BUILDING ON THE MOON USING ADDITIVE MANUFACTURING: A DISCUSSION OF ROBOTIC APPROACHES

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ABSTRACT

We present two concepts for building structures on the moon. The first involves an all-purpose robot with exchangeable tools, able to excavate regolith, produce slurry and print a structure. The second involves a team of robots: one excavator, one sintering using sunlight, and another gathering the sintered bricks and building a structure. ESA's Space Resources Strategy [1] sets the challenge of achieving human presence at the Moon, sustained by local resources, by 2040, which includes in-situ manufacturing and construction. We take a realistic look at the feasibility of these concepts and their component technologies, and their challenges with respect to the state of the art and expected technological readiness in the next 2-5 years.

1 INTRODUCTION

In recent years, in-situ resource utilisation (ISRU) has attracted more attention as a way of creating the first infrastructure on the moon. Lunar regolith material properties have been extensively studied and tested in additive manufacturing technologies based on sintering or involving binders [2, 3]. Furthermore, lunar analogue facilities such as the LUNA environment at the European Astronaut Centre make it easier than ever to test solutions in as realistic an environment as can be achieved on Earth [4].

Robotic exploration offers advantages over human presence in terms of risk and flexibility - a robot can take more risk than a human life and can stay on the moon for extended periods of time. However, human intelligence is far superior to automation and there are critical aspects of robotic operation that cannot be reliably executed in full automation within the next two decades at least. Hence intuitive, stable and transparent methods of teleoperation are necessary. One of the European Space Industry Technology Needs identified in ESA's Technology Strategy for space [5] is to "investigate and develop synergies between crew and robotics". In other words: Human-Robot Interaction for space.

A way to pair the general intelligence of the human with the advances in robot autonomy is the concept of Supervised Autonomy [6, 7]. This is especially relevant in space, where robots would be able to interpret high-level commands from operators over long distances and unreliable communication channels and execute them in the remote environment using local sensing and intelligence [8, 9]. This presents a multitude of ways for operators to control robots, taking more direct control where the task requires human-level intelligence and allowing more high-level commanding where the workload on the operator is reduced. Reducing operator workload improves efficiency and could allow a single operator to control multiple robots effectively.

In this paper we review the state of the art in additive manufacturing of structures on the lunar surface, and discuss the advantages and disadvantages of two approaches to building a simple structure. The first involves a single mobile robot with multiple end effectors: an excavator tool and a printhead. Regolith is loaded into the robot (by itself or another robot). The printhead prints the structure in 3-D. The second approach is a trio of machines: a mobile excavator robot, a solar-powered sinterer, and a mobile robot with attached manipulators. The excavator excavates and levels the ground. It loads regolith into the sinterer, which produces interlocking bricks. The robot with manipulators builds a structure with these bricks without the need for cement.

While prototypes of subsystems of some of these technologies have been built and tested, several practical challenges remain. Besides the necessary technological challenges in materials science, hardware and software, challenges in energy consumption, space-resistant design, control algorithms, and user interface for reliable and intuitive operation. The insights from tackling these challenges will guide and determine the approach we use when we start to build on the moon.

2 STATE OF THE ART

2.1 Additive Manufacturing with Lunar Regolith

Additive layer manufacturing is arguably the most widely considered construction concept for building of extraterrestrial infrastructure using local resources. This is due to its potential for automation and for enabling

Figure 1. *: Examples of 3D printed parts obtained by solar sintering of regolith simulant.*

construction in a continuous process, without additional joining operations. Additive manufacturing is based on the successive deposition of consolidated regolith into the desired 3D structure. Methods for consolidation of regolith can broadly be classified into categories: sintering of regolith by applying heat ad mixture of regolith with a binder. In the following paragraphs, several previously-reported approaches for consolidation and additive manufacturing of regolith are presented.

2.2 Sintering with Solar Power

Sintering is a process of forming a solid mass from granular material via the application of heat and pressure, predominantly carried out below the melting temperature of the particles' material [10]. The ubiquitous availability of loose regolith material across the lunar surface and the possibility to readily sinter such material has already been recognised and researched [11]. Using concentrated solar power on the lunar surface, a resource in general abundance, has been proposed and demonstrated terrestrially as a means to drive a sintering processes using regolith simulant material and to produce three dimensional parts, see Fig. 1 [12–14]. Solar sintering of regolith is arguably the most technological developed approach for large scale ISRU construction.

2.3 Laser Sintering

Laser sintering is a widespread additive manufacturing approach and can be extended to treat lunar regolith. Already there has been a number of demonstrations of geometrically accurate parts, using direct metal deposition [15] or powder bed fusion [16, 17] on regolith simulants. Those studies involved 50 W lasers and the test parts produced were on the order of mm to a couple of cm. Using a more powerful 500 W laser, Mueller et al [18] achieved lower resolution, but could produce bench-top scale free-standing dome-shaped structure. However, it should be noted that large scale manufacturing via laser sintering of regolith has yet to be demonstrated - in [15, 16], the test parts produced with regolith simulant were on the order of mm. Coupled with the intrinsic energy cost of laser systems, large scale construction of buildings with laser sintering techniques may not be ideal. First order calculations based off the work of Balla et al [15] show that creating a sintered layer of 254 μ m with a 50 W laser would require power in the range of approx. 12-16,000 kWh/MT (metric tonne) of regolith material [2].

2.4 Microwave Sintering/Melting

Volumetric heating of regolith material via an applied microwave field would have significant advantages over other technical approaches [19], owing to its relative energy efficiency, processing speed and potential applicability across larger areas. Indeed, the actual lunar regolith may be particularly suited to this form of processing, as demonstrated by Taylor and Meek [20], who showed that the presence of nano-phase iron particles (np-Fe^{o}) in native regoliths create efficient "energy sinks" where the microwave energy is coupled to the np-Fe and potentially other Fe-bearing minerals, as demonstrated by their experiments with Apollo lunar soil. Internal activities within ESA have also confirmed these observations. The technique is relatively understudied in the context of being used for construction, despite smaller test samples being successfully melted and sintered. An exact concept for a microwave driven 3D printing process has yet to be fully defined and demonstrated.

2.5 Binder Mixtures/Concrete

Another logical initial direction of research into lunar construction would be to transfer terrestrial techniques, such as using concrete. Initial work has been carried out in this direction, with examples of lunar "mooncrete" bricks [21]. Consolidation of regolith into a construction material can be achieved by mixing the regolith with a binder which triggers a chemical reaction. The reaction can form a solid material or a paste-like material which can be extruded. Previous activities at ESA have demonstrated the additive manufacturing of three dimensional demonstrator parts in the centimetre to metre range, by spraying a binder onto successive beds of regolith simulants [22] (see Fig. 2) or by extruding the regolith-binder mixture into successive layers [23, 24]. However, such approaches call for the use of binder material brought from Earth, or utilise water that would also need to be brought or sourced locally in-situ, driving an effort to develop processes which minimise the amount of required additives [25, 26]. In addition, loss of water during a setting process in the vacuum environment would be deleterious to the overall structural properties and would potentially necessitate a pressurised environment to compensate. Such approaches are considered not as holistic as other potential ISRU construction processes, which can avail of solar energy (used directly or converted) and only local resources.

2.6 Excavation on the Moon

A comprehensive overview of excavation technologies is provided in [27]. Technologies can be classified into discrete and continuous excavation; continuous excavators providing a continuous stream of regolith (designs

Figure 2. *: Lunar habitat outer shell building block demonstrator produced by the D-Shape additive manufacturing process, using MgCl binder and lunar regolith simulant.*

include bucket chains and impeller based designs) and discrete excavators a large quantity all at once (e.g. the classical backhoe excavator common on building sites).

Key insights relevant to our case are that the density of lunar soil increases greatly with depth, reaching 90% density at only 30cm depth. Drills may be required for higher densities, limiting several excavation techniques to the top few centimetres of regolith. An excavator robot without drilling capabilities would therefore have to be highly mobile to cover the area of ground required for significant quantities of regolith. Lunar regolith is also fine-grained and highly abrasive; significant wear on moving parts is expected. This could indicate that backhoe or front-loading discrete excavator designs may be more durable than impeller- or auger-based designs.

2.7 Robotic Hardware for the Moon

Robotics on the lunar surface presents a plethora of challenges. The lack of atmosphere and magnetosphere mean that the robot is exposed to solar radiation, posing a danger for electronics. Further, heat dissipation is only radiative and not convective, posing problems of extreme temperatures, especially in the harsh light of lunar day or cold of lunar night. One advantage to operating on the moon is the surface gravity, which is one-sixth of that on earth. This means that power consumption can be less than on earth, since joints need not carry the weight of links further along the chain.

In the ROKVISS experiments [28, 29], robotic technology for compliant control was tested on the outside of the ISS between 2005 and 2010. The results from these hardware and telemanipulation experiments led to the development of the robotic arm CAESAR [30], and the robotic arm TINA [31], a more compact design and hence more relevant to our scenario. Their modular design enables different kinematic structures to be achieved, the joints are designed for large temperature ranges (operating temperature between -40°C and 120°C for TINA) and use cases not limited to earth orbit; also lunar and deep space missions are envisaged. The drives are also identical to those used in e.g. the LWR [32], so insights and software can be transferred across from terrestrial research and development with such robots.

2.8 Telerobotics and Autonomy for Space

Telerobotics performance in space, in common with terrestrial applications, is a trade-off between stability or safety, and transparency. The system must keep stable and reliable, on the other hand, the operator must be able to have a clear understanding of what is going on at the remote site, in order to effectively control the robot. In addition, there is the human element of operator fatigue to be considered. The less effort for the operator, the more effective the robots can be or the more robots can be controlled simultaneously.

The foremost challenges in space robotics are in the communication channel: a high end-to-end latency (lower-bounded by the speed of light in a vacuum), packet loss, low bandwidth and frequent losses of signal. Sensing on the remote end may also be limited, due to poor light conditions and a limit on the amount of space-qualified sensors on the remote robotic asset.

One effective way to control robots with minimal effort for the operator is Supervised Autonomy [6, 7]. As the name suggests, the robot executes the low-level control for its tasks autonomously, while receiving higher-level commands at a more supervisory level from the operator. Therefore, depending on the amount of autonomy possible for the robot, commands may be “pick up brick A and connect it to brick B”, “use 10 bricks of type A to complete the section of wall B” or even, “continue building the structure until further notice”. This is safe and robust even with unreliable communication, because the low-level control is local to the commanded robot; if high-level commands are lost or delayed, this is does not have dangerous or unexpected consequences [8, 9]. Such autonomy is, of course, limited by the technology for object recognition in unstructured environments. The robotics community has been struggling with this problem for years, and a solution mature enough to be reliable for space operation will not be available in timescales in line with first demonstrators of construction with ISRU [1].

Furthermore, in real life, things do not always go according to plan: a brick breaks, or slips out of grasp, or cannot be located; the structure of the regolith in a particular area is not suited to sintering, but this cannot be detected by the robot; a section of wall collapses. In these situations, the operator may need more control over the robot as in direct teleoperation, where the robot follows the exact motions commanded by an operator. The remote manipulator can be commanded in Cartesian Impedance Control [33], where the operator commands not the position of the robot end-effector, but rather the position of one end of a virtual spring-damper system, the other end of which is attached to the robot end effector. When contact is made with the environment, the operator does not see this straight away due to the time delay, and may continue commanding motion, however, they are only commanding a force from the manipulator on the environment, which is less damaging to the end effector.

This is still not ideal, and furthermore (especially during such contact events) the operator may benefit from force-feedback. A solution to this is Time Domain Passivity Control (TDPC), where the passivity of the system is conserved: simply put, no more energy comes out of the system than is put into it by the operator. This is done by limiting speed of the manipulator or forces rendered to the operator. It also means that no force is exerted on the environment during initial impact which the operator did not intend to command [34]. A version of TDPC was used in the Analog-1 experiment (see Fig. 3), where an astronaut in orbit was able to directly control a robot manipulator on ground with force feedback, with an delay of 850ms or more, and packet loss [35]. The experiment showed that it is possible and feasible to directly teleoperate a robot from orbit to surface stably, and to build a graphic user interface (GUI) that is intuitive enough to function for an astronaut with minimal training on that GUI.

Thus, robots on the moon, while mostly operating autonomously or semi-autonomously, will require functionality for direct teleoperation to a greater or lesser degree. A way to scale up or down the level of autonomy within the same user interface while remaining intuitive is expected to be necessary in any interface developed for commanding robots in space in the near future. This concept, called *Scalable Autonomy*, is the focus of current research efforts at the Human Robot Interaction Laboratory at ESA and the Institute of Robotics and Mechatronics at the DLR, and is expected to be crucial to effective robotic teleoperation.

Figure 3. *: Analog-1 Experiment. Top left: Astronaut Luca Parmitano controls a robot manipulator with a modified Sigma.7 Device from Force Dimension, on board the ISS. Top right: an image of his screen mirrored on the ground control station. Bottom: the rover controlled by the astronaut in the moon analogue site.*

3 CHALLENGES OF PRINTING OF THE MOON

To date, demonstration of construction techniques for lunar surface applications have been understandably confined to terrestrial research and demonstration. The lunar environment, with its unique challenges, is expected to impose significant constraints on the construction equipment, as well as affect the manufacturing processes. The lunar environment [36–40] is characterised by reduced gravity, the absence of atmosphere, higher solar irradiation than on Earth, large temperature variations - more than 200 K fluctuation in the equatorial regions - at a given location, and potentially extended periods of low temperatures during the lunar nights (reaching up to 14 Earth days at the lunar equator).

The reduced gravity, of about 1/6th of terrestrial level, is likely to affect the adherence between successive layers in additive manufacturing processes and therefore the properties of the constructed material and structures. In absence of atmosphere, the manufacturing equipment at the lunar surface - and their electronic components - will be fully exposed to radiation from cosmic galactic rays and solar events. Sustainable operation of such equipment will require adequate design and/or protection. The radiation environment also leads to electrostatic charging of the ubiquitous sharp regolith particles. The charged abrasive lunar dust was acknowledged by Apollo astronauts as one of the most significant challenges to lunar surface exploration and is expected to impede on the functioning and durability of the ISRU construction equipment [41]. Such equipment will also be affected by the large temperature variations or extended periods of low temperature. Construction operations on the equatorial regions or at latitudes where the duration of the lunar nights is significant will need to address the requirement of alternative energy sources, to protect the equipment from low temperature degradation or ensure continued operation. The multiple

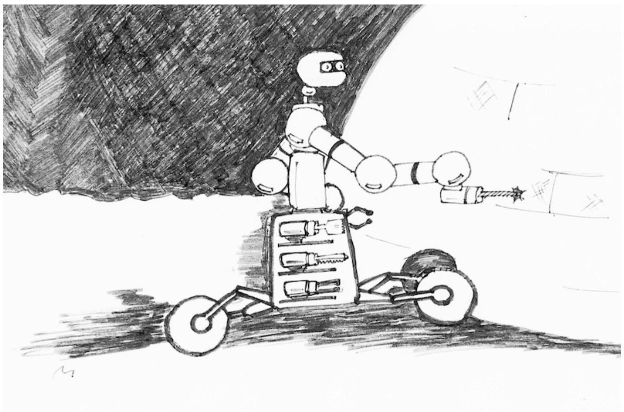

Figure 4. *: Concept sketch of a mobile platform with exchangeable end effector.*

lunar environmental constraints warrant for testing the intended manufacturing equipment and processes in representative environments, in order to validate the ISRU construction concepts developed at laboratory scale.

4 FIRST APPROACH: ROBOT WITH PRINTHEAD

A first approach to building on the moon is a mobile robot with a manipulator, on which an exchangable end effector can be mounted (Fig. 4): at least one for excavation and another for printing. Alternatively, the robot may have excavation apparatus separate from its robotic manipulator and printhead.

A robot with a printhead end effector has been proposed in [42], the MIRA3D prototype. The specifications for the robot and the printhead manipulator are detailed in [43]. The advantage of such an integrated system is the low mass that needs to be sent to the moon. The fact that this is a single robot with as little complexity as possible reduces the required mass per operational system. If this idea is viable, several such robots could be sent to work in parallel or at different sites/different areas on the same site. A robot swarm could be envisaged, able to function even when some assets are taken out of operation.

Drawbacks of this approach could be the power consumption in order to fuse the slurry, requiring a large battery, and in a related way, the speed of progress. High temperatures are required to fuse the slurry, hence large amounts of power are required. Taking a specific heat capacity of 670 J/kg/K [1], in order to heat the regolith up to at least 900°C (as suggested in [43]), and depending on the temperature of the regolith (ranging between -150 and 100°C), this would require between 540-700 kJ/kg.

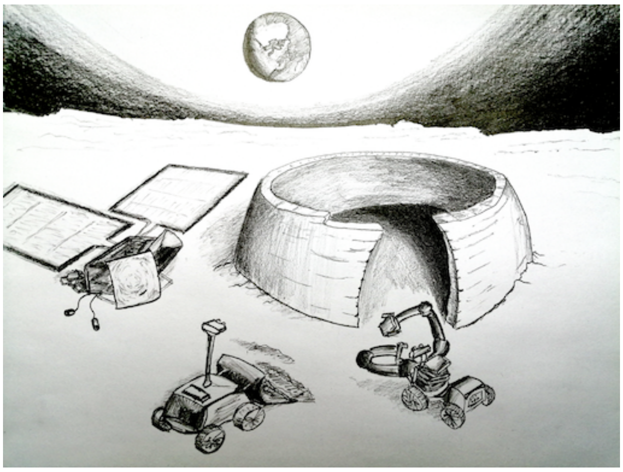

Figure 5. *: The trio of robotic assets: an excavator (middle), sinterer (left) and platform with manipulator(right).*

In order to print 10kg of rock on a single battery charge, the battery required would be 1.5-2 kWh (more, in fact, because the battery should not be discharged fully.). A battery able to provide this would be heavy, around 30-50kg[2]. Even this is optimistic, because the melting of the rock is assumed fully efficient and temperatures higher than 900°C may be required. The printhead would have a large mass, but would not be too heavy on the moon. A preliminary study [43] estimates a mass of 5-8kg, which would be 6-10N on the moon, plus the mass of the regolith to be printed.

The excavator technologies described in Sec. 2.6 deliver in the order of 10's of kg of regolith per hour, whereas printing is expected to be much slower. This suggests to decouple the excavation and printing functions, in order to work in parallel, possibly having a swarm of printer robots for one excavator robot. This decoupling of functions leads us to our second approach.

5 SECOND APPROACH: ROBOT TEAMS

The second approach (Fig. 5) we present uses a team of specialised machines to build a structure: 1) a robotic excavator; 2) a brick sinterer; 3) a mobile robotic platform with manipulator(s). The excavator clears and levels the ground for the structure, and excavates and delivers regolith to the brick sinterer. The sinterer focusses solar light through a lens onto a platen, creating bricks from this regolith by sintering. The mobile platform brings these bricks to the building site and lays them.

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[1] `lpi.usra.edu/wiki/lunaref/index.php/Thermal_Properties_of_the_Regolith`

[2] E.g. from typical suppliers: `canbat.com/lithium-battery/`, `claytonpower.com/products/lithium-ion-batteries/specifications/`, retrieved 28.9.20

One major advantage of this approach is the technological readiness of most aspects of this approach. Although Technology Readiness Level (TRL) of excavation technologies is overall low ([27] points out that most studies have not exceeded the proof of concept stage), solar sintering has been trialled in [13, 14] on earth. Robotic bricklaying consisting of object recognition and pick-and-place tasks is perhaps the most technologically developed element of this approach, being already used in industrial applications[3].

The disadvantage of this approach is that if one of the elements of the team malfunctions, this puts the entire team out of order. When scaling up operations, this danger could be minimised by having several of each type of robot, introducing redundancy into the system.

6 DISCUSSION AND CONCLUSIONS

In this paper we have outlined two potential approaches to realising construction based ISRU using additive manufacturing coupled with robotics. Technicalities of the ISRU processes around excavating and sintering lunar regolith are presented, and the challenges of teleoperated robotics in space highlighted. It is clear that robotics will play a key role in any building ISRU application, and as such, the modalities of using robotics for this application need to be carefully considered, elaborated on and demonstrated terrestrially.

As mentioned in the introduction, subsystems for the two approaches we present exist, but have yet to be fully integrated and tested. With respect to sintering technology and approaches, this continues to be an area of development within ESA and Europe. As recently as October 2019 a call for ideas to address ISRU construction and manufacturing on the lunar surface was issued by ESA [44], within which scope for further technology development around sintering techniques was present. This is alongside other technology development activities within the Agency aimed at further developing construction based ISRU. As the technology stands currently, some confidence can be taken from the variety of terrestrial demonstrations that have been undertaken worldwide. No technical showstopper for sintering of lunar regolith simulant (and by extension, lunar regolith in-situ) have been identified to date and the various technologies investigated are approaching a moderate TRL. However, power consumption and by extension battery weight/capacity need to be analysed and factored in to feasibility studies, especially where mobile robotic assets are concerned. These are non-trivial and may be make-or-break for a particular design concept. Engineering challenges towards the realisation of in-situ sintering are related to the design of construction equipment which can withstand the constraints of the lunar environment described in section 3. These environmental challenges, such as resistance to radiation, dust or temperature variations, are not specific to ISRU equipment, but remain valid for all hardware operating on the lunar surface. They will be addressed through material and component selection and qualification, as well as testing in representative conditions.

Similarly, it has been proven that remote teleoperation of terrestrial robotic assets from orbit is possible, as demonstrated recently by Analog-1 [35]. The conceptual approach of scalable autonomy has been proposed as a methodology to enable construction ISRU. In terms of the TRL, leveraging existing solutions from terrestrial applications, e.g. industrial robotics and robotic building, could ensure fast development of the control for both approaches. Furhtermore, in both approaches, it should now be a focus to start moving beyond limited *ab initio* testing and towards more representative and involved tests - both in simulation and building of prototypes.

Upcoming facilities, such as the aforementioned LUNA, will provide an excellent test bed to demonstrate these technologies in such a combined approach. In order to start converging on robust techniques to enable construction ISRU, the authors would encourage a higher degree of integrated testing by groups working in this domain, bringing as many of the various subsystems together as is reasonably representative. This would serve to both accelerate the resolution of technical issues and interface problems, but also serve as advertisements to the rising readiness level of construction ISRU, an important consideration in raising various exploration stakeholder confidence in the concept and meeting the 2040 expectations described in [1].

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[3] see e.g. `www.mujin.co.jp`

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