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Extra-terrestrial construction processes – Advancements, opportunities and challenges

Sungwoo Lim [a,*], Vibha Levin Prabhu [b], Mahesh Anand [a], Lawrence A. Taylor [c]

[a] *School of Physical Sciences, Faculty of Science, Technology, Engineering and Mathematics, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK*

[b] *School of Engineering and Innovation, Faculty of Science, Technology, Engineering and Mathematics, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK*

[c] *Planetary Geosciences Institute, University of Tennessee, Knoxville, TN 37996, USA*

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Abstract

Government space agencies, including NASA and ESA, are conducting preliminary studies on building alternative space-habitat systems for deep-space exploration. Such studies include development of advanced technologies for planetary surface exploration, including an in-depth understanding of the use of local resources. Currently, NASA plans to land humans on Mars in the 2030s. Similarly, other space agencies from Europe (ESA), Canada (CSA), Russia (Roscosmos), India (ISRO), Japan (JAXA) and China (CNSA) have already initiated or announced their plans for launching a series of lunar missions over the next decade, ranging from orbiters, landers and rovers for extended stays on the lunar surface. As the Space Odyssey is one of humanity's oldest dreams, there has been a series of research works for establishing temporary or permanent settlement on other planetary bodies, including the Moon and Mars. This paper reviews current projects developing extra-terrestrial construction, broadly categorised as: (i) ISRU-based construction materials; (ii) fabrication methods; and (iii) construction processes. It also discusses four categories of challenges to developing an appropriate construction process: (i) lunar simulants; (ii) material fabrication and curing; (iii) microwave-sintering based fabrication; and (iv) fully autonomous and scaled-up construction processes.

Keywords: Extra-terrestrial construction process; Additive manufacturing; 3D printing; Microwave-sintering; *In-situ* resource utilisation

1. Introduction

The current global interest in Space Odyssey and visiting other planetary bodies in and beyond our solar system has been one of humanity's oldest dreams from time immemorial. Wilkins (1640) formally documented in 1640 the Moon's potential as another living environment, the realisation of those dreams only became possible a few decades ago when humans escaped the Earth's orbit for the first time in 1968 (AIAA, 2009). Space-Industry research and enterprise has been subsequently dramatically increased; nowadays, governmental agencies including NASA and ESA and private companies, such as SpaceX and Mars One, plan to send humans to Mars over the next couple of decades and Moon Express will have a rover on the Moon in 2017. As this ambitious plan becomes more detailed and receives greater public exposure through various channels, including the film *The Martian*, the public, industry, and academic researchers are growing concerned about extra-terrestrial environments and potential technologies providing stable and resilient life-support and

* Corresponding author.
E-mail address: sungwoo.lim@open.ac.uk (S. Lim).

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shelter for mission crews, tourists, and/or emigres to the Moon and Mars.

Such curiosity has led people to consider how best we might provide habitats in unfamiliar and potentially hazardous extra-terrestrial environments, and emergent research and practices in the Space Architecture domain are attempting to eliminate technical barriers for making the dreams come true. Space Architecture can be defined as "the theory and practice of designing and building artificial environments in outer space to enable temporary or permanent human presence or human activities in extreme environments" (Millennium_Charter, 2002). It integrates several technical and scientific disciplines with knowledge of space environments, space systems engineering, and the psychology of isolated and confined environments (Osburg et al., 2003). The Space Architecture field was established when architect Maynard Dalton and industrial designer Raymond Lowy persuaded NASA to include a window in their first space station Skylab (AIAA, 2009), which was eventually realised when the Skylab was launched in 1973. Other professionals then began to develop the theory and principles of Space Architecture, and it was officially established as a discrete discipline through a peer-reviewed symposium at the 2002 Houston World Space Congress. Space Architecture has thus over the last decade become an emerging topic for future space exploration, and is increasingly seen as a fundamental requirement for supporting long-term (inevitable) space settlement and exploration on other planetary bodies. Those involved in the Space Architecture field believe robotised Additive Manufacturing (AM, a.k.a. 3D Printing) technologies – the process of joining materials to make objects from 3D model data, usually layer upon layer (ASTM, 2010) – could become a key technology to construct *In-Situ* Resource Utilisation (ISRU) human habitation and infrastructure, including radiation protection shielding, surface paving, bridges, dust-shield walls and spacecraft landing pads, etc.

This paper reviews recent and ongoing efforts related to developing ISRU-based construction materials, fabrication methods, and construction processes on other planetary bodies, with particular focus on the lunar surface environment. One of the main reasons for focusing on the development of lunar exploration is its role as a first stepping-stone to setting up human outposts, laboratories, and observatories anywhere between the Kuiper Belt and Mercury (Metzger et al., 2013), and thereafter in deep-space exploration beyond the solar system. NASA already has relatively plentiful geological data and lunar samples compared with other planetary bodies, including Mars, because of the Apollo Missions and the inherent research conducted in the context of the lunar environment.

This paper's main focus is potential fabrication methods using different techniques (i.e. laser, solar and microwave) for use in AM processes. There are a few more potential areas of extra-terrestrial construction processes, for example, underground construction (for solid surfaced planetary bodies, including the Moon and Mars), underwater construction (for liquid and/or icy surfaced planetary moons, including Europa and Enceladus) construction, assembly of bricks/blocks, and interlocking systems, etc. The technologies used in underground/underwater environments, however, would be significantly different from the solid-surfaced construction reviewed in this manuscript. Therefore, such a comparison between surface, underground and underwater construction for extra-terrestrial environments should be addressed in a separate review paper. In addition, the authors believe that simple shape brick/blocks can be more easily fabricated by casting in a mould, i.e. using a process which is particularly suited for mass production. On the contrary, the strength of AM techniques lies in customisation and complex geometries. Thus, the construction concepts involving the fabrication and assembly of simple-shaped bricks/blocks are deliberately omitted from this review. Furthermore, while the authors are aware of ongoing researches and the practicality of an interlocking system of a space shuttle and extra-terrestrial construction, e.g. (Estrin et al., 2003; Dyskin et al., 2005) which could be broadly included in construction processes, it is part of an assembly process of fabricated components rather than a fabrication method. Thus, techniques of interlocking those bricks/blocks, are also regarded as being outside the scope of this paper.

2. Construction materials, fabrication methods and processes

It is well-known, that the Moon's surface environment is extremely hostile for the survival of Earth's life-forms. Familiar attributes of the lunar surface include: (i) high vulnerability to bombardment by various sizes of micrometeorites and meteorites, due to its virtual high-vacuum environment (Vaniman et al., 1991); (ii) extreme temperature swings – particularly in the equatorial regions – from $-178\,^{\circ}\mathrm{C}$ to $+123\,^{\circ}\mathrm{C}$ (Williams et al., 2017); (iii) severe exposure to Solar Proton Events (SPE, a.k.a. extreme solar wind) and Galactic Cosmic Rays (GCR), due to the absence of a magnetic field and atmosphere (Vaniman et al., 1991); and (iv) highly abrasive and electrostatic lunar surface dust produced through space weathering (Metzger et al., 2010). These hostile factors reflect only a fraction of lunar data from multiple lunar missions, and many other as yet unknown factors may present extreme challenges to construction activities on the Moon. Thus, building a human habitat in hostile environments on other planetary bodies will require: (i) the ability and knowledge to locally source and manufacture construction materials, also known as *In-Situ* Resource Utilisation (ISRU); (ii) fabrication methods appropriate to specific local resources; and (iii) automated construction processes which are optimised for the target environment.

2.1. ISRU based construction materials

The first documented discussion about ISRU took place at the 1981 Case for Mars Conference at the University of Colorado, and concerned producing propellant using local resources to return to the Earth from Mars after an extended exploration mission. NASA later considered building a permanent outpost on the Moon as a base for Manned Mars exploration (NASA, 1989), and the concept of ISRU was expanded to the obtaining of resources for building a permanent outpost. Because ISRU is one of the most important concepts in the potential realisation of deep-space exploration and space architecture, a significant amount of ISRU-related research has been carried out over the past four decades (Anand et al., 2012).

Considerable research has been directed at using lunar resources as potential construction materials, as part of an ISRU concept. It is well-known that lunar rocks and 'soils' consist of minerals and glasses (Heiken et al., 1991) with a large proportion of silicate minerals. Lunar regolith is a layer of bedrock fragments or debris generated by "the continuous impact of large and small meteorites and the steady bombardment of the lunar surface by charged atomic particles from the sun and the stars" (McKay et al., 1991). Lunar soil is part of lunar regolith, comprised of less than 1 cm in grain size, and it has a well-graded particle-size distribution in geotechnical aspects (Taylor and Meek, 2005). Lunar soil is particularly fine grained – over 95% is categorised as smaller than 1 mm in size, approximately 50% of which is below 50 μm and 10–20% below 20 μm (Taylor and Meek, 2004), and less than 20 μm size lunar soil is categorised as lunar dust. It is believed that space weathering effectively produces single-domain metallic iron particles (3–33 nm in lunar soil and dust, a.k.a., nanophase Fe^0 or np-Fe^0) (Keller and McKay, 1993, 1997).

Researchers initially attempted to create conventional construction materials, e.g., cement (Agosto et al., 1988; Yong and Berger, 1988; Lin and Bhattacharja, 1998), concrete (Lin, 1987; Namba et al., 1988; Lin et al., 1997), and brick (Strenski et al., 1990), using resources on the Moon to create a lunar outpost – details of which are summarised in (Ponnada and Singuru, 2014; Khitab et al., 2016). However, a conventional concrete production process would require large amounts of water and necessitate a pressurised chamber, as water content tends to evaporate during the "setting" of concrete. Excess evaporation of water can cause formation of severe porosity in the concrete, leading to weakening of the strength and structural failure of the hardened material. Recent works have tried to further extend the potential of lunar concrete by developing a water-less concrete (Toutanji et al., 2005; Koh et al., 2010; Wang et al., 2016), including a sulphur-based concrete (Leonard and Johnson, 1988; Omar, 1993; Casanova and Gracia, 1998; Grugel and Toutanji, 2008), phosphoric acid-based concrete (ESA, 2017), a new lunar simulant with a special binder to be used with a direct manufacturing technique (Cesaretti et al., 2014), and a glass-fibre based reinforcement for lunar concrete (Tucker et al., 2006). However, ESA's test of lunar simulant printing with a liquid binder (Cesaretti, 2012b) indicated the potential freezing of the binder and the related operation with a wet-mix based printing process under the lunar environment's extreme temperature changes. Despite these valuable efforts, the material treatment and curing process of lunar resources as a construction material still present significant challenges, primarily the use of *in-situ* materials versus those from Earth. In order to avoid/minimise these challenges, interest has recently grown in exploiting the raw lunar regolith, particularly lunar soil and dust, as a construction material with only minor pre-treatment and liquid-state binder. This would entail using a specific fabrication method: sintering-based additive manufacturing technology.

2.2. Fabrication method – Sintering

Sintering is the heating of a porous material to a temperature below its melting point to enable the particles to bond together with a concurrent reduction in the volume of porosity in order to form a solid (Pletka, 1993). Some researchers have investigated the potential of lunar regolith sintering using a high-powered laser, solar concentrator, or microwave energies, as the natural lunar regolith is potentially an excellent construction material, consisting mostly of soil and dust (≤1 cm and ≤20 μm, respectively, by lunar conventional definition; (McKay et al., 1991), particles which require only mechanical sieving, without crushing, with minimal disruption of the lunar surface. It was observed that some AM techniques, including Fused Deposition Modelling and Selective Laser (or Solar or Microwave) Sintering, could be used as potential fabrication methods for lunar construction processes (Mueller et al., 2016) and dust mitigation (Wilson and Wilson, 2005), because the method does not require any liquid-state binder (Lim and Anand, 2015). Some existing research on each method (laser, solar, and microwave) is summarised in the following sections.

2.2.1. Laser and solar sintering

There are relatively few researches on laser sintering of lunar regolith/simulant – only three research works (Balla et al., 2012; Fateri and Gebhardt, 2015; Goulas et al., 2017) were found. Despite the thermal transient stresses and residual stresses of direct laser sintering of raw lunar regolith (Balla et al., 2012), the initial experiments with the lunar simulants, e.g. 10 × 25 mm cylinder using JSC-1AC (Balla et al., 2012), 30 × 30 mm net-shape object using JSC-1A (Fateri and Gebhardt, 2015), and 20 × 20 × 5 mm cube using JSC-MARS-1A (Goulas et al., 2017), showed that the samples were successfully melted and formed into the desired parts with high geometrical accuracy. Regardless of the interesting results, however, direct laser sintering alone may not be an ideal fabrication method for a construction-scale object for following reasons:

- Balla et al. (2012) claimed that their method requires low energy, 2.12 J/mm^2, with a layer thickness of 254 μm, using 50 W of laser power. Note that 2.12 J is equivalent to 5.89e−7 kW h, and one meter thickness would need 4000 layers of 254 μm thickness. Thus, 2.12 J/mm^2 would be equivalent to 23,556 kW h/m^3 or 12,398–15,704 kW h/MT (metric tonne), considering the average density of lunar regolith (Heiken et al., 1991) is around 1.5–1.9 tons/m^3 (see Table 1). However, the area and volume of one outpost would easily exceed 260 m^2 and 2000 m^3 for ten mission crews (Doule et al., 2011). Thus, the total energy required for construction of the structure protecting the volume of a practical outpost would be extremely high, e.g. requiring a nuclear power source.
- Another noticeable drawback of direct laser sintering is that only a small volume of material can be thermally treated at a time, with a longer printing time for a wider area and extremely high-temperature gradients within the sintered component.

However, solar sintering could be a suitable fabrication technique as solar energy is unlimited and readily available on the lunar surface. Researchers investigated the potential of producing lunar glass composite structures (Magoffin and Garvey, 1990), lunar concrete (Lin et al., 1997), oxygen production by pyrolysis (Sauerborn et al., 2004), surface stabilisation (Hintze et al., 2009), and lunar brick (Meurisse et al., 2016) using solar energy. Despite the advantages of solar-concentrated sintering methods, it also has its limitations.

- The depth penetration of heat from the solar concentrator is better than laser but rather more limited than microwave (up to 13.4 mm for 2.45 GHz microwaves (Allan et al., 2013a)). For example, it was reported that solar sintering could penetrate materials up to 6 mm deep in a fixed position or 1–2 mm deep in a raster scanning mode (Hintze et al., 2009; Hintze and Quintana, 2013). Thus, it would require much longer times to fabricate than using microwave energy.
- The system requires extra complexity, including cleaning mirrors and lenses from lunar dust to sustain the concentrator efficiency (Gaier, 2005), and maintaining positioning controls to locate the desired focal spot location relative to the movement of the sun and the solar concentrator (Allan et al., 2013b; Hintze and Quintana, 2013).
- The efficiency of the concentrator may be affected by the optical properties of the lunar regolith. For example, the darker mare regions absorb more light, so it would be heated more efficiently by the solar concentrator than highlands regolith, if all other properties are the same (Hintze and Quintana, 2013). Besides, the mare soils melt at considerably lower temperatures than those of the highlands.
- Some potential lunar landing-sites, including the Shackleton Crater near the Moon's south pole may not be exposed to direct sunlight, an environment where a solar concentrator would not be an option.

2.2.2. Microwave sintering

Researchers have considered microwave sintering – volumetric heating by absorbing and coupling a microwave field (Agrawal, 2006) – because it has significant advantages over conventional heating such as a furnace using fossil fuel and promises substantial energy savings of up to 90% (Sato et al., 2003). Microwave energy can be used for fabricating wider areas, e.g. pavement and/or spacecraft launch and landing pads, etc., and the importance of microwave energy in application to lunar regolith has been made by (Taylor and Meek, 2005; Taylor et al., 2010a).

Microwave radiation is in the electromagnetic spectrum region with a frequency range between 300 MHz and 300 GHz, and wavelength between 1 mm and 1 m. Researchers tested microwave sintering with lunar regolith or simulant for various purposes, including palaeontological experiments (Hale et al., 1978), volatiles extraction (Etheridge and Kaukler, 2011), and nano-phase iron (np-Fe^0) production (Tang et al., 2012), etc. For construction purposes Kingery et al. (1976) believed the complex morphology of the raw lunar regolith might improve sintering because the glass portion of the regolith could assist in densification during sintering, and Meek et al. (1985, 1988) noted that ilmenite ($FeTiO_3$) couples well with high-frequency microwave resulting in densified basalts. Moreover, Pletka (1993) observed that sintering the MLS-1 simulant Minnesota Lunar Simulant in a conventional oven is not feasible because the extensive porosity of the sintered specimens led to poor bonding between powdered particles, even though the material was heavily pre-compressed to minimise porosity. He suggested microwave or radiant heating as a viable alternative. Some researchers experimented with the potential of a microwave furnace (Allen et al., 1994) to make lunar bricks. Taylor and Meek (2005) later claimed that the ubiquitous presence of nano-phase iron (np-Fe^0) in the raw lunar regolith enhances its suitability for microwave sintering, and hypothesised that the microwave radiation creates 'energy sinks' with the effective generation of large quantities of heat coupling with np-Fe^0 in the lunar soil, using Apollo lunar soil for their experiments. Taylor et al. (2010b) have an outstanding patent on the microwave heating/sintering/melting of any material containing np-Fe, especially the lunar soil.

Until now, most researches into microwave sintering of both actual lunar soil and lunar simulants have been conducted at 2.45 GHz microwave frequency, which is used for domestic cooking appliances, because of its easily affordable accessibility (Lim and Anand, 2015). Actual lunar soil is hard to source because of the limited amount collected from the Moon – only 381.7 kg of rock and soil samples were collected from six US Apollo missions on the near side of the Moon close to the equator – so most researchers have experimented with various lunar simulants. Some thirty simulants had been used for various research purposes at the time of the NASA's Simulant Working Group survey (LEAG-CAPTEM_SWG, 2010), including the commercially produced lunar simulant JSC-1A. Detailed evaluation of existing lunar simulants are also summarised in (Taylor et al., 2016). Simulant JSC-1A was developed with crushed volcanic tuff, including abundant glass and large amounts of nano-meter sized magnetite ($Fe^{2+}Fe_2^{3+}O_4$) grains with similar particle size distribution to that of actual lunar soil (LEAG-CAPTEM_SWG, 2010). Although JSC-1A is suitable for certain ISRU activities (Hill et al., 2007), it does not fully represent the geotechnical properties of lunar soil, due to the absence of np-Fe^0.

Recent studies involving sintering of lunar simulant also reported that 2.45 GHz microwaves could melt it up to 13.4 mm depth (Allan et al., 2013a), and a few researchers (Khoshnevis and Zhang, 2012; Barmatz et al., 2014; Lim and Anand, 2014; Mueller et al., 2016; Srivastava et al., 2016) have further investigated a microwave sintering technique coupled with a lunar simulant as a potential fabrication method. Considering the composition and dielectric characteristics of lunar regolith, microwave sintering is thought to be one of the most attractive fabrication methods for lunar construction (Srivastava et al., 2016).

2.3. Extra-terrestrial construction processes using additive manufacturing techniques

NASA researchers believe robotics and AM technologies have matured enough for terrestrial applications and have enormous potential to become a game-changer for space colonisation, but an appropriate construction technology will be needed to advance and simplify the complexity of the construction process to fabricate components in order to be adapted in hostile and extreme extra-terrestrial environments. To achieve such advancement and simplicity, they believe AM technologies require advancement beyond their current achievements (Metzger et al., 2013). For example, Kennedy (AIAA, 2009) imagined that combining biotechnology with fabric and matrix structures could produce a protective, self-healing and self-regulating system – similar to human skin – optimised for space conditions in the future, which could provide life-support for both people and plants. However, it requires far more advanced technological evolution and a paradigm shifting concept. In order to realise such an ambitious concept, embedding sensors, processors, and mechanical apparatuses in a structure would be a first step toward such intelligent structures; these would autonomously and continuously monitor their own condition and outer environment, including the atmosphere. As AM processes are capable of embedding such functions on the fly, several current research projects in various sectors are developing an advanced concept of extra-terrestrial construction processes beyond current knowledge, which maximises the practicality of the AM processes.

According to (AIAA, 2009), extra-terrestrial habitations can be classified in three types (Fig. 1): (i) Class I: pre-integrated hard-shell modules such as the International Space Station (Fig. 1, left) (AIAA, 2009), which are deployed in space with a limited extension capability; (ii) Class II: prefabricated on Earth and surface-assembled modules, e.g. inflatable structures (Fig. 1, centre) (NASA, 2014); and (iii) Class III: ISRU-derived structures which can be integrated with the other Class I and II modules to expand the habitat (Fig. 1, right) (Rousek et al., 2012). The ongoing efforts of several institutions proactively working on these concepts are summarised below.

2.3.1. USC/NASA JPL – Robotic construction of lunar and Martian infrastructure

In early 2000s, the University of Southern California (USC) developed a 3D printer called Contour Crafting (CC) (Khoshnevis, 2004), which is capable of fabricating plastic, ceramics, composites, and cementitious objects. This CC utilises an extrusion-based 3D printing technique, similar to the Fused Deposition Modelling (FDM) technique, but using liquid-state binder to crystallise materials instead of heat to sinter materials. Initially, USC exploited the potential of CC with the NASA Jet Propulsion Laboratory (JPL) and the Marshall Space Flight Center (MSFC) for a development of ISRU-based lunar habitat (Khoshnevis et al., 2005), and later further explored the potential of CC embedded on the All-Terrain

Fig. 1. Three types of extra-terrestrial habitation. Left: Class I (NASA, 2001) Image courtesy of NASA; centre: Class II (NASA, 2014) Image courtesy of NASA; right: Class III (Rousek et al., 2012). Note that Rousek et al. (2012)'s design is actually a combination of Classes II and III.

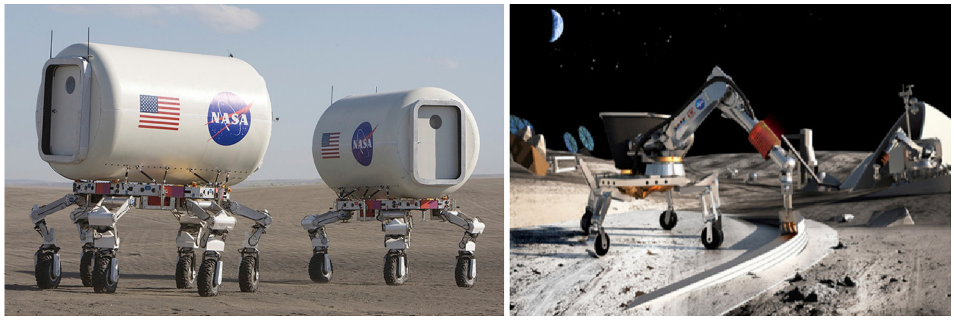

Fig. 2. ATHLETE and Contour Crafting: left: Two ATHLETE rovers used for field tests near Moses Lake, WA. (Boston.com, 2008), Image courtesy of NASA; right: Construction concept using the CC embedded on the ATHLETE (Khoshnevis and Zhang, 2012).

Hex-Limbed Extra-Terrestrial Explorer (ATHLETE), developed by NASA JPL (Khoshnevis and Zhang, 2012) through a NASA Innovative Advanced Concept (NIAC) project (see Fig. 2). This ATHLETE was developed as a multi-purpose rover, and NASA started to work with USC to develop a combined concept using both CC and ATHLETE for fabricating lunar construction components, such as a protection cover for a lunar habitat, dust-shield walls, and spaceship landing-pads (Howe et al., 2013), through the NIAC initiative. CC and ATHLETE systems have been well demonstrated – their technologies are currently considered to be around Technology Readiness Level (TRL) 3 for space applications – and a preliminary experiment on sulfur concrete using lunar simulant was reported in (Khoshnevis and Zhang, 2012). However, more detailed research outcomes have not yet been revealed, possibly because the R&D activities are ongoing.

2.3.2. European Space Agency (ESA) led D-Shape study – 3D printing using a liquid binder

In 2010, the European Space Agency (ESA) (Cesaretti, 2012a, 2012b; ESA, 2013; Cesaretti et al., 2014) collaborated with the world-renowned UK architecture firm, Foster + Partners (F + P) and D-Shape, to investigate the potential and capability of AM processes to build *in-situ* structures on the lunar surface using lunar soil as a base material (Fig. 3). The F + P firm designed a lunar outpost, and D-Shape provided a gantry-based 6 × 6 m printing frame to perform the experiment. The D-Shape concept uses a Direct Manufacturing technique, similar to an inkjet printer technique, which produces a three-dimensional object through an additive layering process of materials. The fabrication process consists of: (i) deposition of the sand material for a single layer; (ii) densification of the layered material using a heavy roller; (iii) applying a

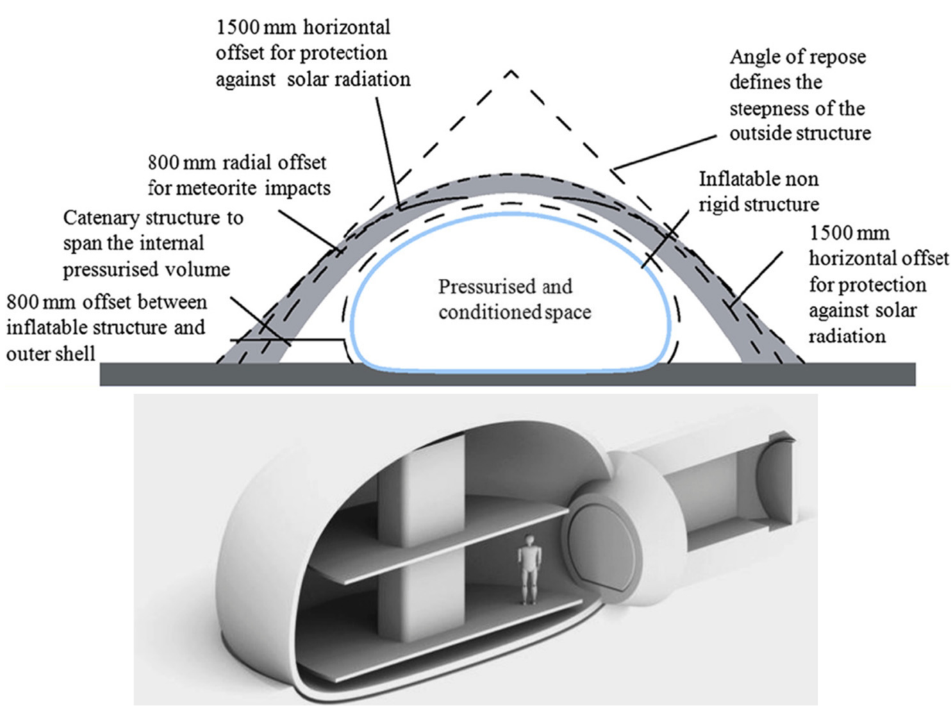

Fig. 3. Top: Schematic of the inflatable non-rigid core structure with a support module covered by a protection cover; below: Section view of the core structure (Cesaretti et al., 2014).

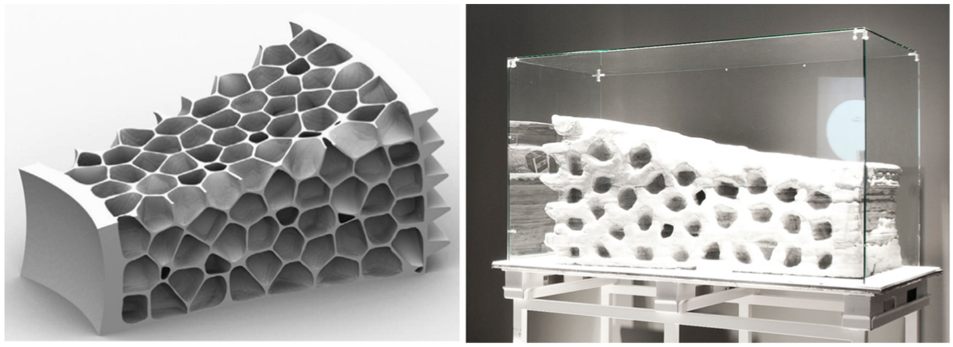

Fig. 4. Left: Rendered CAD model of the closed-cell structure (Cesaretti et al., 2014); right: Printed lunar building-block using a Lunar simulant DNA-1 (Picture reproduced from (ESA, 2015).).

chlorine-based liquid binder on the layered material following pre-defined printing paths; (iv) curing the bonded layer; and (v) repeating the process until the final layer is reached. A detailed review of the D-Shape technology appears in (Lim et al., 2012). The chosen construction material was a new simulant, DNA-1, manufactured from a quarry in a volcanic structure in Italy, the chemical composition of which is similar to the familiar lunar simulant JSC-1A, but more cost-effective in this instance. The design concept of the lunar outpost, developed by F+P, comprises a simplified modular system (support module + inflatable core module) and a 3D-printed lunar-regolith cover for (micro)meteorites and radiation protection.

The design iterations and structural feasibility study of the lunar outpost to optimise the concept are described in (Cesaretti et al., 2014). Despite the base architecture's shortcomings (e.g., deployability and placement of the skylight structures which should not be placed in a high-radiation environment on inhabited system), the ESA team succeeded in designing and testing a closed-cell structure (Fig. 4) which both retains loose regolith and ensures shielding from cosmic rays and solar flares.

2.3.3. European Astronaut Centre (EAC) at ESA – Microwave sintering of lunar simulant

Since 2014, extensive experiments on microwave sintering with DNA-1 simulant have been conducted at the European Astronaut Centre (EAC) at ESA. Preliminary results, EAC has suggested that (i) absence of np-Fe^0 in lunar simulants does not affect the sintering process, and (ii) additional ilmenite and infrared preheating of the material actually enhanced the reliability and controllability of the sintering process (Häfner, 2015).

The main aim of the EAC/ESA experiments was to demonstrate the practicality of the selected 3D printing technologies on the Moon. Through their experiment, EAC/ESA realised that numerous potential issues must be addressed about operation, logistics and economic viability, etc., before planning a first space mission for building the human outpost/habitat on the Moon. Detailed issues are further elaborated in the Discussion section.

2.3.4. Made in space/NASA MSFC – 3D printing in micro- and zero-gravity

In 2013 NASA MSFC and Made in Space Inc. demonstrated the potential of 3D Printing in a Zero-G environment using ABS thermoplastic resin materials (Fig. 5) over a period of four weeks of microgravity testing with parabolic flights. Although this is not directly related to extra-terrestrial construction processes, the experiments produced some invaluable results to be referred to developing the next generation of AM techniques. The tests enabled measurement of the correlation between gravity and the layer thickness of the printed specimens using commercially available FDM 3D printers: MakerBot and BFB 3000 (Snyder et al., 2013). The initial results show the

Fig. 5. 3D printing test in zero- and microgravity during a flight aboard a modified Boeing 727 from the Zero G Corporation. Left: A 'Made In Space' experiment box; right: A Microgravity Science Glovebox Engineering Unit. Courtesy of NASA (NASA, 2016).

average layer thickness is (i) around 1.4–1.5 times larger in micro-gravity, (ii) around 1.1–1.15 times larger in lunar gravity (1/6 of the Earth), (iii) slightly larger in Martian gravity (1/3 of the Earth), and (iv) about 0.8 times smaller in 2G compared with the Earth's gravity. The results indicate that printing on micro-gravity would reduce self-compacting of extruded materials, which possibly leads to weaker bonding (tensile) strengths between layers.

In 2014, NASA launched the 3D printing in Zero-G technology demonstration mission to the International Space Station (ISS, to further explore the potential and capabilities of FDM techniques in micro-gravity environments. NASA used a 3D printer, developed by Made In Space, Inc., to print and compare the same specimen both on the ground and in space using various analyses including photographic/visual inspection, mass and density evaluation, structured light scanning, X-ray and computed tomography, mechanical properties testing, and optical microscopy (Prater et al., 2016). A summary report was published in 2016 with some key lessons learned through the mission, including the need for: (i) a highly controlled fabrication process to isolate the effect of micro-gravity on the FDM process; (ii) a warmed build chamber to minimise distortion of the printed specimens in order to improve the reliability of the FDM process; (iii) a careful strategy on the printing direction depending on the geometry of the components to be printed, in order to improve tensile and flexural strengths of printed specimens; and (iv) a refined microstructural evaluation of printed specimens using a Scanning Electron Microscope (SEM) to optimise the printer settings and fabrication process, e.g. extrusion flow-rate, nozzle correction factor, and curing setting, etc. NASA is also actively promoting a 3D-printing challenge competition as part of NASA's Centennial Challenges programme (NASA, 2015). Through the Phase 1 $50K design competition, NASA selected thirty designs and awarded the top three design finalists. Most designs focus on architectural planning and design with some insights for a construction process. Phase 2 of the competition, which closes in August 2017, is seeking the best technologies utilising indigenous and recyclable materials for the fabrication process.

Further to the research outline above, several other activities are directed towards extra-terrestrial construction research. For example, in 2013 The Open University established a new interdisciplinary research initiative called MISSION (http://www.open.ac.uk/researchprojects/mission/), which draws on ideas grounded in the Built Environment discipline. Supported by the concept of 3D Concrete Printing research (Le et al., 2012a, 2012b; Lim et al., 2012, 2016), the research team is focusing on microwave-sintering based additive manufacturing techniques (Lim and Anand, 2014, 2015; Lim et al., 2015; Mueller et al., 2016; Srivastava et al., 2016). In 2015 the German Space Agency (DLR) secured a European Commission supported research project – Regolight (http://regolight.eu) focusing on a solar concentrator based sintering technique (Meurisse et al., 2016).

3. Discussion

Despite interesting research developing extra-terrestrial construction processes utilising existing AM technologies, such efforts remain in their infancy, requiring further developments to become a practical application. In order to further development, some challenges particularly relevant to the lunar surface environment and materials are yet to be addressed, some of which are discussed below.

3.1. Lunar simulants

Existing researches focus on lunar soil and dust as potential construction materials, which can be collected by scraping up the lunar surface rather than by breaking or crushing rocks. Lunar soil contains various chemical and mineralogical resources – an area of lunar science of considerable on-going importance for ISRU investigations (Anand et al., 2012; Taylor et al., 2016). Due to the lack of availability of actual lunar regolith, developing lunar simulants would be the best way to conduct regolith-related research, – particularly for destructive experiments. In order to support research on raw lunar materials, NASA MSFC (Sibille et al., 2005) identified the criteria for lunar simulant development, which can be used for construction-related experiments on the Earth. There are currently around thirty variations of lunar simulants as mentioned earlier, a few patents relevant to the lunar simulant developments (Hung and McNatt, 2010; Weinstein and Wilson, 2013), and one ISO standard (ISO, 2014). Several simulants – including ALS-1 (Garnock and Bernold, 2012), DNA-1 (Cesaretti et al., 2014), and KLS-1 (Ryu et al., 2015), which followed the specification of JSC-1/1A – have been developed for construction purposes. However, experimenting with potential construction materials using existing lunar simulants should not be the only option as they do not represent the full chemical/mineralogical diversity of lunar regolith. For example:

- The portion of a lunar core at a depth of 4 cm, acquired by Apollo 16, revealed that lunar regolith can contain large particles (~8 mm) (Rickman et al., 2013), and the large particle content of the lunar regolith can reach up to 30% by mass (Iai and Gertsch, 2013). However, the existing lunar simulants including JSC-1A only provide a grain size of 1 mm or less, as it is designed mainly for scientific experiments. However, in general, the <1 μm portion of the lunar soil constitutes some 85–95% of the total soil (McKay et al., 1991).
- According to Liu et al. (2008), lunar regolith has irregular particle shapes, and the specific surface area is

approximately 0.5 m^2/g, which is about eight times larger than an aggregation of sphere shapes with the same particle size distribution. Park et al. (2008) and Liu et al. (2008) discussed the particle shape distribution of lunar dust, and concluded that lunar dust contains high percentages of elongated and rugged shapes. Such irregular and rugged shapes of lunar regolith are not considered as one of the criteria for the design of existing simulants, although the shapes could affect the mechanical properties of the fabricated objects using lunar regolith. For example, Barmatz et al. (2013) argued that the sharp-edged particles included in most lunar samples allow more efficient microwave heating than rounder-edged particles mostly found in existing lunar simulants, and speculated that the particle shape may be one of the main reasons for exceptional microwave heating of the lunar regolith as discussed in (Taylor and Meek, 2005; Taylor and Liu, 2010).

- Lunar regolith, particularly lunar dust mainly consists of around 60–80% of impact-produced glass, i.e. agglutinitic glass (Taylor et al., 2001; Taylor et al., 2005, 2010a; Taylor and Liu, 2010), and contains significant quantities of single-domain iron (np-Fe^0) (Taylor, 1988), which exists as a stable phase (presumably because of the water-poor lunar environment) but is absent in virtually all natural materials on Earth. As a result, the existing lunar simulants, which use natural Earth materials without pre-processing, contain no np-Fe^0. Although a few researchers (Liu et al., 2005, 2007; Tang et al., 2010) and a patent (Hung and McNatt, 2010) discussed potential methods of synthesising np-Fe^0 in a lunar simulant, their ideas have not yet been implemented on a simulant design.
- The Apollo landings were restricted to the lunar equatorial regions, so the samples collected represent only limited geographical coverage. The existing simulants have been designed based on the currently available samples. Lunar geology, including the composition of lunar regolith, varies at different locations. For example, the regolith properties of the potential lunar landing site – such as the Shackleton Crater near the Moon's south pole – would be very different from the Apollo samples used for designing current simulants. This means a single lunar simulant cannot represent the entire lunar surface environment, a conclusion repeatedly stated by (Taylor and Liu, 2010; Taylor et al., 2016).

The best way to create an appropriate simulant is by having access to the actual lunar regolith samples from the target-landing site. Several remote-sensing missions have provided global coverage of the lunar surface which provides the best currently available information about the geological/mineralogical characteristics of the target landing-site in the polar regions. However, it is acknowledged that such remote sensing data can only provide information about the very outer lunar surface, and although unlikely, there could be considerable mineralogical/chemical variations with depth. Nevertheless, these are our best approximation until a lander and/or sample return mission to the lunar polar regions takes place. The logical pathway meantime would be to: (i) utilise existing remote sensing data; (ii) source appropriate analogue materials; and (iii) design new simulants or redesign existing simulant compositions for various lunar locations based on the remote sensing data. As was discussed, np-Fe^0 may not be the only one element effecting on microwave sintering; thus, a new lunar simulant will need to be designed with/without np-Fe^0 and thoroughly tested in both dry and wet conditions to determine whether these elements should be regarded as crucial factors of the new simulant for construction purposes. In reality, it can be other factors in a simulant that give it good microwave coupling – e.g., nano-phase magnetite in JSC-1A and other volcanic-based lunar simulants.

3.2. Material fabrication and curing

Previous researches at the University of Southern California (Contour Crafting (Khoshnevis, 2004; Khoshnevis and Zhang, 2012)), Loughborough University (3D Concrete Printing (Lim et al., 2012, 2016)), and the ESA's recent experiment with D-Shape (Cesaretti et al., 2014) indicate that an extrusion-based fabrication would be the most appropriate method for manufacturing construction components, while Selective Laser Sintering (SLS)-type fabrication would be more suitable for infrastructure development including pavement of roads and launch/landing-pad, etc. The combination of microwave sintering and extrusion-based fabrication seems a logical pathway for this purpose. The challenges raised by existing researches on microwave sintering based fabrication as a practical fabrication method are described below.

- Due to the highly abrasive and electrostatic nature of lunar dust and an almost non-existent lunar atmosphere, using lunar soil and dust as a fabrication material would pose significant challenges, particularly on vacuum tribology – friction, lubricant and wear – for a material feeding process prior to sintering and extrusion for fabrication. The overall design of the prototype, including: (i) the material feeding path; (ii) the nozzle size and shape; and (iii) the entire extrusion mechanism, should therefore be optimised to overcome those challenges. A little appreciated factor that will affect microwave applications on the Moon is the 10^{-12} torr vacuum that will greatly enhance shorting of the microwaves, defusing microwave coupling with the soil components.
- Due to weak gravity, less self-compacted materials during deposition will also present a considerable challenge, as they reduce both the density of the fabricated parts and the bonding strengths between layers. It is believed that the compaction of material allows the porosity in

the materials to minimise and enables (i) less shrinkage, (ii) a shorter sintering time, and (iii) higher density (Pletka, 1993). Thus, the compaction of material prior to fabrication (e.g. sintering and extrusion) is another key criterion for strengths.

- As already discussed, there is considerable speculation that the presence of np-Fe^0 is one of the main reasons for effective microwave coupling of lunar regolith. As the actual impact of np-Fe^0 on microwave sintering remains unidentified, the role of np-Fe^0 during microwave sintering process should be carefully investigated.
- Once the sintered material is deposited following a predefined printing path above the previous layer, the entire layer needs to be hardened enough to support the next layer while preserving a good bonding capability with the next layer. This would be particularly challenging, as there is no conduction/convection on the Moon and heat can only be dissipated through radiation (via infrared waves) in the lunar environment. Clearly, poorly designed curing mechanism for the AM process would affect the printing speed and quality, e.g. deformation of stacked layers. Thus, an efficient curing mechanism – either active or passive – for sintered materials will need to be investigated.

3.3. Microwave-sintering based fabrication

This article's focus is microwave sintering for fabricating construction components in extra-terrestrial environments, particularly on the Moon, as it has unique advantages compared with solar concentration and laser sintering, as already mentioned. However, all the existing works discuss the potential of microwave sintering as an alternative fabrication method without demonstrating its feasibility for use yet as part of AM technologies. Microwave sintering has its own unsolved challenges to becoming an ideal fabrication method. For microwave, higher frequencies penetrate materials less well (i.e. less depth), while lower frequencies penetrate better but are weakly absorbed, so the materials would not absorb enough energy to be adequately sintered, without use of considerably more power. Although 2.45 GHz frequency was specifically chosen for cooking food because of its efficiency in heating liquid water, this frequency may or may not be optimal for sintering other materials, e.g. lunar regolith and simulants. Certain considerations, listed below, need to be addressed in order to maximise the potential of a microwave sintering technique.

- *It is important to understand the factors contributing to the behaviour of lunar soil and simulants when they are heated using microwave energy.* Some of these factors relate to the fundamental physical properties of natural materials, which affect and govern the nature of microwave coupling. The absorption of microwave energy depends on the dielectric properties of the material, which are dielectric constant and dielectric loss of lunar soil or lunar simulant. Both properties are major criteria to determine the rate of a material heating in the presence of an electromagnetic wave such as the microwave. However, few research works have investigated the dielectric properties of actual lunar soils from the Chang'e-3 (Feng et al., 2017), the Apollo missions (Olhoeft and Strangway, 1975; Strangway and Olhoeft, 1977; Olhoeft, 1981; Taylor and Meek, 2005; Barmatz et al., 2011), and existing lunar simulants (Calla and Rathore, 2012; Allan et al., 2013a). Existing lunar simulants were not designed to simulate the microwave properties of lunar regolith (Allan et al., 2013b). These properties are dependent on the frequency and are also influenced by density, mineral composition, grain size, moisture and temperature, and particle shape, etc. (Calla and Rathore, 2012). The dielectric constant of lunar soils is mainly dependent on density at higher frequencies (Olhoeft, 1981), and ilmenite contents in the Apollo lunar soils appear to have a correlation with the dielectric constant (Olhoeft and Strangway, 1975). On the other hand, the dielectric properties of the lunar simulant JSC-1A were increased with raised temperature at different frequencies (Calla and Rathore, 2012). Although these results provide insight into understanding the potential correlation between the density, temperature, and frequencies of microwave sintering, *more thorough researches on this subject are needed in order to clarify the appropriateness of the simulant.*
- It was observed that the microwave radiation using 2.45 GHz frequency was not effective for lunar soil and the lunar simulant JSC-1A at lower temperatures between 200 °C and 400 °C (Allan et al., 2013b), then it heated up rapidly at higher temperatures melting the materials completely between 1100 °C and 1400 °C (Allan et al., 2013a). In this case, thermal runaway condition (Tiegs et al., 1993), self-insulation (Kenkre et al., 1991), and weak absorption of microwave energy at low temperatures (Allan et al., 2013b) would be the major challenges associated with microwave heating to be a realistic fabrication method. Microwave could also be used as a catalyst rather than thermally, and microwave energy is preferentially absorbed by the inner portions, leaving the surfaces less thoroughly heated. Some other form of radiant heating such as the use of a microwave absorbing material (e.g. a susceptor (Allan et al., 2013a; Heuguet et al., 2013; Muhammad and Abdullah, 2016), which is a material used for absorbing electromagnetic energy and converts it to heat) may need to be combined with the microwave heating to enhance the efficiency of the heating process and temperature uniformity (Allan et al., 2013b). With this method, a microwave-susceptor could be used as a catalytic element while laser fuses materials selectively following pre-defined printing paths. Such hybrid heating techniques could also

reduce thermal imbalance in the material which can cause weak mechanical properties in the finished product. More research should be carried out to design an appropriate fabrication system.

- While addressing the challenges at 2.45 GHz*, it is equally important to examine the behaviour of lunar soil at other frequencies in the microwave range*. Because of the shallow penetration depth of 2.45 GHz microwave frequency for lunar soil and lunar simulants (Taylor and Meek, 2005; Allan et al., 2013a) and decreasing depth of penetration when the frequency increases, a set of frequencies might be required for processing different depths of material. In this case, each frequency could be used to change materials in a different phase in order to improve energy efficiency – similar to the concept of Taylor et al. (2010b). Thus, measuring the efficiency of microwave with a different range of frequencies would be the first step to identifying optimal parameters for sintering simulant.
- It was observed that the decrease of the grain size causes the increase of the agglutinitic glass content, increasing the presence of np-Fe^0 particles in the lunar soil (Taylor et al., 2001; Taylor and Liu, 2010; Taylor et al., 2010a). This indicates that microwave heating of lunar soil will be improved with smaller grain size due to the abundance of np-Fe^0 particles. However, it does not necessarily mean the change in grain size will also affect the microwave heating even in the absence of np-Fe^0 particles, which is the case in existing lunar simulants. Varying grain size would also change the dielectric properties of a material, making it an important factor requiring investigation to clarify how it could influence microwave heating of lunar simulants.
- In terms of the power requirement, researchers estimated energy consumption for microwave sintering of lunar regolith and simulant, requiring a temperature of up to 1400 °C, around 360 kW h/MT (metric tonne) (Benaroya, 2010) or 50,000 kW h/314.159 m^2 (20-m diameter of a landing pad) (Taylor and Meek, 2005). Table 1 shows that a laser sintering would require around 33–44 times more energy than a microwave sintering (compare with Benaroya, Taylor and Meek's estimates). Note that the given temperature would completely melt most if not all lunar soils and lunar simulants, including JSC-1A. Although the estimate does not reflect the actual energy for microwave power – which appears to be much more energy efficient than laser – it is clear that a powerful energy source is still required, e.g. nuclear energy, considering the construction scale mentioned in Section 2.2.1.

3.4. Fully autonomous and scaled-up construction processes

Conventional construction processes, which require massive manual intervention, may not be suitable for extra-terrestrial construction due to the extreme and hazardous environments. The initial construction process including an AM-based printing system should therefore be built to be either fully- or semi-autonomous, similar to the present-day operation of lunar and Mars rovers. Unlike those rovers' current tasks mainly related to material sampling and analysis, however, the proposed printing system needs to: (i) establish infrastructure including stabilising the foundation; (ii) collect construction materials; (iii) sinter the materials for fabrication; and (iv) deposit and cure the sintered materials to build a fairly large habitat module for at least four to ten mission crews. The high complexity of the construction operation would eventually lead to futuristic operations, such as self-sustainable robotic ecologies (Colombano, 2004), but developing a fully autonomous and scaled-up printing system for a construction process would be a first step.

Over the last thirty years, improvements in AM materials and processes have resulted in successful commercial realisation. The AM is now an integral part of modern product development (Hague et al., 2003), and the technology has been commercialised to the extent where machines are now affordable for home use. Generally, AM techniques have been applied for relatively small-sized component fabrications. However, several recent research and enterprise efforts have scaled up the AM processes to apply in a construction process despite the slow adoption of new construction technologies and the relatively short history – less than two decades – of AM in construction. Contour Crafting (Khoshnevis et al., 2006) and 3D Concrete Printing (Lim et al., 2012) systems used an extrusion-based AM technique similar to a FDM technique while D-Shape (Dini, 2009) used a powder bed (drop-on-powder) technique, and all use a liquid-state binder as a bonding agent. The performance of these systems indicates that a single large-scale printing

Table 1
Estimated energy consumption of microwave and laser sintering of lunar regolith and simulant.

	Microwave sintering	Laser sintering
Balla et al. (2012)	N.A.	2.12 J/mm^2 with a depth of 254 μm (equivalent to 23,556 kW h/m^3 or 12,398–15,704 kW h/MT)
Benaroya (2010)	360 kW h/MT (equivalent to 540–684 kW h/m^3)	N.A.
Taylor and Meek (2005)	[a]50,000 kW h/314.159 m^2 (no information regarding the depth)	N.A.

Note:MT: Metric tonne.
Average density of lunar regolith: 1.5–1.9 tonnes/m^3.
[a] 314.159 m^2: Total area of a landing pad with 20 m diameter.

system may not be an optimal solution for construction processes. Such material fabrication techniques are, however, still only one part of an entire construction process. Other operations, including printing system design strategies, material excavation, collection, delivery, infrastructure, support structure, reinforcement, radiation protection, and location specific design, etc., will also need to be investigated. Some specific concerns should be addressed to realise fully autonomous construction processes:

- Some construction activities (including excavation, trenching, backfilling, compacting of materials) are not ideal methods because of lunar dust, which consists of ~20 wt.% of all lunar soils (Taylor et al., 2001; Taylor et al., 2010a) and is universally regarded as a design and operational problem (Taylor et al., 2005). Although conventional excavation and drilling activities may not be appropriate in a lunar surface environment, and thus such activities should be minimised, it may not be possible to avoid it completely. A proactive approach to dust mitigation is required, considering the construction scale on the Moon. A few researchers have attempted to mitigate the problem by developing an electrostatic cleaning device (Tatom et al., 1967; Calle et al., 2008; Kawamoto, 2012) and a lunar dust collector (Aoyoma and Masuda, 1971; Taylor, 2002; Afshar-Mohajer et al., 2012), and none are used for real applications yet, particularly for construction processes.
- The near-surface lunar environment includes exposure to Solar Proton Events (solar wind) and Galactic Cosmic Radiation (GCR). According to Miller at al. (Miller et al., 2009), who performed the only radiation attenuation measurements using Apollo lunar soils, covering a habitat with a minimum 1.0 m thickness of local regolith, which is somewhat different from NASA's analysis (AIAA, 2009) estimating 2.5 m thickness, would protect mission crews from all SPE and the majority of the most energetic and infrequent highest-energy GCR particles. The shield needs to be solidly fabricated to keep its thickness and shape in order to withstand continuous micrometeoroid impacts. Although the proposed 1.0 and 2.5 m thickness are based on the use of unsintered regolith, which may not be applicable for sintered regolith, it still suggests that a decent thickness of protection cover would be needed. Considering the expected volume of habitat/outpost (Doule et al., 2011), a single printing system may not be an ideal solution to complete an entire protection cover as it would require a long construction duration. Thus, an alternative construction operation scenario, e.g. a collaborative construction using smaller and modular swarm robots, etc., would need to be investigated.

4. Conclusion

Space exploration is an expensive undertaking, with return on investment mostly measured in terms of scientific output. However, the global community is increasingly realising the potential of resources available on extra-terrestrial bodies for the future benefit of humankind. Identification of extra-terrestrial resources, and developing techniques to use them, could therefore both reduce our dependence on Earth-based resources and aid in the establishment of financially sustainable space exploration programmes. Moreover, in the longer term, as the Earth's natural resources continue to be depleted, the emphasis on exploring extra-terrestrial resources will inevitably grow; development of extra-terrestrial construction methods using local planetary resources will be mutually beneficial in both extra-terrestrial and terrestrial settings.

This article has reviewed the existing efforts on developing an extra-terrestrial construction process with three categorisations: (i) ISRU-based construction materials; (ii) fabrication methods; and (iii) construction processes. Current trends in this field focus on sintering-based AM techniques, and microwave is considered the most appropriate alternative method for extra-terrestrial environments, particularly on the Moon. The review of current trends highlights concerns and challenges which need to be addressed in order to develop an appropriate construction process, which are discussed more thoroughly under the following four categories:

Lunar simulants:

- The particle size and shape distribution should be matched or at least similar to real lunar regolith.
- The need for np-Fe^0 in lunar simulants should be carefully investigated, but is probably not required.
- Simulant properties should be designed with regards to the regolith of a potential landing site.

Material fabrication and curing:

- The printing system should be designed to minimise the vacuum tribology issue with lunar dust, as well as the use of microwave methodology in a high vacuum, such as on the Moon.
- Material compaction (or any other similar approach) prior to sintering should be considered to maximise the component strengths.
- The actual effect of np-Fe^0, particularly for microwave sintering, should be evaluated further.
- An effective and efficient curing mechanism needs to be developed.

Microwave-sintering based fabrication:

- In-depth studies are needed on correlation between material density, temperature, feedstock composition, and microwave frequencies in microwave sintering.
- Some other form of radiant heating, e.g. a susceptor, should be considered to increase microwave sintering efficiency.

- The efficiency of microwave with a different range of frequencies should be investigated to identify optimal parameters (e.g., power versus depth) for sintering simulant.
- The influence of material grain size on microwave heating should be investigated.
- An appropriate energy source for microwave sintering for construction should be identified.

Fully autonomous and scaled-up construction processes:

- Effective and efficient dust mitigation approaches should be developed.
- Fully autonomous and collaborative construction systems and operation strategies should be developed.

Compared with other disciplines, the construction industry is slow to adopt innovation in construction processes and technologies, because it is constantly subjected to the boom-and-bust economic cycle, making it hard for companies to maintain consistent technological progress. A similar situation exists in construction materials, e.g. concrete – first invented by the Ancient Romans (688 BC) and widely used by the Romans from 300 BC to 476 AD – remains one of the main construction materials. The needs of Space Architecture will stimulate the Built Environment industry to address tough construction problems applicable to highly hostile and extreme environments, which may require innovative technologies and materials for an entirely new construction process. With increasing public interest in space travel and settlement supported by academic research and public engagement, the Built Environment and space industries would enjoy new interdisciplinary R&D and enterprise opportunities, leading to new job opportunities in Space Architecture-related businesses. In the Built Environment industry, current growth of high-density populations may eventually force humans to look for alternative habitats on Earth. New human habitation in extreme areas including undersea and Antarctic environments, and improved living standards in the developing world, would thus be viable terrestrial applications of extra-terrestrial construction processes and technologies.

In summary, greater understanding of the unexplored concepts of Space Architecture would enable better use of its value, development, implementation, and evaluation; the success of extra-terrestrial construction processes would eventually support long-term scientific researches on and settlement of other planetary bodies beyond the Moon and Mars. A logical pathway for those purposes is, therefore, to address the important challenges of construction processes in an extra-terrestrial environment, investigate alternative construction processes and materials for Space Architecture particularly on the Moon, and develop an appropriate AM-based printing system.

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