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In-Situ Resource Utilisation (ISRU) derived extra-terrestrial construction processes using sintering-based additive manufacturing techniques – focusing on a lunar surface environment. S. Lim¹ and M. Anand^{2,3},

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Introduction: Space Architecture is the theory and practice of designing and building an extraterrestrial environment for human habitation [1]. It combines engineering and aesthetics, requiring knowledge of space environments, space systems engineering, and the psychology of isolated and confined environments [2]. Over the last decade, Space Architecture has become an emerging issue for future space exploration, and is increasingly seen as a fundamental requirement for supporting long-term space exploration and settlement on other planets.

Building a human habitat in hostile environments on other planets requires locally sourced and manufactured construction materials, known as *In-Situ Resource Utilisation (ISRU)*, and a fully automated construction assembly. Because ISRU is one of the most important concepts in the potential realisation of a deep-space exploration and space architecture, a significant amount of ISRU-related research has been carried out over the past 4 decades [3]. In general, extraterrestrial habitations can be categorized as (i) Class I: pre-integrated hard-shell modules, e.g. the International Space Station; (ii) Class II: prefabricated and surface assembled modules, e.g. inflatable structures; and (iii) Class III: ISRU derived structures integrated with the Class I and II modules [4]. As more and more complex lunar missions are planned by various space agencies, the topic of ISRU will gain prominence, and be of fundamental importance for the viability of such ambitious undertakings. Thus, those involved in the Space Architecture field believe ISRU is particularly important for deep-space exploration; for example, ISRU on the Moon would produce propellant, shielding materials, water and oxygen which can reduce the amount of mass launched from the Earth to other planets such as Mars, thereby saving billions of dollars of the space budget. As a result robotised manufacturing technologies are likely to be key technologies in the construction of Class III human habitations and infrastructure, including radiation shields, surface paving, bridges, dust-shield walls and spacecraft landing fields, etc.

Background Technology: Over the last 30 years, improvements in Additive manufacturing (AM) materials and processes have resulted in successful commercial realisation. AM is now an integral part of modern product development [5] and the technology has been commercialised to the extent where machines are now affordable for home use. The linear cost/production relationship for small-

batch production is unique in the manufacturing sector providing a strong business case for mass-customisation or personalisation of components. For example, a comparison between AM and injection moulding demonstrates that AM can be cost-effective for smaller batches (up to 10,000x) [6]. In construction, a range of construction forms has been identified where geometrical freedom has great potential for introducing mass-customisation in the construction industry, replacing the need to restrict component variability to the limits of how many moulds can be economically produced [7]. Because of the slow adoption on new construction technologies and the relatively short history of AM in construction – less than two decades, however, only two large-scale AM processes focus on the built environment in the academic literature: Contour Crafting [8] and 3D Concrete Printing [7], and one in industry: D-Shape [9].

Regarding a lunar construction material, initially researchers tried to develop a lunar concrete using lunar regolith. Lunar regolith contains various chemical and mineralogical resources – an area of lunar science of considerable importance for ISRU investigations [10]. For example, the native Fe (elemental Fe⁰) abundance in the regolith is at least ten times greater than in the rocks from which it is derived [11]. Recently, the interest in exploiting the lunar regolith as a construction material [12, 13] has increased, including previous investigations into setting up lunar outposts that have focused on developing conventional cement [14-16], concrete [17, 18], brick [19] and sulphur-based concrete [20, 21] using lunar regolith simulants.



Figure 1: *Printed block using a Lunar simulant (D-Shape)* [22]. The approximate footprint of the block is less than 1,000 by 2,000 mm.

In 2010, ESA and Foster+Partners (F+P) collaborated with D-Shape to investigate the potential of the wet-mix based D-Shape process to be used for Space Architecture. The team tested a closed-cell structure (Fig. 1), which retains loose regolith and ensures shielding from cosmic rays and solar flares, and raised a potential freezing issue of the binder and the related operation with a wet-mix based printing process under the extreme temperature changes of a lunar environment [22].

Potential of Sintering method: A sintering-based printing process using microwave or laser power, which does not require any binder, is thought to be an appropriate technique. Some researchers have investigated the potential of lunar regolith sintering using a high-powered laser and/or microwave, as the natural lunar regolith is potentially an excellent construction material, as it mostly consists of soil (≤ 1 cm) and dust (≤ 20 μm) particles which require only mechanical sieving, without crushing. Kingery [23] proposed that the complex morphology of raw lunar regolith might be more suitable for sintering because its glass portion could assist in densification during sintering. Similarly, Taylor [24] proposed that raw lunar regolith is a strong microwave absorber due to the presence of nanophase iron (np-Fe⁰), indicating its suitability for microwave sintering. He observed that microwave energy is easily deposited into a regolith depth of around 65 cm at low temperature, while the half-power depth of penetration decreases as temperature increases. Recent studies involving sintering of lunar simulant found that microwaves could melt the lunar simulant up to 13.4 mm depth [25] while a solar-concentrator could melt up to 6 mm depth [26].

Discussion: Some potential lunar landing-sites, including the Shackleton Crater near the Moon's south pole may not be exposed to sunlight, which means a solar concentrator would not be an appropriate method for sintering in such environments. Although some researchers have discussed the potential of microwave heating for sintering lunar regolith for construction and oxygen production [24, 25, 27, 28], their experiments are limited to one lunar simulant (JSC-1A) and only at 2.45 GHz microwave frequency. The main reason for using 2.45 GHz in their experiments was because it is easily sourced from domestic cooking appliances. The 2.45 GHz frequency was chosen for cooking because of its efficiency in heating liquid water but not necessarily other materials. Usually, if the frequency is much higher the waves would penetrate less well, and lower frequencies would penetrate better but are weakly absorbed – so the food (or other materials) would not absorb enough energy to cook (or sinter) well. Microwave, therefore, is believed to be more useful as a catalyst rather than a thermal source. Thus, various combinations need to be investigated

with other sintering methods and a wider range of microwave frequency for sintering a lunar simulant.

As part of a research consortium comprising members of a number of academic institutions across Europe and SMEs, we are embarking on a multi-disciplinary research project to integrate our existing expertise in 3D Concrete Printing [7] and knowledge of ISRU potential on the Moon [29] to perform a series of experiments using lunar simulants to optimize 3D printing process and its potential application to building structures and components on the Moon in the context of future habitation of the Moon.

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