Automated Additive Construction (AAC) for Earth and Space Using In-situ Resources

Conference or Workshop Item

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for Earth and Space Using In-situ Resources

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ABSTRACT

Using Automated Additive Construction (AAC), low-fidelity large-scale compressive structures can be produced out of a wide variety of materials found in the environment. Compression-intensive structures need not utilize materials that have tight specifications for internal force management, meaning that the production of the building materials do not require costly methods for their preparation. Where a certain degree of surface roughness can be tolerated, lower-fidelity numerical control of deposited materials can provide a low-cost means for automating building processes, which can be utilized in remote or extreme environments on Earth or in Space. For space missions where every kilogram of mass must be lifted out of Earth's gravity well, the promise of using in-situ materials for the construction of outposts, facilities, and installations could prove to be enabling if significant reduction of payload mass can be achieved. In a 2015 workshop sponsored by the Keck nstitute for Space Studies, on the topic of Three Dimensional (3D) Additive Construction For Space Using In-situ Resources, was conducted with

additive construction experts from around the globe in attendance. The workshop explored disparate efforts, methods, and technologies and established a proposed framework for the field of Additive Construction Using In-situ Resources.

This paper defines the field of Automated Additive Construction Using In-situ Resources, describes the state-of-the-art for various methods, establishes a vision for future efforts, identifies gaps in current technologies, explores investment opportunities, and proposes potential technology demonstration missions for terrestrial, International Space Station (ISS), lunar, deep space zero-gravity, and Mars environments.

INTRODUCTION

What is In-situ Additive Construction? Why In-situ Resources?

A new technology discipline is emerging called Automated Additive Construction (AAC), which is distinct from Additive Manufacturing. AAC refers to automated processes that create civil engineering structures that are relatively large (>1 m^3), and compared to manufactured parts, tend to have lower accuracy and precision and lower dimensional tolerances. A variety of materials and processes are being used and developed, which range from traditional Portland cement concretes to novel methods using indigenous materials on Earth and in Space. All of the existing and emerging methods aim to produce large scale civil engineering products which have structural integrity and meet the needs of the end user in a safe and reliable manner, including inhabitation by people in the general public.

AAC is the process of forming a large scale structure by sequentially adding and bonding material under automated computer control, without any waste. It is the opposite of subtractive construction that starts with a larger topographical feature or raw material and then removes material by methods such as excavating, contouring, tunneling, boring, and others to create the final desired net shape.

The advantages of AAC include, but are not limited to, new architectural forms and functions, better structural designs and implementations, increased efficiencies and a reduction in the logistics train due to the use of indigenous materials. Many experts believe that two dimensional (2D), (e.g. foundations, landing pads) and three dimensional, (3D) Automated Additive Construction (e.g. habitats) have the potential to lead to a new 21st century construction technology revolution that could substantially impact the building construction markets on Earth and beyond (Mueller et al, 2014).

Launching mass into space is difficult due to the gravity well of the Earth which requires a change in velocity impulse (Delta-V) of 9.3 – 10 km/s. This means that complicated space transportation vehicles must be used to provide a large amount of energy transfer through the use of chemical rocket propulsion. An additional Delta-V of 6.4 km/s would be required to land this mass on the surface of Earth’s moon. If in-situ materials could be used on the moon (such as regolith or regolith derived concrete), to build large civil engineering structures, then large amounts of mass launched from Earth could be avoided, making space exploration more economical.

This paper focuses on AAC using local in-situ resources on extra-terrestrial bodies in the form of regolith – the loosely consolidated layer of crushed rock and other materials covering the surface of extra-terrestrial bodies. This could enable construction at distant locations in our solar system (Moon, Mars, Asteroids, outer planets and their moons) without transporting the construction materials through Earth’s deep gravity well, with an expensive rocket launch. 3D

AAC could provide the solution for extra-terrestrial shelter (electromagnetic space radiation, thermal, micro-meteorites, dust storms, vacuum, fission power plant shielding, rocket blast ejecta at launch/landing, etc.) for human crews and robotic equipment on planetary surfaces. New possibilities for space exploration and space mission architectures may arise out of this technology that is currently under development.

Mass is a critical component of spaceflight and must be minimized in order to maximize cargo. The further one travels from Earth the more critical this becomes (McLemore et al, 2008). In-situ Resource Utilization (ISRU) means having the capability to extract and process resources at the site of exploration into useful products such as propellants, life support and power system consumables, and radiation and rocket exhaust plume debris shielding (Sanders & Larson 2011). ISRU has the potential to significantly reduce launch mass, risk, and cost of space exploration; thus, ISRU is considered as a key technology that enables long-term exploration, expansion of space activities, and settlement in space (Iai & Gertsch 2013).

The use of ISRU into missions can also significantly influence technology selection and system development in other areas such as propulsion, life support, and power. For example, the ability to extract or produce large amounts of oxygen and water in-situ would minimize the need to completely close life support air and water processing systems, and generate propellant for ascent vehicles.

Table 1. ISRU connectivity to other exploration system elements (Sanders & Larson 2011)

Requirement Connectivity	
Propulsion systems	Propellant / pressurant quantity Propellant/pressurant type Residual amount (scavenging) Storage type and capability
Life support / EVA systems	Consumable Quantity Consumable type Waste products/trash quantity Waste products/trash type Storage type and capability
Surface mobility	Vehicle size Terrain mobility capabilities Power requirements Fuel cell reagent quantity Fuel cell reagent type
Surface power	Daylight power amount Nighttime power amount Fuel cell storage capability Nuclear reactor placement/shielding
Habitat	Placement Shielding/protection Assembly/inflation capability

Hardware Element Connectivity	
Propulsion systems	Propellant/pressurant storage and valving Solar collectors/solar thermal propulsion
Life support / EVA systems	Consumable storage and valving Water processing/electrolysis Carbon dioxide processing Liquid/gas separation Solar collectors/trash processing
Surface mobility	Mobility platforms Actuators, motors, and control software
Surface power	Consumable storage and valving Water processing/electrolysis Liquid/gas separation Solar collectors/solar thermal Storage
Science instruments	Geotechnical properties Mineral characterization Volatile characterization Subsurface access Inert gas storage and valving
Testing and certification	Surface analogs Environment simulation chambers Lunar and Mars stimulants

In general, there are five main areas of ISRU: (1) resource characterization and mapping, (2) mission consumable production, (3) civil engineering and surface construction (radiation shields, landing pads, habitats, etc.), (4) in-situ energy generation, storage, and transfer, and (5) in-situ manufacturing and repair (Sanders & Larson 2013). Unlike other types of surface or transportation systems, ISRU does not exist on its own. By definition, it must connect and tie into one or more 'users'. Also, ISRU capabilities would often not consist of a single system but would involve multiple technical discipline elements, such as mobility, material processing, and product storage and distribution. Because ISRU systems can provide products to and receive feed-stock and communities from other systems, incorporation of ISRU into an architecture can strongly effect the requirements, technology, and hardware selected for these other systems if an integrated perspective is utilized. Both the requirements and hardware connectivity (Table 1) ISRU systems have with other major exploration surface and transportation system elements have been depicted in Sanders & Larson (2011).

The greatest potential mass and cost reduction benefits of incorporating ISRU in mission architectures occur when surface and space transportation elements utilize in-situ produced propellants. Since propellant mass is a significant fraction of launch and lander mass (83% to 96%), producing propellants for ascent to orbit or hopping to other locations can significantly increase the delivery of other exploration payloads or reduce overall launch mass and cost. Other ISRU capabilities such as civil engineering for landing pads and habitats and in-situ energy production and storage for day/night operations and heat rejection can also reduce the risk and increase mission flexibility compared to Earth provided capabilities while allowing the human presence in space to be expanded through growth of these critical capabilities.

This paper describes the state-of-the-art for Automated Additive Construction methods, materials, material extraction, and performance for mission concept planning purposes (see Table 2). A 10, 25, 50, and 100 year vision is also discussed, with considerations for phasing, investment, and funding.

STATE-OF-THE-ART FOR AUTOMATED ADDITIVE CONSTRUCTION USINGIN-SITU RESOURCES

The state-of-the-art for AAC can be summed up through methods, materials, and material extraction processes. Some methods are described in detail, and performance parameters are listed for mission planning purposes.

A. State-of-the art: Methods

Additive Construction can be accomplished by a variety of methods from slurry extrusion to sintering to melting techniques, with varying levels of difficulty, costs and technological readiness. In addition, special challenges arise from Additive Construction for space applications; critical challenges include construction in a vacuum or low atmosphere as well as under reduced gravity (e.g., on Earth's moon or on Mars) or zero/milli-gravity (such as on an asteroid). We note that those challenges also promise to enable new techniques or to overcome difficulties commonly faced on Earth. For example, although the lack of atmosphere makes powder-based methodologies difficult or even impossible, it also prevents oxidation during melting or sintering. Also, while low levels (or lack) of gravity disqualify some layer deposition techniques, it enables the construction of complex three-dimensional shapes without the need for support structures.

Additive three dimensional (3D) printing has reached maturity on Earth for a variety of methods, primarily for polymeric or metallic base materials with many commercial and large-scale realizations. AACfor space using in-situ resources is still in its infancy but can, in principle, adopt terrestrial techniques, especially those used for civil and structural engineering.

The matrix in Table 2 gives a (non-exhaustive) overview of available techniques along with specific parameters and some performance characteristics. All methods have been proven terrestrially, whereas only the plastic extrusion process has been demonstrated in micro-gravity on the International Space Station (ISS). Materials Processing refers to the techniques explained in Table 3, Table 4, and Table 5. The listed demonstrations in commercial or university settings can only serve as representative examples.

In considering all advantageous and shortcomings of the methods listed in Table 2, extrusion-based techniques appear to have the greatest potential for space applications. Specifically, the extrusion of a slurry of regolith and binders or the extrusion of a regolith melt (possibly in combination with sintering techniques) are applicable in a vacuum and can be applied at reduced and micro-gravity, if suitable materials resources, metrology systems, and robotic mobility are available.

Some of the methods in Table 2 are discussed below.

1. Cementitious Examples

Like all 3D Printing processes Fused Deposition Method (FDM)-based machines are slow because they build objects with small layers. A major leap toward large-scale fabrication was made in 1995 by the University of Southern California extrusion technology called Contour Crafting (Khoshnevis 1998; Khoshnevis 2004; Khoshnevis et al, 2006).

The major innovations that Contour Crafting (CC) introduced were: a) large orifice extrusion nozzle which allowed the inclusion of relatively large solids in the extruded slurry material, hence making viscous concrete extrusion possible, b) the addition of computer controllable trowels that made the creation of smooth surfaces possible for unusually thick layers in the layer-wise fabrication, and c) introduction of complex hybrid nozzle systems that could build hollow walls with various internal structures (e.g., corrugated). Terrestrial applications of Contour Crafting may include building construction as well as construction of numerous types of medium-scale objects such as furniture, bathtubs, etc. More recently and under NASA support, extraterrestrial applications of Contour Crafting are under research and development. For this purpose several advancements have been made in the construction of Lunar and Martian infrastructure elements using molten regolith extrusion and sulfur concrete extrusion using Contour Crafting (Khoshnevis et al, 2005). Contour Crafting received the NASA technology grand prize in 2014.

Another development in extrusion based large-scale 3D Concrete Printing (3DCP) has been at Loughborough University (Le et al, 2012a; Le et al, 2012b; Lim et al, 2012) where free-form structures have been built, including some horizontal ones which have been printed over sacrificial support structures (Figure 1).

Figure 1. Free-form large scale concrete parts printed at Loughborough University (Le et al, 2012a; Le et al, 2012b; Lim et al, 2012)

Table 2: Overview of Additive Construction methods with potential for space applications and in-situ resource utilization, including performance parameters for mission planning (ISRU Materials Processing codes refer to Table 3, Table 4, and Table 5) – blank cells show unknown or proprietary data (table compiled by Samuel Wilkinson, Foster + Partners)

Construction Method	Binding Method	Base Material	Additives	Support	Partial/ Zero-G Capable?	ISRU Materials Processing	Comments	Example	Deposition Rate [cm^3/s]	Power Consumption [kW]	References
Extrusion deposition	Cementitious	Regolith / Sand	Sulfur, Portland, plastics, Sorel cement	YES	OK	1L, 1A, 1M	Portland/Sorel cement not appropriate in vacuum. Regolith + sulfur for vacuum	Loughborough University, Skanska, F+P	75	10	Lim et al, 2011
				-	OK	8L, 9A, 8M	Portland/Sorel cement are not appropriate in vacuum. Regolith + sulfur is an ISRU option.	WinSun	-	-	WinSun 2015
								WASP	-	-	WASP 2015
								BetAbram	-	-	Betabram 2015
								Spetsavia	-	-	Specavia 2015
								Rudenko	-	-	Krassenstein 2014
								Contour Crafting USC	1000	10-20	Khoshnevis et al, 2005
	Fused-deposition method (FDM)	Plastics	-	-	OK	6L, 8A, 4M		Dirk van der Kooij	-	-	Vander Kooij 2015
								KamerMaker	-	-	DUS 2015
		Glass	-	-	OK	1L, 1A, 1M		MIT Mediated Matter	-	-	Klein et al, 2015
		Ceramics	-	-	OK	2L, 5A, 5M		IAAC	-	-	IAAC 2015
								Robocasting SNL	-	-	Cesarano 1998
	Microwave melting	Regolith	-	-	OK	1L, 1A, 1M	Melted in chamber and extruded.	JPL, PISCES	-	0.02	Barmatz et al, 2014
	Gluing	Regolith	Urethane	-	OK	6L, 8A, 4M	Not appropriate large scales.	Adherent	-	-	Gosau 2012
	Powder spray	Regolith / Sand	Water, air	-	Partial	1M	In a vacuum only possible if molten powder is sprayed.	IAAC	-	-	IAAC 2015
	Additive welding	Metal	-	-	OK	7L, 7A, 7M	Requires pre-processed metal, time consuming.	Cranfield	-	-	Kazanas et al, 2012
Layered in-situ	Chemical	Regolith / Sand	MgCl2	YES	Partial	8L, 8M	Time consuming, energy intensive.	D-shape	-	-	Cesaretti et al, 2014
								Voxeljet	-	4.28	Voxeljet 2015
	Laser sintering	Regolith	-	YES	Partial	1L, 1M		Loughborough University	-	-	Goulas & Friel 2015
		Basalt	-	-	Partial	1L, 1M	Advantageous in vacuum.	KSC	-	-	Muelle et al, 2014
								PISCES	0.0167	0.02	-
		Regolith / Sand	-	-	Partial	1L, 1M		Aachen Uni	-	0.01	Fateri & Khosravi 2012
			-	-	Partial	1L, 1M		NUS	-	-	Tang et al, 2003
			-	YES	Partial	1L, 1M		EOS	0.69	6	EOS 2015
	Solar sintering	Regolith / Sand	-	YES	Partial	1L, 1M		Kayser, M. (MIT)	-	-	Kayser 2011
		Regolith	-	-	Partial	1L, 1M	10kW concentrator at 1700K	PSI	3.66	0	Nakamura & Senior 2008
	Microwave sintering	Regolith	-	-	Partial	1L, 1M	Melted in-situ. Good penetration properties. Assisted by inf heating. Difficult to shape.	JPL, PISCES	0.2	1	PISCES 2015
								University of Knoxville, USC	150	20	Taylor & Meek 2005
	Selective inhibition sintering	Regolith	With or Without (MgO, Portland / Water)	YES	Partial	1L, 1M	Requires pressure. Good for additive assembly e.g. tiles.	USC	3000	5	Khoshnevis et al, 2003

Recently there have been other implementations of concrete extrusion systems for construction around the world, such as Radiolaria by Enrico Dini (D-Shape 2015). Work by Cesaretti et al (2014) demonstrated an application of the D-Shape 3D printing technology to large-scale building components using a lunar regolith simulant and liquid binder. In addition, tests were conducted in air and in vacuum to show that evaporation or freezing of the binding liquid can be prevented through a proper injection method. Other examples include construction of semi-complete buildings by WinSun Co of Shanghai (WinSun 2015), castle construction by American architect Andrey Rudenko (Krassenstein 2014), and clay hut builder WASP (WASP 2015). These efforts follow the Contour Crafting precedent and serve to further prove the feasibility of AAC.

2. Fused-Deposition Method (FDM) Examples

Early developments in extrusion-based 3D printing started with extrusion of thermoplastic materials through a heated nozzle with fine orifice. The process, called Fused Deposition Modeling (FDM), is now adopted by numerous small companies that offer FDM machines. Attempts have been made by various research groups to process non-polymeric materials such as ceramics, as in Sandia Research Lab's Robocasting method (Cesarano 1998), and the recent glass printing process by MIT Mediated Matter (Klein et al, 2015).

Adherent Technologies proposes to use a urethane binder mixed with native materials to stabilize planetary surfaces and produce building components. Using a 20:1 regolith to binder ratio, prefabricated blocks were manufactured out of JSC-1A regolith simulant that resulted in a compressive strength of over 1000psi (Gosau 2012). The demonstration utilized two part low-outgassing polyurethane resins. One part polyol was blended with the regolith in advance, followed by the mixing of liquid isocyanate in a vacuum environmentAdherent Technologies also produced a spray system that could apply the polysol and isocyanate parts in a controlled manner in a vacuum for possible paving and soil stabilization.

3. Microwave Melting / Sintering Examples

The microwave JPL "sinterator" approach uses focused microwaves to melt or sinter native regolith in a controlled manner. Research has shown that lunar regolith samples can be sintered and melted using microwaves (Barmatz, et al 2013). It was shown that the unique volumetric heating associated with microwaves leads to a temperature gradient within the heated sample. The interior of the sample can be significantly hotter than the surface leading to sintering and then melting initially occurring within the sample, rather than at the surface. One option for using microwaves to process lunar soil is heating the surface (Figure 2, left), or heating in a tube (Figure 2, right). A magnetron power source is used to excite a single mode resonance in a rectangular waveguide chamber.

A high temperature resistant tube runs vertically through the chamber along a path of maximum electric field strength. Lunar regolith is pressed into the tube from above using an auger and is slowly pushed through the tube as it is heated, sintered, and then melted. The molten sample falls out of the bottom of the chamber where it can be delivered to any desired location. A roller on the leading end sets the height of the layer, and a spring-loaded roller on the trailing end presses the hot mixture into a smooth layer between sliding forms where it is left to cool. Microwave sintering can require very high levels of power, even with a tuned microwave chamber. However, the resonant frequency and impedance coupling (through an iris hole) to this microwave chamber can be automatically tuned in real time for maximal efficiency for a given material during heating to significantly reduce the power and heating time required (Barmatz, Iny, Yiin, Kahn 1995).

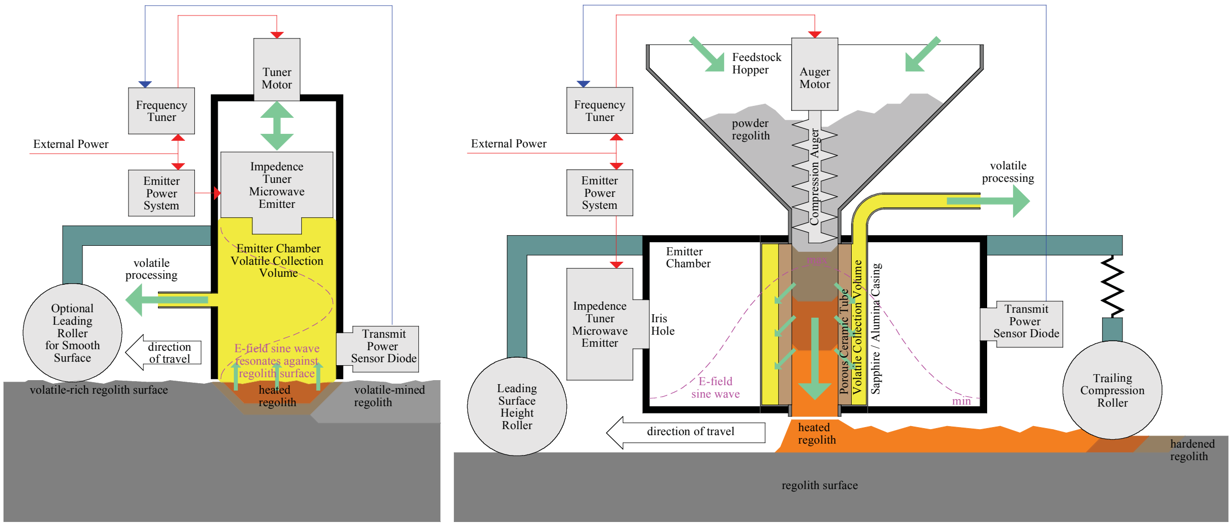

Figure 2. Microwave heating of the surface (left), or regolith in a tube (right)

4.   Solar / Laser Sintering / Melting / Melt Pool Examples

A strong candidate for melt pool processes would include solar concentrator technologies. For space-based in situ resource utilization (ISRU), solar power is a readily available heat source. For energy intensive materials processing such as melting and sintering of regolith or rock, direct use of solar power would be an efficient option. However, solar power available from conventional solar concentrator systems is not always an ideal heat source for materials For example, materials to be processed must be brought to the location where concentrated solar power is available, while electric power can be brought to the location where it is needed. For this reason, electric power, in spite of low overall system efficiency, has been considered as the heat source for most materials processing.

Figure 3. Melting of Tephra at 1800°C (left), and surface sintering at 1100°C (right) demonstrated through solar concentrator (Nakamura & Smith 2011)

Physical Sciences Inc (PSI) developed the Optical Waveguide (OW) Solar Power System for materials processing with NASA funding support (Nakamura & Senior 2008; Nakamura & Smith 2009). An OW solar power system which was recently developed for high temperature lunar materials processing is shown in Figure 3. The system consists of the concentrator array with seven 27in parabolic concentrators. At the focal point of each concentrator is an optical fiber cable made of 55 optical fibers (1.2mm dia.) which transmits the concentrated solar radiation to the interface optics for heating of the materials. This system was developed as the heat source for the carbothermal oxygen production process in which lunar regolith must be heated to 1800°C (Gustafson et al, 2009). The interface optics (quartz rod) inject high intensity solar radiation into the carbothermal reactor (Gustafson et al, 2010). This system was successfully deployed in the NASA ISRU Analog Test at Mauna Kea, Hawaii (Nakamura & Smith 2011), where melting (6, left) and surface sintering (6, right) were demonstrated.

B. State-of-the-art: Materials

Six materials have been identified as the main deposition media of an Automated Additive Construction system. These are sulfur concrete, Portland cement concrete, sorel cement concrete, plastics, basalt, and metals.

1. Sulfur Concrete

Terrestrially, sulfur has been considered as an alternative binder to Portland cement since the 1970s due to a growing surplus of sulfur (Walker 1982; Loov et al, 1974). Sulfur concrete is of particular interest as it provides a practical use for sulfur by-products of the mining and natural gas industry.

Analyses of Apollo return samples have verified the presence of lunar sulfur, with particularly higher concentrations in the high-Titanium mare basalt (Gibson et al, 1975; Gibson et al, 1977; Vaniman et al, 1988). Observations of the LCROSS ejecta plume show relatively high concentrations of the sulfur compounds H_2S and SO_2 (Colaprete et al, 2010).

Utilizing analyses of meteorites to infer asteroid composition, we can assume some availability of sulfur. Both chondritic and achondritic meteorites have shown the presence of sulfur, predominantly in the form of troilite (FeS). Gibson et al (1985) reports a range in median sulfur concentrations between 0.12% and 0.60% for achondritic meteorites, with enstatite achondrites representing the highest abundances. Dreibus et al (1995) report abundances of sulfur in both carbonaceous chondrites and ordinary chondrites ranging from 0.45% to 5.41% by weight, with CI carbonaceous chondrites yielding the highest concentrations.

The resource potential, and presence, of sulfur on the moon and asteroids makes it an appealing candidate binder to investigate for in situ additive construction.

2. Portland Cement Concrete

Portland cement is a long-established and highly successful binding agent for terrestrial construction applications. Because Portland cement concretes need between 10-20% water by weight, their uses on planetary and asteroidal bodies would be problematic at best. Vacuum conditions, temperature variations, in-situ manufacturing of Portland cement and life support/fuel needs of water all conspire to exclude traditional wet mix concretes on extraterrestrial bodies. Work has been done to mitigate these problems through a Dry Mix / Steam-Injection (DMSI) method (Lin et al, 1987). The weight percentage of water in a DMSI concrete is about 5% (much less than 50% for a conventional wet-mix concrete), however it requires a pressurized vessel and a source of steam (Lin et al, 1998).

3. Sorel Cement Concrete

Sorel cements are a mixture of solid MgO and $MgCl_2$ brine. The traditional terrestrial applications are for concrete repairs that need a quick-set. Presently the USACE and NASA Marshall Space Flight Center are investigating the use of Sorel concretes for additive construction. The hurdles to using Sorel cements on extraterrestrial bodies are the same as those for Portland cement ($MgCl_2$ brine is approximately 65-70% water by weight). Additionally, there are some indications that exposure to x-rays can significantly alter the material properties of the product (Ring & Ping 2007).

4. Plastics

Plastics have been used on a limited scale for terrestrial construction applications for concrete forms and primarily as a waste-plastic solution (Verma 2008). On extraterrestrial bodies, recycling of plastics for binding material may offer a short-term solution as an aggregate binder.

5. Basalt

Basalt has historically been used as a building material in regions where it is present (e.g. the Roman Empire), as an aggregate for concretes, basalt fiber rebar, cast elements, and for masonry. There has been much work in recent years on basalt sintering and basalt melting for additive construction uses. Cast basalt has been reported with compressive strengths ranging upwards from 300MPa and hardness between 8 and 9 mohs (Jakes 1998; CBP Engineering Group 2013).

6. Metals

Terrestrial additive manufacturing with metals has been well-established with processes such as laser deposition (LD), laser engineered net shaping (LENS), direct metal laser sintering (DMLS), ultrasonic additive manufacturing (UAM), selective laser sintering (SLS), selective laser melting (SLM), electron beam freeform (EBF), and high velocity oxy-fuel spraying (HVOF). In all of these techniques, special care is taken to produce the metal feedstock precursor for the manufacturing. This material, which takes the form of uniform powder, wire and metal tape, is produced with utmost quality control to assure predictable and repeatable components. Some mixing of metals during printing has also been performed to create functionally graded alloy, demonstrating that the process can be used for multiple materials (Hofmann et al, 2014a: Hofmann et al, 2014b). When trying to print with metal that has been mined, extracted and refined from regolith, the infrastructure required must be considered. Even in the lowest technology applications, metal would still have to be mined and extracted from in-situ regolith and would likely not have uniform size or composition. A consolidation process for printing with such metal would need to accommodate large variations in feedstock size and composition, which complicates delivery systems and melting parameters. Laser sintering is likely the first way to achieve any additive manufacturing derived hardware from in-situ metals recovered from regolith, followed by full melting in a crucible and then molten metal extrusion. More advanced processes require significant developed of mobile mining and extraction technologies needed to make uniform powder or wire.

C. State-of-the-art: Material Extraction

The levels of material processing are summarized in tables for the Moon (Table 3), asteroids (Table 4), and Mars (Table 5).

Table 3: Materials Processing with Lunar Resources

Label	Builds Upon	Additional Processes (cumulative with "builds upon")	Additional Materials Produced (cumulative with "builds upon")
1L	N/A	Sieve and/or grind regolith	Regolith
2L	1L	Molten Regolith Electrolysis	"Mongrel Alloy", Ceramic, Oxygen
3L	1L, 2L	Vacuum Distillation or equivalent	Elemental Aluminum, Iron, Magnesium, Calcium, Silicon, Titanium. (Also, if regolith obtained from KREEP terrane, then Potassium, Rare Earth Elements, and Phosphorus)
4L	1L-3L	Metals Refinery	Various alloys
5L	N/A	Ice Mining & Distillation	H_2O, CO, CO_2, NH_3, many compounds and trace metals
6L	5L	Fischer Tropsch process	CH_4, plastics, rubbers
7L	1L-6L	Metals Refinery including carbon from 5 & 6	Steel
8L	1L-3L	Slaking and cement production	Lime and cement
9L	1L-8L	Advanced processes	Most other materials

Table 4: Materials Processing with Asteroid Resources

Label	Builds Upon	Additional Processes (cumulative with "builds upon")	Additional Materials Produced (cumulative with "builds upon")
1A	N/A	Crush and sieve	Regolith
2A	1A	Magnetic beneficiation	Fe-Ni alloy (some asteroids)
3A	1A, 2A	Mineral beneficiation (electrostatic? Density separation?)	Clay (carbonaceous asteroids)
4A	N/A or 1A	Heating and volatile capture with distillation	H_2O, complex organics
5A	1A	Molten Regolith Electrolysis	Mongrel alloy (all asteroids), Ceramic, Oxygen
6A	1A, 5A	Vacuum Distillation or equivalent	Elemental Aluminum, Iron, Magnesium, Calcium, Silicon, Titanium (depending on minerals in the asteroid)
7A	1A, 5A, 6A	Metals Refinery	Various alloys
8A	4A	Fischer Tropsch process	CH_4, plastics, rubbers
9A	1A, 5A, 6A	Slaking and cement production	Lime and cement
10A	1A-9A	Advanced processes	Most other materials

Table 5: Materials Processing with Mars Resources

Label	Builds Upon	Additional Processes (cumulative with "builds upon")	Additional Materials Produced (cumulative with "builds upon")
1M	N/A	Sieve and/or grind regolith	Regolith, Clay if you drive to a deposit of it
2M	N/A	Ice mining & distillation	Water, unknown chemicals
3M	N/A	Atmospheric Capture	CO_2, N_2
4M	1M-3M	Fischer Tropsch	CH_4, Plastics, Rubbers
5M	1M	Molten Regolith Electrolysis	"Mongrel Alloy", Ceramic, Oxygen
6M	1M, 5M	Vacuum Distillation or equivalent	Elemental Silicon, Iron, Aluminum, Magnesium, Calcium, Sulfur, Sodium, Phosphorus, Titanium, Chlorine, Potassium, Chromium, Manganese, trace elements (depends on the local soil mineralogy)
7M	1M, 5M, 6M	Metals Refinery	Various alloys
8M	1M, 2M, 5M, 6M	Slaking and cement production	Lime and cement
9M	1M, 2M	Frasch Process	Sulfur
10M	1M-9M	Advanced processes	Most other materials

The simplest material for additive construction in space is unprocessed regolith. A next simplest step to improve the flow properties of the regolith is to sieve and crush it, controlling the particle size distribution. Another simple step is to grind, melt and re-use materials from the spent spacecraft. Spacecraft can be designed with recycling in mind to improve the economics of settling space. Beyond these simple steps, many processes may be developed to create increasingly refined materials with desirable engineering properties.

Regolith may be melted and electrolyzed in a process known as Molten Regolith Electrolysis (MRE), alternatively called Molten Oxide Electrolysis (Curreri et al, 2006; Sacksteder & Sanders 2007; Dominguez et al, 2009; Sibille et al, 2009; Sibille et al, 2010; Sirk et al, 2010; Standish 2010; Vai et al, 2010; Schwandt et al, 2012; Sibille & Dominguez 2012). This chemically reduces the minerals, which are oxides, to liberate the oxygen and create two molten material streams: a "mongrel alloy" of iron, aluminum, titanium, silicon and trace metals; and a slag of unreduced oxides. The properties of the mongrel alloy have not been measured but it is expected to demonstrate some ductility and improved tensile strength compared to just melted or sintered regolith. The ceramic slag from MRE may thus be printed with reinforcement bars of this alloy automatically embedded using a two-material printer head. Although the alloy is expected to have poor properties compared to well-designed metal alloys, in low lunar gravity or in zero gravity it may be adequate for many structures including solar array supports or habitat trusses. Recent progress in developing MRE has included multi-physics simulations of specific reactor designs (Schreiner et al, 2015a; Schreiner et al, 2015b; Schreiner 2015), which quantified the material throughput rates and energy requirements, demonstrating that MRE scales appropriately for space construction projects. MRE is presently at Technology Readiness Level 3 (TRL-3). An alternative that exists in the concept stage (TRL-2) is fluorine processing (Burt 1992; Sebolt et al, 1993; Landis 2007). In either case, a subsequent stage such as vacuum distillation will be needed to produce higher quality metals and silicon (Jarrett et al, 1980; Pettit 1985).

For a simple reinforcement material, an alternative to making a crude metal is to create basalt fibers by melting basalt and pulling small ceramic rods out of the melt as it cools (Tucker & Etheridge 1998; Tucker et al, 2006; Meyers & Toutanji 2007).

Another way to extract metals from regolith is the use of ionic liquids (Marone et al, 2009; Paley et al, 2009; Poulimenou et al, 2014), which provide low temperature dissolution of oxides such as those found in lunar, asteroid or Martian regoliths. Silicon dioxide does not effectively dissolve in ionic liquids, so the reduction of the regolith may be enhanced by addition of a silica-dissolving acid like phosphoric acid. Experiments have dissolved up to 72% of simulated lunar regolith at just 120°C in four days, with silica being the underrepresented element in the ionic liquid (IL) solution (Paley et al, 2009). The failure to reduce all the silica does not present a problem since unreduced silica will be needed at space outposts for manufacturing glass (or fused quartz) and photovoltaic cells. The metals are dissolved as cations in the IL while producing water that may be electrolyzed to regenerate the ionic liquid, returning hydrogen cations into solution as free metals precipitate out. Multiple processing stages may be designed to precipitate the metals separately through the addition of various salts, each of which may be regenerated in turn. The reduction of regolith via IL producing mixed metals has been demonstrated to TRL-3, while the separation of all the metals is still conceptual (but based on firm theory and supporting experiments) so it is TRL-2. Once metals have been separated, a foundry may remix them in desired ratios to create desirable alloys of iron, aluminum, and magnesium. Carbon obtained from other resources may be added to iron to create steel. Carbon is significantly present in lunar ice (Colaprete et al, 2010; Gladstone et al, 2010), in the Martian atmosphere, and in the organic content of carbonaceous chondrite asteroids.

Calcium extracted by any of the above processes may be kept in the oxidized state as CaO (quicklime). This is the binder that was used historically in Roman Concrete, so it may be mixed with raw basalt regolith as the aggregate for additive construction. Alternatively, slaked lime may be formed by hydrating quicklime, which may be further processed with silica, metal oxides, and sulfates (if available) to form a variety of cements.

The water for making and using cement may be obtained by excavating and distilling lunar or Martian ice or by thermal extraction from the clay in carbonaceous asteroids. Carbon can also be obtained from all three locations. Lunar ice contains a large fraction of carbon monoxide and carbon dioxide. Carbon dioxide may be captured by liquefaction from the Martian atmosphere. Carbon compounds may be extracted from carbonaceous asteroids by simple heating or pyrolysis. Carbon may be combined with the hydrogen electrolyzed from water to form methane by flowing through a catalyst (Randall & Gerard 1928). Methane may then be polymerized to form complex hydrocarbons via the Fischer Tropsch process, including plastics, rubbers or other compounds that can serve as binders for printing regolith. Alternatively, large-scale plastic elements may be printed without regolith as structural members in low gravity.

Sulfur is not abundant on the Moon but may be obtained by heating large volumes of regolith. It may be obtained from high concentration deposits of sulfates on Mars or from the sulfates in carbonaceous asteroids. The Frasch process (Lebowitz 1931) is the dissolution of sulfates in superheated water to obtain elemental sulfur, which may be melted for use as a binder in regolith.

With the resources available in space, essentially any construction material used on Earth may be manufactured for use in space. The trade-off is that better building materials generally require more complex processing with a higher mass of infrastructure including power generation, mining and processing assets. A good strategy may be to start with the simplest construction materials in early phases of space settlement, advancing to more complex materials and processes as space industry grows.

VISION FOR AUTONOMOUS ADDITIVE CONSTRUCTION USING IN-SITU RESOURCES

The vision matrix (Table 6), shows a plan for the development of additive construction using in-situ resources and the auxiliary technologies that must evolve contemporaneously.

In ten years, it is envisioned that additive construction techniques and in-situ materials processing will mature on-Earth, along with space manufacturing technologies (Johnston et al, 2014; National Research Council 2014) These capabilities ought to be demonstrated in extreme environments that mirror, however imperfectly, the conditions expected on the Moon or Mars. Regolith will be processed and separated on site. Sintering and melting techniques will be used to construct low-precision structures such as landing pads, blast walls, and shelters. Manufacturing techniques will include entire robots, including actuators, sensors, controllers, and mechanisms (Malone & Lipson 2004). During this period, robotic missions should extend the knowledge of resource sites through prospecting and characterization. Human missions could return to cis-lunar space, to visit the Moon and a captured asteroid (Wilcox et al, 2015). At that point spacecraft will likely remain bound by terrestrially manufactured energy sources, but volatile collection should be demonstrated.

In twenty-five years, bulk regolith construction should be harnessed to support human outposts on the moon and Mars. The techniques developed on Earth should allow autonomous construction of landing pads, berms, and radiation shielding around habitats. Regolith separation techniques should be tested in space by that time, paving the way for more advanced structures. Volatiles could be collected in-situ from planetary surfaces and asteroids (Lewis 1996), and separated into their constituent gasses. Asteroids, nudged into a Mars cycler orbit, could be hollowed and treated to serve as protective vessels for human-crewed trips. The supporting structure for solar concentrators may be constructed on site, but more complex parts for energy sources would still be fabricated on Earth.

At the fifty year mark, resource utilization should be at the point where autonomously processed regolith can be separated into the compounds or alloys needed for construction. This leap could be realized through sustained process development and projected increases in computing capability. Material processing would support factories that should be capable of partial self-replication (Freitas & Gilbreath 1980), producing not only habitats and more refined structures, but also many of the parts necessary for their own construction and self-assembly (Howe 2007). This would enable long-term colonization on both the Moon and Mars, in what will need to be a financially self-sustaining industry off-planet. Financial independence may occur through energy production; solar concentrators and photovoltaics would need to be manufactured in-situ, and at least limited fuel production should be implemented by that time.

One hundred years into the future, additive construction is envisioned to become a developed, sustainable industry. Self-replicating, fully autonomous factories (Freitas & Merkle 2004) construct and maintain human communities that are independent of Earth resources. Asteroids could be colonized (Joyce et al, 2013; Joyce & Snyder 2014), while lunar and Martian cities are likely to be enclosed with large-scale life support systems. Off-Earth resources should be used to create energy sources and storage, and resource processing enables sustainable, independent fuel production.

Table 6: Vision matrix for the future of Automated Additive Construction

Time Frame (years)	Resource Utilization	Humans Off-planet	Automated Additive Construction Technology	Energy	Byproducts
10	Terrestrial demonstration of regolith processing / separation; Extraterrestrial prospecting	Trips to Moon / Mars / asteroids	Demonstrate terrestrial 3D printing with sintering / melting, print landing pads / shelters	All systems Earth manufactured	Volatile collection demonstration
25	Harness bulk regolith; Test regolith separation in space; Mars cyclers for radiation shielding	Habitation / outposts on Moon/Mars	Autonomous construction with bulk in-situ resources; 3D construction of landing pads, shelters in space	Exporting solar cells from Earth; manufacture concentrators in-situ	In-space collection of water separation into constituent gasses
50	Autonomous materials processing into desired elements / compounds; Cu/Fe extraction	Colonies; financially self-sustaining industries off-planet	Partial self-replicating factories; habitats/structures made in-situ	Sustainable off-world energy sources: solar concentrators, photovoltaics manufactured in-situ	Limited off-Earth fuel production: hydrocarbon, oxygen
100	Resource independence; terraforming asteroids; enclosed lunar / Martian cities	Communities on Mars / Moon / asteroids	3D additive industry; silicon / biologically based self-replicating factories	Communities independent of Earth resources; harness off-planet resources to create energy sources and storage	Sustainable off-Earth fuel production

IV. Conclusion

A workshop was conducted in August, 2015 at the W.M. Keck Institute for Space Studies in Pasadena, California, where many of the leading practioners discussed, strategized and defined a new field of technology: *Three Dimensional (3D) Additive Construction For Space Using In-situ Resources*. Future workshops and events are also envisioned as the field develops and matures.

Automated Additive Construction using in-situ resources is defined in this paper by many of the current experts active in the field, including state-of-the-art for processes, materials, and material extraction. Future vision, knowledge gaps, and possibilities for future investment are also described. For purposes of mission concept design and timelines, performance parameters for a variety of methods are outlined in Table 2. Suggested technology demonstrations include terrestrial activities, ISS demonstrations, and proposed applications for zero-G and partial-G environments.

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