.A.M.; Knez, D. Experimental Investigation on the Relationship between Biot's Coefficient and Hydrostatic Stress for Enhanced Oil Recovery Projects. *Energies* **2023**, *16*, 4999. [CrossRef]
117. Knez, D.; Rajaoalison, H. Land Subsidence Assessment for Wind Turbine Location in the South-Western Part of Madagascar. *Energies* **2022**, *15*, 4878. [CrossRef]
118. Knez, D.; Khalilidermani, M.; Zamani, M.A.M. Water Influence on the Determination of the Rock Matrix Bulk Modulus in Reservoir Engineering and Rock-Fluid Coupling Projects. *Energies* **2023**, *16*, 1769. [CrossRef]
119. Vaniman, D.T.; Martínez, G.M.; Rampe, E.B.; Bristow, T.F.; Blake, D.F.; Yen, A.S.; Ming, D.W.; Rapin, W.; Meslin, P.Y.; Morookian, J.M.; et al. Gypsum, bassanite, and anhydrite at Gale crater, Mars. *Am. Mineral.* **2018**, *103*, 1011–1020. [CrossRef]
120. Fornaro, T.; Steele, A.; Brucato, J.R. Catalytic/Protective Properties of Martian Minerals and Implications for Possible Origin of Life on Mars. *Life* **2018**, *8*, 56. [CrossRef] [PubMed]
121. Karl, D.; Cannon, K.M.; Gurlo, A. Review of space resources processing for Mars missions: Martian simulants, regolith bonding concepts and additive manufacturing. *Open Ceram.* **2022**, *9*, 100216. [CrossRef]
122. Khalilidermani, M.; Knez, D. A Survey on the Shortcomings of the Current Rate of Penetration Predictive Models in Petroleum Engineering. *Energies* **2023**, *16*, 4289. [CrossRef]

123. Wen, Y.; Zhang, G.; Xie, H.; Gao, M.; Zhang, X.; Wang, Y.; Li, C. Design and Dynamic Analysis of the Wire-Line Coring Robot for Deep Lunar Rocks. *Appl. Sci.* **2023**, *13*, 1722. [CrossRef]
124. Vondrak, R.; Keller, J.; Chin, G.; Garvin, J. Lunar Reconnaissance Orbiter (LRO): Observations for Lunar Exploration and Science. *Space Sci. Rev.* **2010**, *150*, 7–22. [CrossRef]
125. Rajaoalison, H.; Knez, D.; Zamani, M.A.M. A Multidisciplinary Approach to Evaluate the Environmental Impacts of Hydrocarbon Production in Khuzestan Province, Iran. *Energies* **2022**, *15*, 8656. [CrossRef]
126. Verdino, A.; Arena, O.; Bottiglieri, O.; Cafaro, F.; Dini, E. Performance of Lunar Regolith Shield under Meteoroid Impact: Uncertainties of a Numerical Prediction. *Appl. Sci.* **2022**, *12*, 10885. [CrossRef]
127. A Resilient ExtraTerrestrial Habitats. Available online: https://www.nasa.gov/directorates/stmd/space-tech-research-grants/resilient-extraterrestrial-habitats-institute-rethi/ (accessed on 22 May 2019).
128. Ashok, A. Will Marsquakes Have an Effect on Future Human Colonies on Red Planet? Available online: https://www.ibtimes.co.in/will-marsquakes-have-effect-future-human-colonies-red-planet-841030 (accessed on 25 September 2021).