Faxing Structures to the Moon: Freeform Additive Construction System (FACS)

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Using the highly articulated All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robotic mobility system as a precision positioning tool, a variety of print head technologies can be used to 3D print large-scale in-situ structures on planetary surfaces such as the moon or Mars. In effect, in the same way CAD models can be printed in a 3D printer, large-scale structures such as walls, vaults, domes, berms, paving, trench walls, and other in-situ derived elements can be FAXed to the planetary surface and built in advance of the arrival of crews, supplementing equipment and materials brought from earth. This paper discusses the ATHLETE system as a mobility / positioning platform, and presents several options for large-scale additive print head technologies, including tunable microwave "sinterator" approaches and in-situ concrete deposition. The paper also discusses potential applications, such as sintered-in-place habitat shells, radiation shielding, road paving, modular bricks, and prefabricated construction components.

Nomenclature

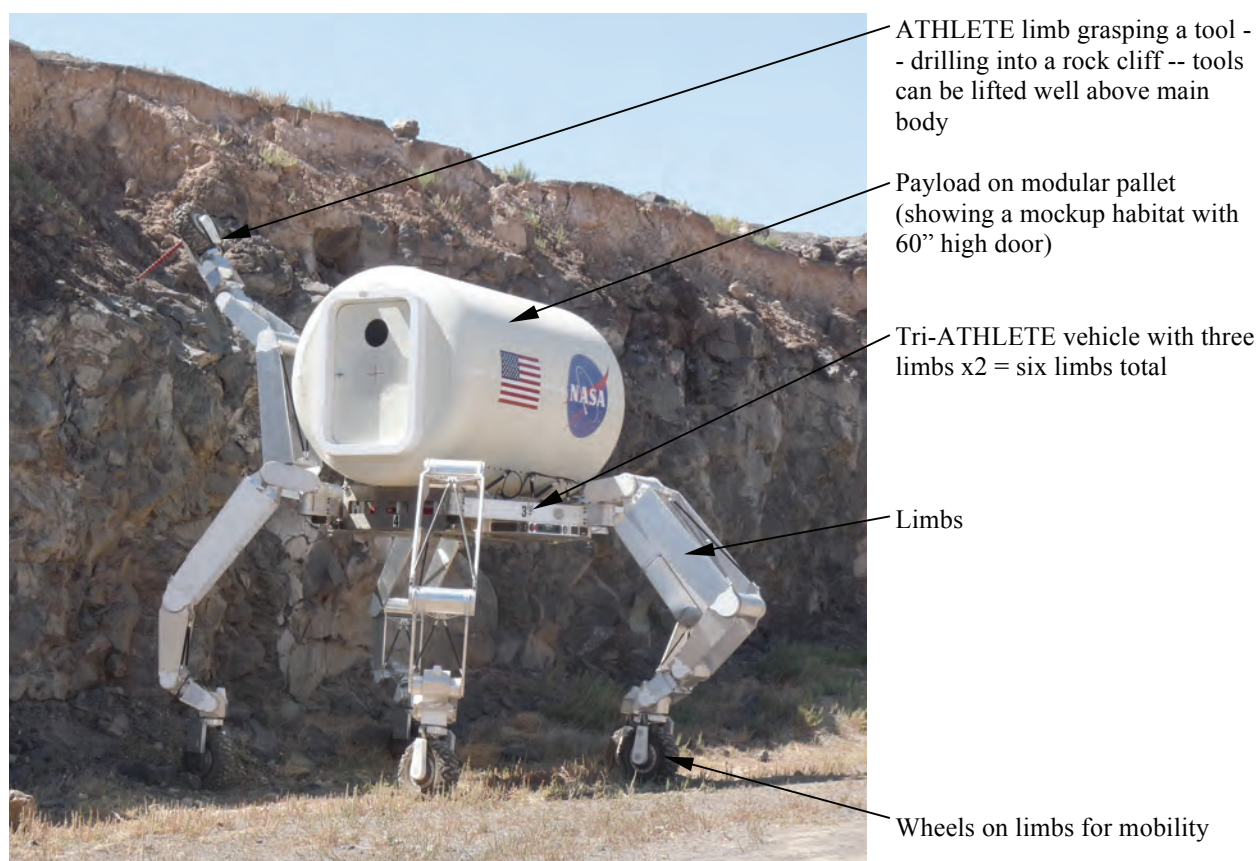|		
ATHLETE	=	All-Terrain Hex-Limbed Extra-Terrestrial Explorer robotic mobility system
CAD	=	Computer Aided Design
DOF	=	Degree Of Freedom
FACS	=	Freeform Additive Construction System
GPS	=	Global Positioning System
IMU	=	Inertial Measurement Unit
ISRU	=	In-situ Resource Utilization
OW	=	Optical Waveguide
RASSOR	=	Regolith Advanced Surface Systems Operations Robot

I. Introduction

SPACE architects have identified three classes of construction for planetary surface habitats and structures (Smith 1993; Cohen, Kennedy 1997; Kennedy 2009). Class I construction is pre-integrated modules with single pressurized volumes ready for occupancy, such as the Apollo Lunar Module. Class II construction puts together multiple modules or inflatables assembled in place in larger groupings, where connection and construction must occur before occupancy can begin. This paper falls under the third type of construction, Class III, that uses in-situ derived materials to construct various structures in place. Class III structures may require infrastructures and equipment imported from earth, but allow for unlimited structures built from local materials. The Freeform Additive Construction System (FACS) is proposed to produce Class III structures from local materials.

Traditionally we have understood a construction project to consist of a site or locality where human laborers assemble raw materials into target structures using a variety of tools. However there are two major difficulties with

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applying the traditional construction method to space structures. First, the high cost of human presence in space comes directly from the mass of equipment required to lift out of Earth's gravity well and maintain a pressurized environment for the crew's safety and well-being. When the cost of launching and maintaining a pressurized environment for human crews is taken into account, an hourly rate for space construction workers poses a significant financial burden. Second, having a human crew available onsite for the construction project already requires a substantial outpost or pressurized facility just for the workers, which may or may not outshadow the scale of the proposed construction project. Instead of the traditional method, it may be significantly cheaper to perform the construction using robotic constructors that do not need a pressurized environment, and launch the crew once the outpost has been checked out and is running properly. Then rather than extremely high-cost construction workers, the human crews can be used for the value that they provide over robotic infrastructures.

The challenge of constructing orbital, deep space, and planetary surface space infrastructure has been discussed from a human habitation and space architecture perspective (Howe, Sherwood 2009), and from the perspective of robotic infrastructures (Howe, Colombano 2010). In particular, Howe and Colombano (2010) point out a difference in space manufacturing that may require high precision, and the construction of in-situ structures which may be of a lower resolution. Space manufacturing is more attentive to the properties of specific materials, and may require extraction of more pure elements and powders. Some forms of construction may also require precision tolerance and specific material properties, especially for optimized tensile structures such as pressure vessels, trusses, etc. However, there are certain structures that are mainly compressive in nature that are useful for their bulk and mass, that do not need such precision and may be constructed out of any found material in the environment and still allow for rough surfaces and edges. These compressive in-situ structures can include simple excavations and berming, or a cruder form of melting and bonding of found materials regardless of what material properties that may be present. The technology required for various melting and bonding may require the production of high temperatures and the extraction of local material would need support excavators and material handling only briefly touched upon in this paper.

ATHLETE limb grasping a tool -- drilling into a rock cliff -- tools can be lifted well above main body

Payload on modular pallet (showing a mockup habitat with 60" high door)

Tri-ATHLETE vehicle with three limbs x2 = six limbs total

Limbs
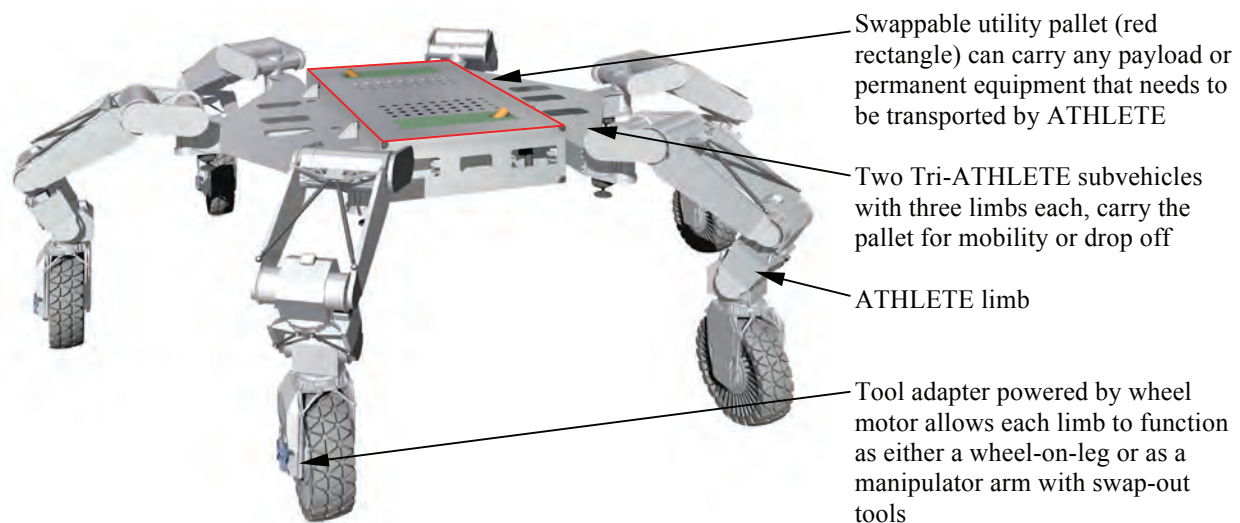
Wheels on limbs for mobility

Figure 1: ATHLETE mobility system carrying a payload and using a modular tool

However, depending on the availability of materials in the target environment, simple excavation and fairly low temperatures may be sufficient, such as in the case of 3D printing of compressive ice structures in a location where ice is abundant. This paper will only discuss such environments in very general terms and does not go into specifics of any particular environment.

Using the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE), we propose a large-scale additive manufacturing system that is capable of producing walls, hard paving, vaults, domes, and a variety of pre-fabricated bricks and other components, using materials extracted from the local environment. This paper discusses the ATHLETE as a construction and mobility platform assuming that native regolith has already been gathered and processed into construction materials, but does not discuss how the gathering and processing would be accomplished.

II.   ATHLETE System

The ATHLETE is a six-limbed wheel-on-limb robotic mobility platform that is capable of transporting large cargo efficiently on both rolling and rough terrain (Wilcox, et al 2007). The fundamental premise of the ATHLETE system is that for sufficiently large systems, by designing the wheels and wheel actuators for relatively benign terrain, the system saves enough mass to offset the mass of the robotic limbs. A key feature of this design, exploited by FACS, is that these limbs can serve as general-purpose robotic manipulators.

Swappable utility pallet (red rectangle) can carry any payload or permanent equipment that needs to be transported by ATHLETE

Two Tri-ATHLETE subvehicles with three limbs each, carry the pallet for mobility or drop off

ATHLETE limb

Tool adapter powered by wheel motor allows each limb to function as either a wheel-on-leg or as a manipulator arm with swap-out tools

Figure 2: ATHLETE parts and functions

ATHLETE is able to mitigate the risk of embedding a wheel by simply locking the affected wheels and walking out of the troubling terrain or stepping over the obstacle. At gravities less than 1-g, especially the 1/6-g of the moon or 3/8-g of Mars the system makes sense at surprisingly small scales. The system is designed with 6 identical fully articulated robotic limbs that are usually used in 4 or more different modes: 1) Locked out as passive independent suspension arms; 2) Actively controlled suspension arms; 3) Actively controlled legs used in walking or sliding gaits; 4) Actively controlled manipulator arms (Figure 1). In this way the multipurpose robotic limbs are not only part of the mobility system, but are able to be used as capable manipulator arms as well. The addition of a tool adapter with an interface to a power takeoff shaft eliminates the need for individually powered end effectors.

The ATHLETE concept is adaptable for a wide variety of applications. The cargo deck and manipulators are highly scalable and can stow compactly for delivery. The ATHLETE concept for the lunar Constellation program called for a vehicle with limbs over 6m long and a cargo deck 8m across. ATHLETE has also been envisioned at small scales as a deployable science rover for rough-terrain exploration (Wilcox 2009). Recently, the ATHLETE concept has been demonstrated as a viable concept for grappling and anchoring to asteroids in a microgravity environment (Wilcox 2012).

The current ATHLETE prototype divides into two identical three-limbed robots, called Tri-ATHLETEs, which can traverse independently or dock together to carry a cargo pallet as a unified six-limbed system. The Tri-ATHLETE configuration of ATHLETE consists of two three-legged subvehicles (Tri-ATHLETEs) and a single swappable utility pallet that can pick up, carry, and drop off large cargo or equipment. The 1/2 scale Tri-ATHLETE

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prototypes were designed to demonstrate that it was possible to unload multiple cargo pallets from the proposed 6.4m tall Altair Lander. The concept splits the more traditional monolithic ATHLETE vehicle into three parts (Figure 2). Two Tri-ATHLETEs with independent computer, power, and communications gear are both able to operate easily and independently as tripods on benign terrain. This feature makes ATHLETE highly reconfigurable even after deployment on a remote planetary surface. The Tri-ATHLETEs are able to dock either with each other or with the third component of the system, a central cargo or utility pallet, to form a more robust hexapod. Any payload designed to comply with ATHLETE's cargo pallet interface can be carried between the two Tri-ATHLETEs, and payloads can be interchanged during the course of the planetary mission. This pallet is generally thought to have its own power system, as well as serve as the base for any number of types of cargoes ranging from human habitats, telescopes, power plants, scientific instrumentation packages, or to be more task specific such as logistics modules or large scale manufacturing modules. Control signals can be integrated into the cargo pallet interface to enable cargo pallet payloads to interface directly with the ATHLETE robotic system, although wireless communications were assumed in the Constellation program. In this way the problem of loading and unloading cargo, material movement, and otherwise maximizing the utility of the mobility system is solved. The same pair of Tri-ATHLETEs can act as forklift, backhoe, drilling rig, cement truck, mobile habitat or manufactory.

A. Mechanical System Design

At the heart of the ATHLETE concept is the limb, which is repeated six times around the body of the robot. Each multi-link limb is a six or seven degree-of-freedom (DOF) robotic arm (depending on the number of modular links that have been attached to the chain), consisting of rotary actuators at each joint and lightweight aluminum links between the joints. Each joint consists of an electric motor mated to a high-reduction planetary gearbox and harmonic drive, which provides high torque capability and excellent precision. The torque on each joint is measured and together with the known stiffness of the limb can be used to approximate the true position of the end effector.

Each limb has a general-purpose tool adapter at its tip that allows robotic change-out of tools such as scoops, augers, grippers, or other hardware. Tools can be coupled to the limb's wheel motor, providing a high-power rotary mechanical input.
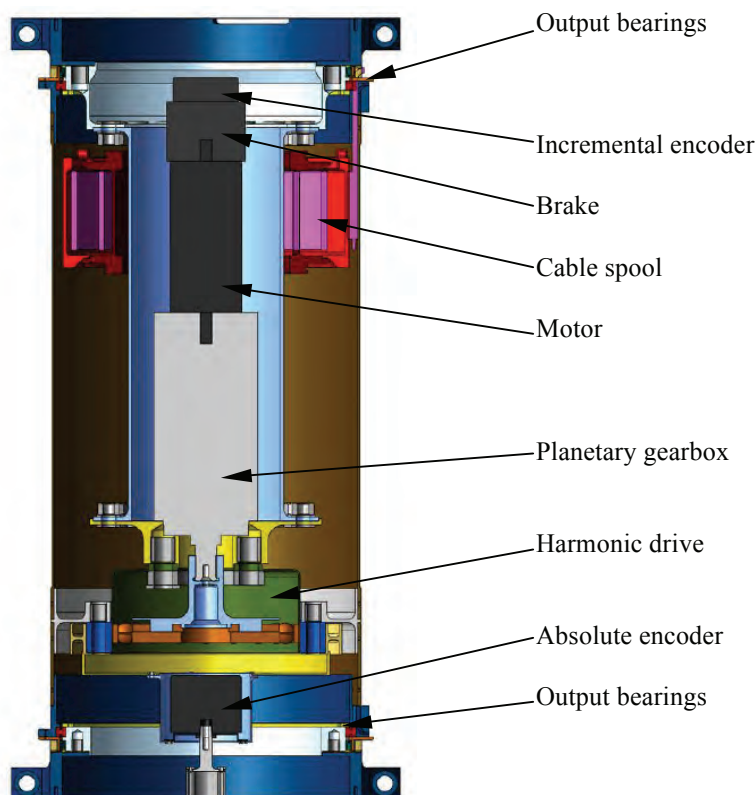

Figure 3: ATHLETE limb joint cross-section (Heverly, Matthews, Frost, McQuin 2010)

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The ATHLETE concept is easily scaled to suit mission needs. The earthbound Tri-ATHLETE prototypes developed in 2009-2010 each have a mass of ~750 kg and when docked together and can stand at a height of over 4m. The combined payload capacity of the system exceeds 500 kg. In lunar gravity it is expected that the mass fraction of the whole system dedicated to mobility would account for ~15% of the total vehicle weight (Heverly, Matthews, Frost, McQuin 2010). In more recent years the vehicles have been lightened by shortening the seven DOF limbs to be more manageable within the practical confines of the lab without sacrificing capabilities except for height. The current six DOF configuration of each limb is Yaw-Pitch-Pitch-Roll-Pitch-Roll although this configuration can be relatively easily changed. Each limb is an exact copy of each other, simplifying design and manufacturing of the system. Further simplifying the design is that the layout of each joint is very similar to the others, resulting in only two types of joints. The two types of joints are the roll joints, and the pitch/yaw joints.

The joint design is relatively simple. The pitch joints for example consist of a brushless DC motor with incremental encoder and power-off brake, intermediate planetary gear stage, and harmonic drive output gear stage attached to an absolute encoder. Each stage in the actuator is axially coupled with the next giving a fairly long stacked length. This length is taken advantage of with a pair of thin section output bearings separated by a thin wall tube concentric with the actuator (Figure 3). This results in a fairly lightweight design with a large moment carrying capability. The output of each joint is then configured as a dual pronged yoke and is connected to the next link in the kinematic chain. An additional benefit of this configuration is that each limb is able to nest inside itself for compact stowing for launch or during surface operations. Limb structural loads were defined as ratcheting torques of the output harmonic drives while the actuator generated loads were designed to be 66% of that number. Actuator speeds were defined by the requirement to servo the limbs while traveling over undulating terrain at 3 kph nominal driving speed.
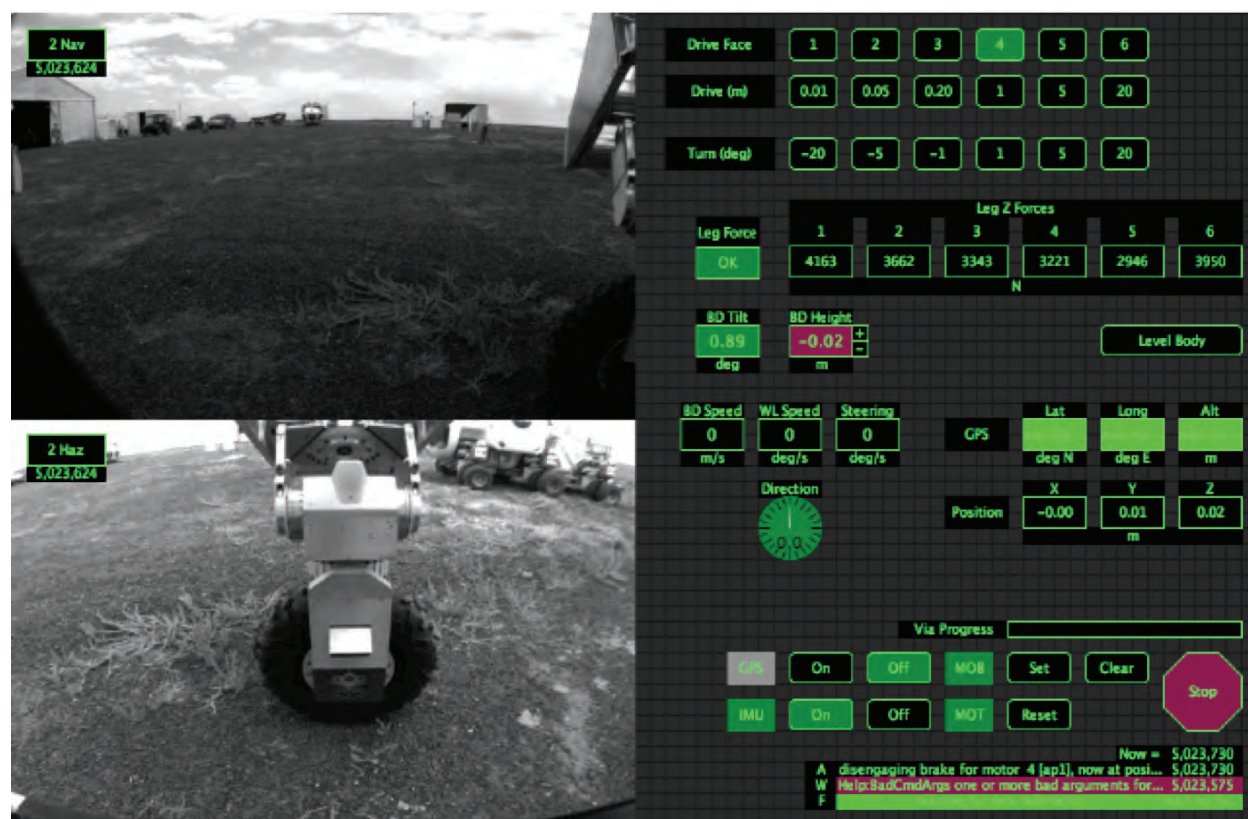
Figure 4: Onboard navcam (above left) and hazcam (below left) views -- tool adapter and toolcam are visible in the lower left

The construction of each link of the limbs consists of boxed aluminum extrusions with thin wall face sheets. Lateral loads are countered with tubular cross-members resulting in a lightweight and rigid link segment. The face sheets are bonded and riveted to the aluminum extrusions resulting in extremely easy to manufacture and inexpensive links. The cross-members consist of aluminum tubes with turnbuckle end fittings that are bonded and

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riveted in place and terminate in spherical bearing rod ends. The Tri-ATHLETE chassis is constructed as a bonded and riveted box structure that results in fairly large internal space for electronics packaging as well as a stiff and lightweight design.

B. Control

ATHLETE's onboard software provides coordinated joint motion, including cartesian positioning of limb end effectors and wheels. Waypoints are used to achieve straight-line paths between cartesian locations. Motions of multiple limbs are also coordinated to enable body positioning. Driving is executed through coordinated control of the wheels and steering actuators, using Ackermann steering solutions (explained in Wikipedia 2013) to achieve arcing motion. Drive segments are supported in any direction and with any arc, including zero-length arcs which are executed as turns in place. When two Tri-ATHLETEs are docked to a cargo pallet, they operate in a master-slave mode, in which motion of all six limbs is coordinated by the master platform.

Also implemented in ATHLETE's software is an autonomous algorithm for driving with active wheel compliance over sloped or undulating terrain. This algorithm makes use of sensor data, including wheel contact forces and inertial body orientation, to maintain an even loading distribution among the driving wheels and to keep the cargo deck level (Townsend, Biesiadecki, Collins 2009). The ATHLETE software infrastructure is based on software used on the Opportunity and Curiosity Mars Rovers and can support future implementation of all forms of navigation autonomy used on those vehicles.

An ATHLETE robot has over 48 independently controllable actuators, each with multiple sensors. A control system is implemented to allow the operator to specify high-level direct commands for both driving and manipulation. For example, an operator might issue a command to the robot to drive a specified distance in a specified direction, or to move a specific limb to a specific point and orientation in space. There are 24 pairs of stereo cameras on a Tri-ATHLETE system, providing full coverage of hazards for driving, as well as limb activity during manipulation. Cameras are provided on the top of the limb at the tool adapter, allowing close observation and fine manipulation of tool use (Figure 4).

C. Operation

The ATHLETE platform is designed to accommodate a variety of operating paradigms. For Lunar missions, ATHLETE would be controlled primarily via remote teleoperation from Earth. The ATHLETE robot is teleoperated via a workstation that has both a command uplink and video/telemetry downlink from the robot (Figure 5). A remote operator would maintain good situational awareness through the use of state displays and stereo imagery streamed from ATHLETE's onboard cameras, and would control ATHLETE using computer interfaces or handheld physical controllers tailored to the current task. This philosophy of remote teleoperation could also be implemented for use by an astronaut onboard an orbiting spacecraft or inside a lunar habitat. Astronauts deployed alongside the ATHLETE platform could operate the robot via local on-site control, making use of gesture recognition or handheld physical interfaces similar to those used by the teleoperators.

Multiple displays for streaming video, control windows, etc

ATHLETE remote driver in operations loop

Real-time operations, remote or otherwise, must be from nearby, such as using a local crew

Figure 5: ATHLETE telerobotics workstation

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Operators can select between camera feeds and easily drive the robot as well as manipulate limbs and tools (Figure 4). For tool use, special commands and command sequences are implemented to automate repetitive or sensitive behaviors, such as maintaining constant force on an auger while following a specified tool path.

Operations tools exist for operating in both real-time and time-delay scenarios. Driving and limb manipulation can be done with a joystick or similar input device, but also can be done in a very well-controlled and deliberate manner using a sequence of scripted commands. ATHLETE could also be operated using a similar philosophy as that used for existing mobile surface assets like the Opportunity and Curiosity rovers. These rovers are controlled using sets of pre-planned commands and autonomous behaviors that execute over a period of one or more days. While this operations method is less time-efficient than live teleoperation, it dramatically reduces the requirements for power, communications, and personnel resources, making it an attractive option for long-term activities.

The ATHLETE prototypes were designed with teleoperation in mind, and are outfitted with an extensive suite of sensors (Townsend, Mittman 2012). Stereo cameras provide views from each face of the cargo pallet, as well as underbelly views for assessment of wheel position and terrain contact. For precision teleoperation or autonomous positioning of manipulated tools, each limb carries a pair of cameras that can be positioned to view the contact point of any grasped tool and that stow into a dust-protective housing during traverse. The cargo deck is outfitted with an Inertial Measurement Unit (IMU) that enables autonomous leveling of the cargo deck in uneven terrain and a Global Positioning System (GPS) unit for absolute position tracking. Force feedback is available for each limb to enable autonomous load distribution across the six limbs, compliance to uneven terrain, and force-based control for manipulation tasks.

The ATHLETE system is designed for both strength and accurate limb positioning. The current prototype mobilizes a cargo load of up to 500 kg and can lift over 100 kg with a single limb. As a lunar cargo handler, ATHLETE was projected to manipulate and mobilize payloads of up to 20 metric tons in lunar gravity. Despite its size, weight, and long limbs, ATHLETE manipulates payloads with impressive precision. In demonstrations of mating cargo capsule door frames, ATHLETE aligned bolted interfaces with relative positioning precision of a few millimeters (Townsend 2011). Accuracy in robotic systems comes with a trade-off – for extreme accuracy complex sensing, vision systems, control, feedback, and actuation are required. Less complex robotic systems can be compensated for with design and configuration, such as bevels, rails, guides, cup & cones, and other physical alignment devices. The current prototype ATHLETE accuracy of less than one centimeter would not be accurate enough for precision manufacturing, but would be more than adequate for positioning of additive print heads for in-situ site structures.

Since the project's inception in 2005, the ATHLETE platform has been used to demonstrate a wide variety of tasks, including visual inspection of itself and other prototype lunar assets, transport and handling of small and large cargo elements, mounting and dismounting a half-scale prototype Altair lander with a 3m cargo deck, transport of cargo elements over distances of up to 80 km over rugged natural terrain and over obstacles up to 1m in height, manipulation and use of tools for auguring, gripping, digging, and leveling terrain, including teleoperated retrieval and exchange of tools from a body mounted tool holster.

III. Freeform Additive Construction System (FACS)

The proposed FACS system will function as an onsite robotic construction tool that does not require the presence of human operators, but can alternatively function at the direction of onsite human crews. The FACS system is an additive manufacturing system that is capable of "3D printing" large-scale walls, paving, vaults, domes, and hardening trench walls. The acronym comes from the idea of faxing CAD models remotely to the additive manufacturing printer onsite, to allow the construction and build-up of in-situ structures autonomously and via remote control. Figure 6 shows one possible configuration of the FACS system, with deployable solar arrays for power needed to achieve the high temperatures required at a print head. General features of the FACS system are discussed, followed by specific technologies that can be used for the actual fusing and deposition of native materials into site structures.

It is assumed that target structure and environment would determine which process would be used in surface construction scenarios. The FACS printing system could be used on the moon, Martian, or other planetary surface, creating compressive structures via melting and bonding loose regolith material. The structures produced would initially be low-fidelity massive stone, that could provide significant radiation protection, but not be pressurized on their own. Pressurized habitats, garages, and other structures would eventually need an inflatable pressure liner, or would require an inner layer consisting of spray-on material to prevent leakage of the cabin atmosphere. A simple construction scenario for a pressure module using the FACS system will be described later.
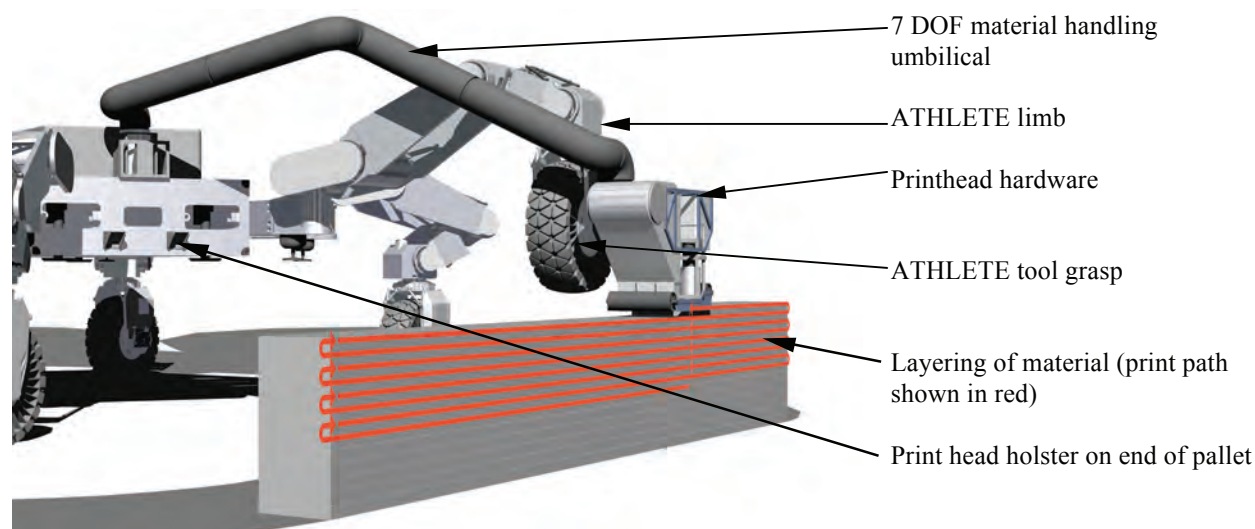
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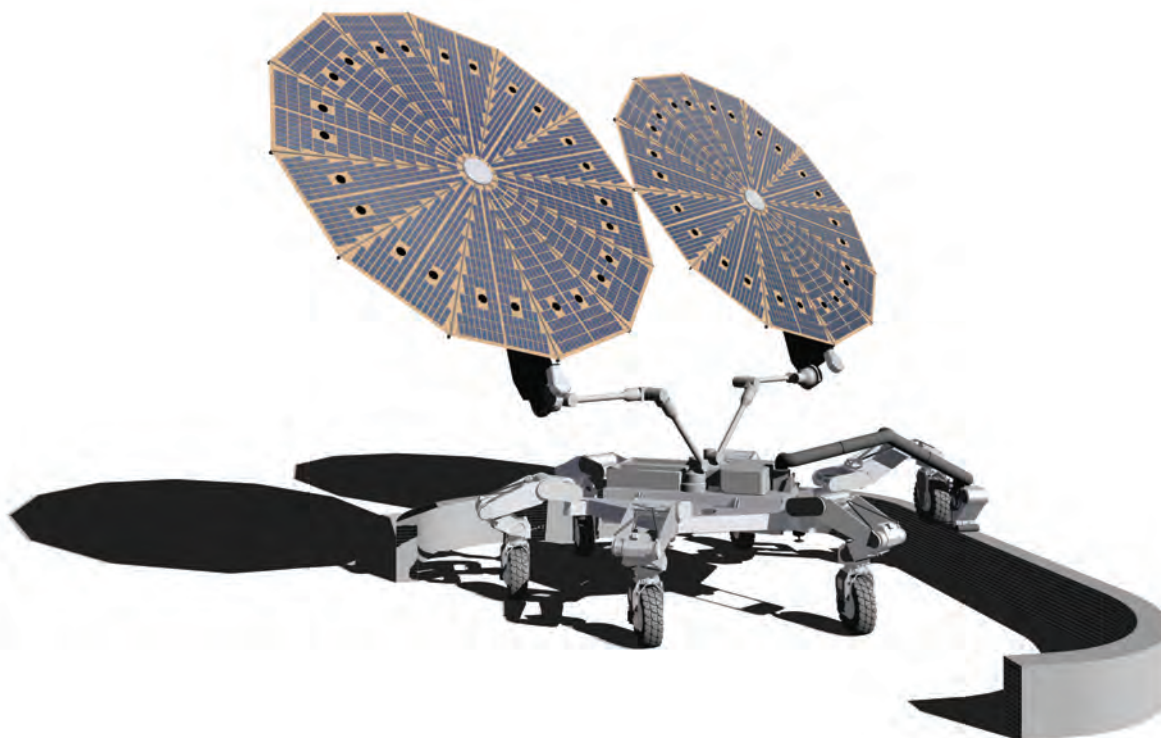
Figure 6: Freeform Additive Construction System (FACS) building a section of wall

A. FACS Configuration

The FACS system is built upon the ATHLETE mobility platform. Five ATHLETE limbs will be available for mobility, while the sixth limb will be devoted to tool manipulation. Material reservoirs, filters, crushers, processors, sorters, and mixers will be installed on the pallet, with a material handling system that delivers processed material to a printhead manipulated by the sixth limb. The mobility system situates the platform in an accessible location, whereupon the ATHLETE limb positions the printhead to build up in-situ structures in a layered fashion (Figure 7).

7 DOF material handling umbilical

ATHLETE limb

Printhead hardware

ATHLETE tool grasp

Layering of material (print path shown in red)

Print head holster on end of pallet

Figure 7: Additive manufacturing concept for walls and other structures

B. ATHLETE Precision Positioning

ATHLETE's system design enables relative positioning of manipulators and the cargo platform with precision of a few millimeters. This capability was showcased in a 2008 demonstration in which a pair of ATHLETE prototypes

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precisely aligned the doorways of their mockup habitat cargo elements. A printhead mounted to a single ATHLETE tool fixture can be positioned with this accuracy via motion of the manipulating limb or through motion of the cargo platform coordinated by the five supporting limbs. This precise positioning will enable accurate rendering of structural shapes within the stable work volume of the body and manipulating limb. The absolute positions of these shapes within the ATHLETE work volume may be affected by gravitational droop due to the weight of the printhead and the printing material, but these effects can be mitigated, particularly if the weight distribution can be accurately modeled.

Larger structures may require one or more relocations of the manipulator work volume, achieved through use of the ATHLETE mobility system. These relocations can be performed with the printhead held clear of the surface, as all of ATHLETE's mobility and navigation functions are compatible with a five-wheeled mobility base. While the mobility system positioning cannot achieve the sub-centimeter positioning accuracy of the manipulators, precise alignment of sections of a structure laid down at different rover locations can be achieved using 3D visual feedback. At each new rover position, visual cues drawn from stereo imagery of existing structural segments can be used to calculate positioning error, which can then be removed through precise adjustment of the cargo platform or manipulator position.
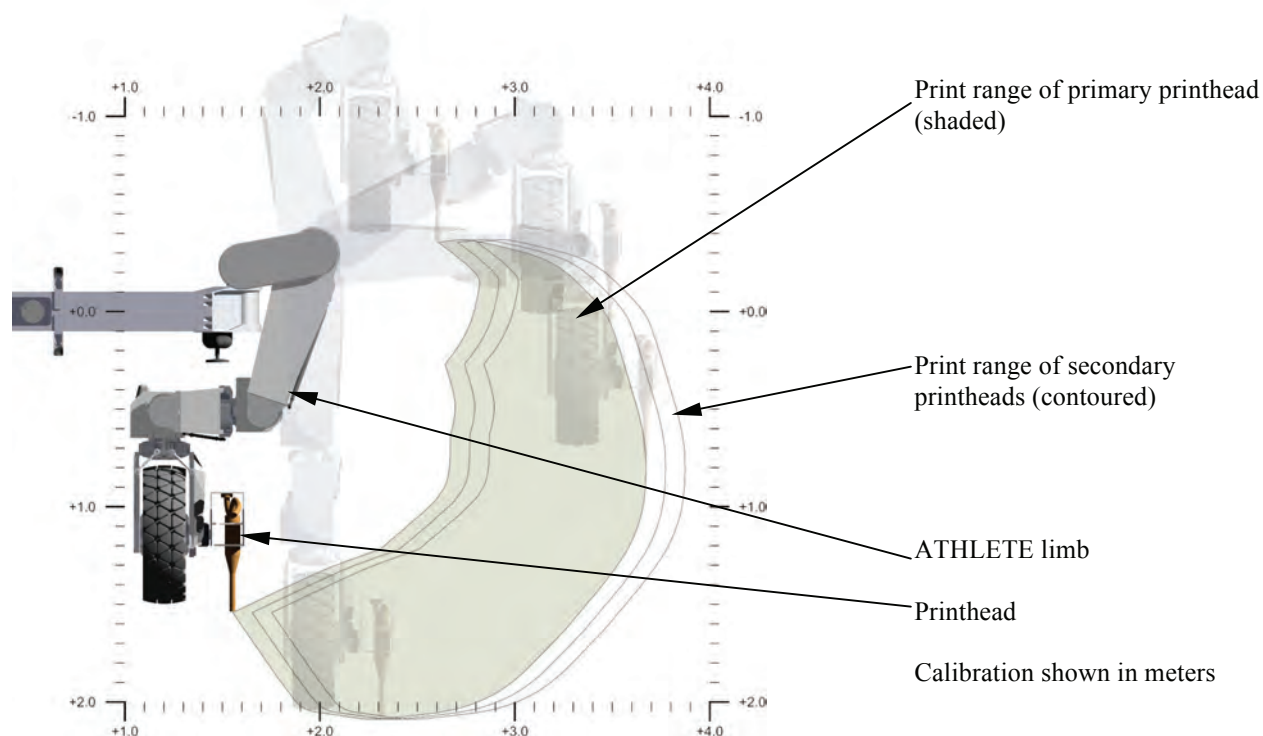
Additive printhead top view is shown in Figure 8. The print range of the additive printing system can first be calculated with the assumption that the ATHLETE body is stationary (Figure 9). With the ATHLETE vehicle in a static position, the limb grasping the printhead can trace out a cross sectional range determined by joint constraints (Figure 10). Figure 11 shows the top view of the print range assuming the ATHLETE body is static. However, the print range can be greatly extended if all the limbs are used to shift the ATHLETE body. Note that print range may also be affected by the weight of the printhead, regolith feedstock, and how far the ATHLETE limb needs to cantilever out from the body in order to reach a target location. These adjusted ranges will need to be explored as each printing technology and related hardware is developed.
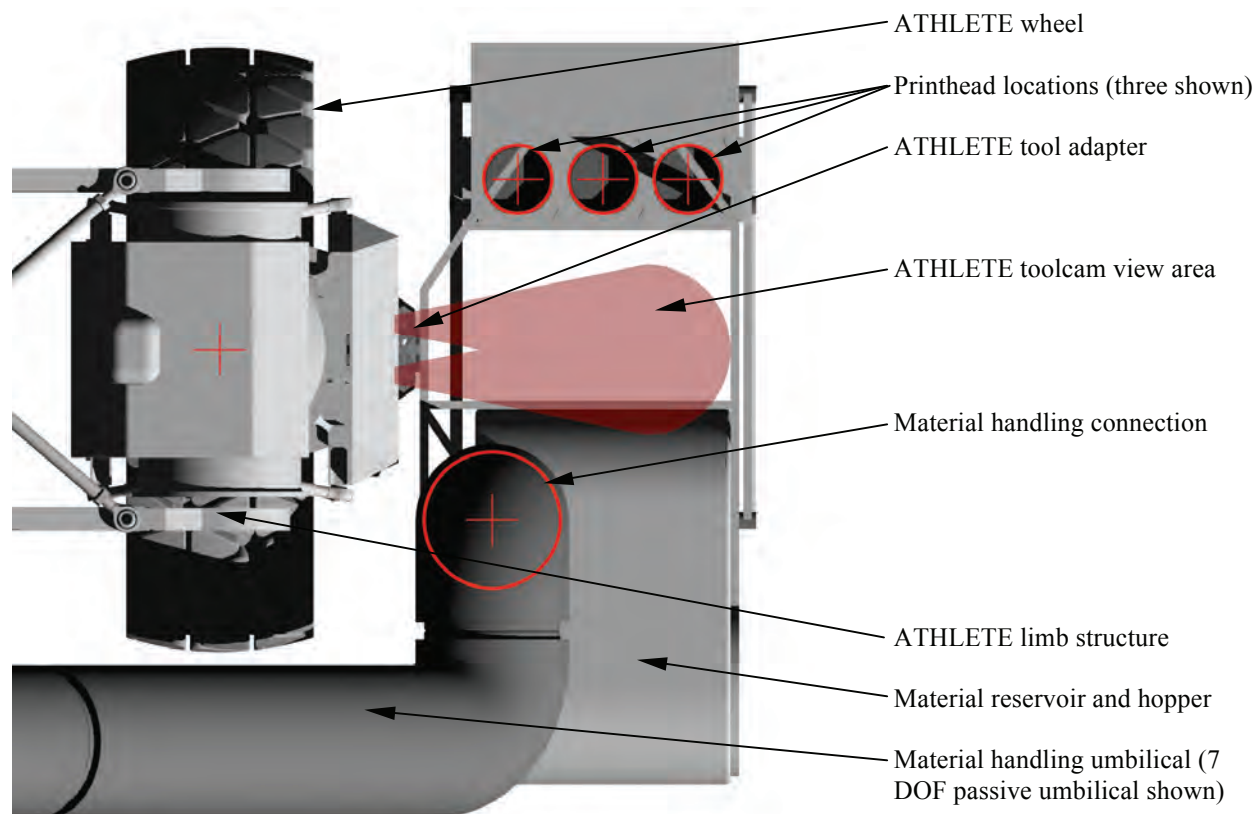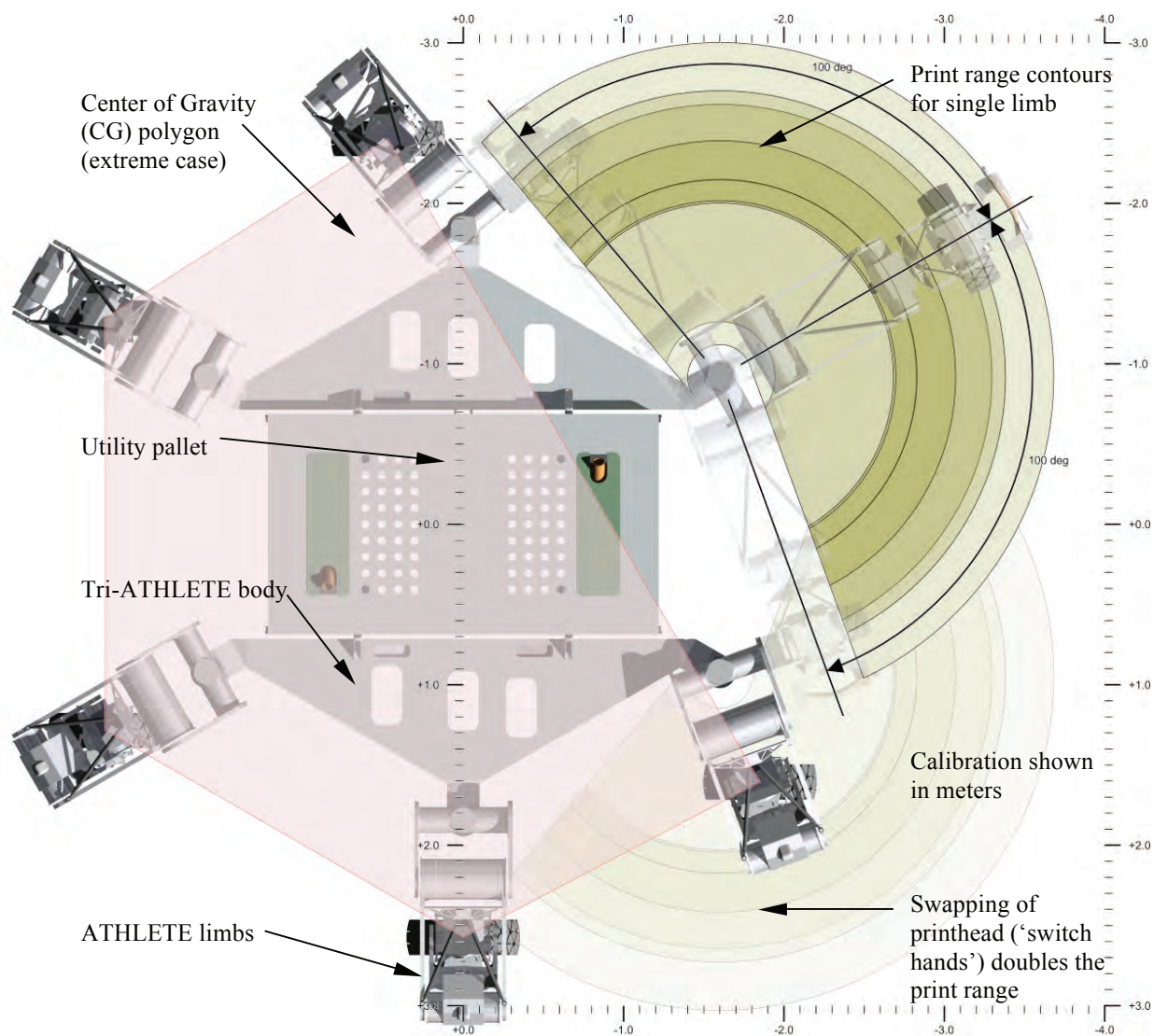

Figure 8: Additive printhead top view

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Figure 9: Static print range of single limb with stationary ATHLETE body, perspective view

Print range of primary printhead (shaded)

Print range of secondary printheads (contoured)

ATHLETE limb

Printhead

Calibration shown in meters

Figure 10: Static print range of single limb with stationary ATHLETE body, side view (note that this diagram shows the printhead oriented vertically – tilting the printhead at an angle, or upside down would vastly increase the print range)

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Figure 11: Static print range of single limb with stationary ATHLETE body, top view

C. 3D Additive Manufacturing

The work envelope of the FACS system with vertically-oriented printhead on a static ATHLETE stance is illustrated in Figure 9, Figure 10, and Figure 11. Tilting the printhead, or using it upside down would greatly increase the envelope volume. Shifting the ATHLETE body with wheels locked will widen the envelope even more (by how much depends on a detailed FACS hardware system design). Finally, using the ATHLETE's five mobility limbs to traverse across the surface effectively expands the work envelope across an entire flat surface plane, and possibly up sloped hilly surfaces and shallow canyons as well. With such a vast work envelope, it will be possible to construct any number of useful vaults, domes, walls, trenches, berms, tunnels, and paving.

Four technologies have been explored for potential application to a FACS 3D additive manufacturing printing process. The four technologies are, (1) microwave sintering "sinterator", processing and melting in-situ regolith that is found locally onsite; (2) fiberoptic solar concentrator, also processing and melting in-situ regolith; (3) single-part in-situ derived concrete, laying a slurry that will harden in place; and (4) multi-part binder agent using in-situ aggregate. Each of the four technologies are discussed as follows:
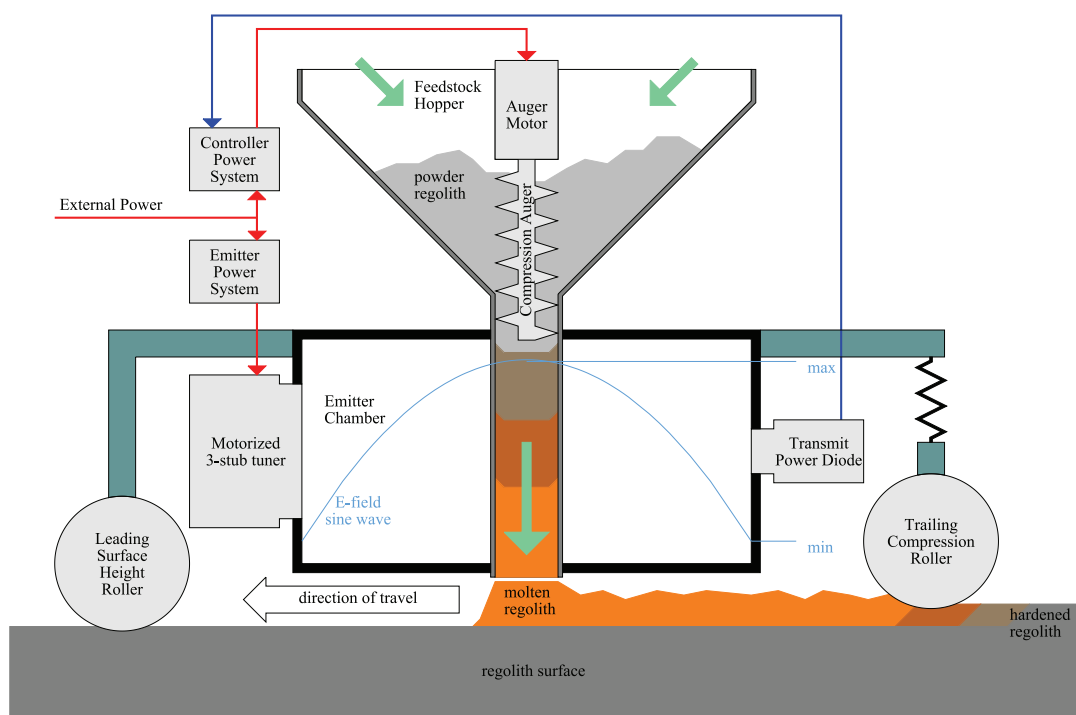
1. Microwave Sintering

The microwave "sinterator" approach uses focused microwaves to melt or sinter native regolith in a controlled manner. A preliminary vehicle configuration for a microwave sinterer is shown in Figure 12, where support excavation vehicles would deliver native regolith to the top of the pallet, to be filtered and carried through either a 3

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DOF or 7 DOF umbilical material handling system (discussed later) to the print head. Research has shown that lunar regolith samples can be sintered and melted using microwaves (Barmatz, et al 2013).

Figure 12: FACS using microwave sintering and melting of native regolith -- "Sinterator"


Figure 13: "Sinterator" tunable resonance chamber for regolith sintering and melting

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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 shown in Figure 13. 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).

For start-up, the high temperature tube will be empty. The ATHLETE limb will position the printhead on the starting point with the leading roller firmly on the surface. Powdered regolith (filtered and processed for uniform particulate size) is inserted into the feedstock hopper, then forced down into the tube using the auger. A temperature sensor aimed through a side window will monitor the rise in temperature of the feedstock. Once the powder reaches melting point, a continuous feed by the auger and sideways travel of the printhead is maintained, pressing a thin layer of melted regolith in place.

For shut-down the printhead will be quickly moved to the side with auger running. The microwave emitter will be shut down, and remaining partially melted material still in the tube flushed out on the ground.

The majority of the research has focused on Lunar simulant samples with sharp edged particulates. However, it is assumed that some degree of microwave melting can occur on many native soils, including rounded weathered particulates that might be found on Mars. Microwave testing of Mars simulants to confirm this is a future research activity. Also currently unknown is how microwave sintering or melting can be optimized for low power consumption, melted volume, and coverage in order to complete projects on a practical time schedule. Microwave melting of native regolith soils can be used for paving and dust mitigation, panel production, or for producing larger in-situ structures (Varga, et al 2013; Rousek, Eriksson, Doule 2012).
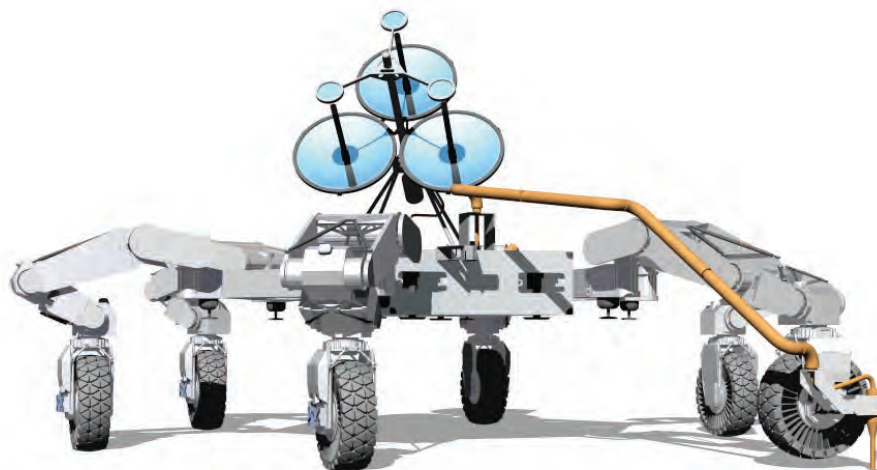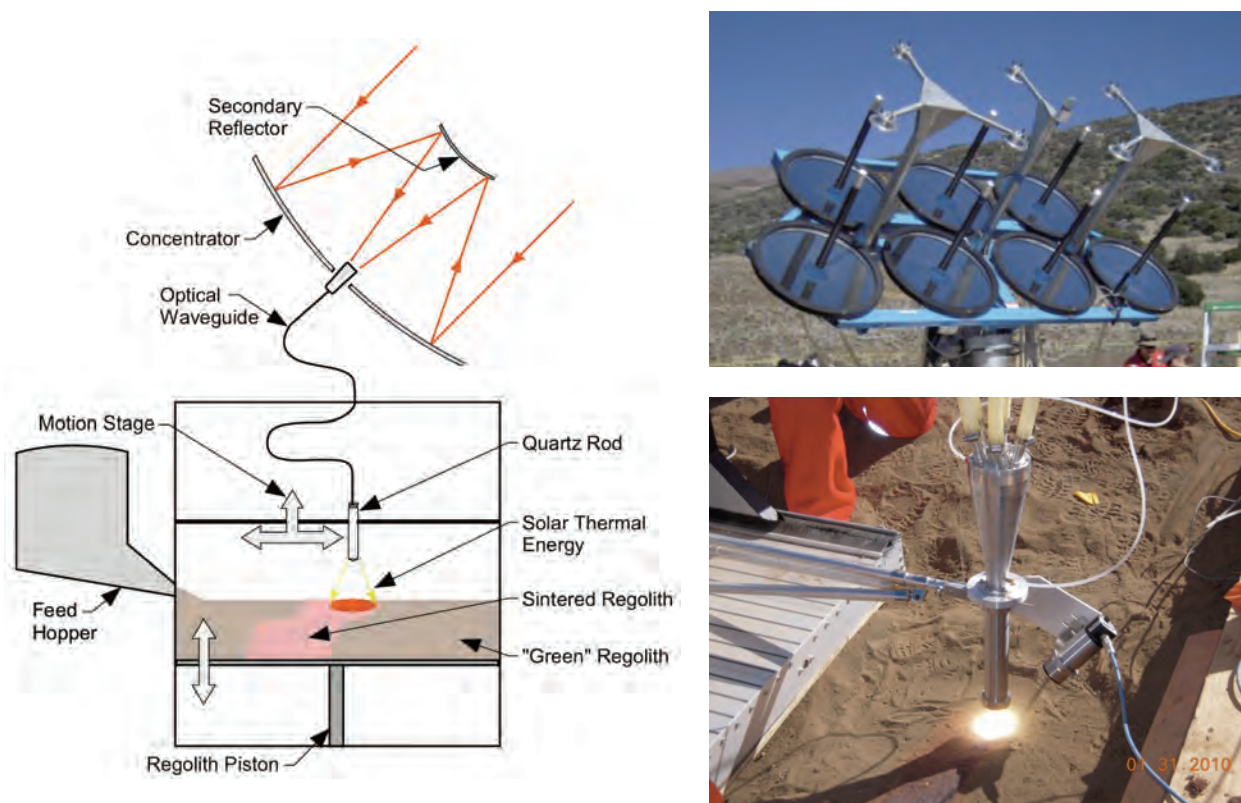

Figure 14: FACS using fiberoptic solar concentrator to melt surface material

2.   Fiberoptic Solar Concentrator

The Physical Sciences "Optical Waveguide" (OW) fiberoptic solar concentrator uses sunlight in intense heat to melt native regolith. A preliminary vehicle configuration for an OW construction is shown in Figure 14. The illustration shows a simple application of the technology optimized for paving, where solar concentrator mirrors focus sunlight into a fiberoptic umbilical and concentrates the heat onto the surface using the precision positioned

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ATHLETE limb. However, as with the microwave technology, adding a 3 DOF or 7 DOF material handling system would allow for three-dimensional additive manufacturing of structures.

Parabolic mirrors tracking the sun transfer energy along fiberoptic cables and focus intense light through a quartz rod (Figure 15, left). Temperatures exceeding 1150 degrees centigrade can be achieved (Nakamura, Smith 2011) without any power generation equipment, except for what is needed for the vehicle, control, and tracking motors. Tests performed at the 2010 NASA Mauna Kea Analog ISRU Test show that native soils can be melted even with less optimal solar radiation conditions (Figure 15, right).

Figure 15: Fiberoptic solar concentrator demonstration functional diagram (left), array & concentrator (right), courtesy of Physical Sciences, Inc

In addition to solidifying native particulates into useful in-situ structures, the OW solar concentrator team has also demonstrated that heating certain materials, such as lunar regolith, can extract oxygen for a variety of in-situ resource utilization.

3. Single-part In-Situ Derived Concrete

In-situ concrete systems may enable semi-liquid slurries to be formed into three dimensional shapes of walls and other structures and allowed to harden. Figure 16 shows a preliminary vehicle configuration with 7 DOF passive umbilical that pumps in-situ concrete through to a printhead, based on the University of Southern California (USC) Contour Crafting system (Khoshnevis, et al 2005).

A variety of concretes have been proposed for the moon (Beyer 1985; Ishikawa, Kanamori, Okada 1988; Omar, Issa 1994; Hatanaka, Ishida 2004). The USC Contour Crafting system has demonstrated additive manufacturing of full-sized wall sections (Figure 17) and scaled structures. In addition, Khoshnevis and team have developed printing techniques for constructing vaults and domes without the need for scaffolding or support structures to hold up the roof while the material is curing. The Contour Crafting system has also demonstrated the additive manufacture of prefabricated beams and trusses that can be lifted in place to support floors and ceilings.

Though the actual recipe for a lunar concrete was not within the scope of this paper, the FACS system can function as a delivery vehicle for Contour Crafting lunar concrete mixtures precision positioned to construct vaults, domes, walls, and other in-situ structures. A reservoir and batch plant can be manufactured into an ATHLETE pallet, whereupon the slurry can be pumped through a 7 DOF umbilical to the printhead.

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Figure 16: FACS using single-part in-situ derived concrete


Figure 17: Contour Crafting concrete printing of walls and other elements, nozzle (left), printed concrete wall (right), courtesy of the Center for Rapid Automated Fabrication Technologies (CRAFT) at USC

4. Multi-part Binder Agent with In-Situ Aggregate

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 environment. An illustration and photo of the automated brick maker is shown in Figure 19 (left and center).

Figure 18: FACS using multi-part binder agent with in-situ aggregate
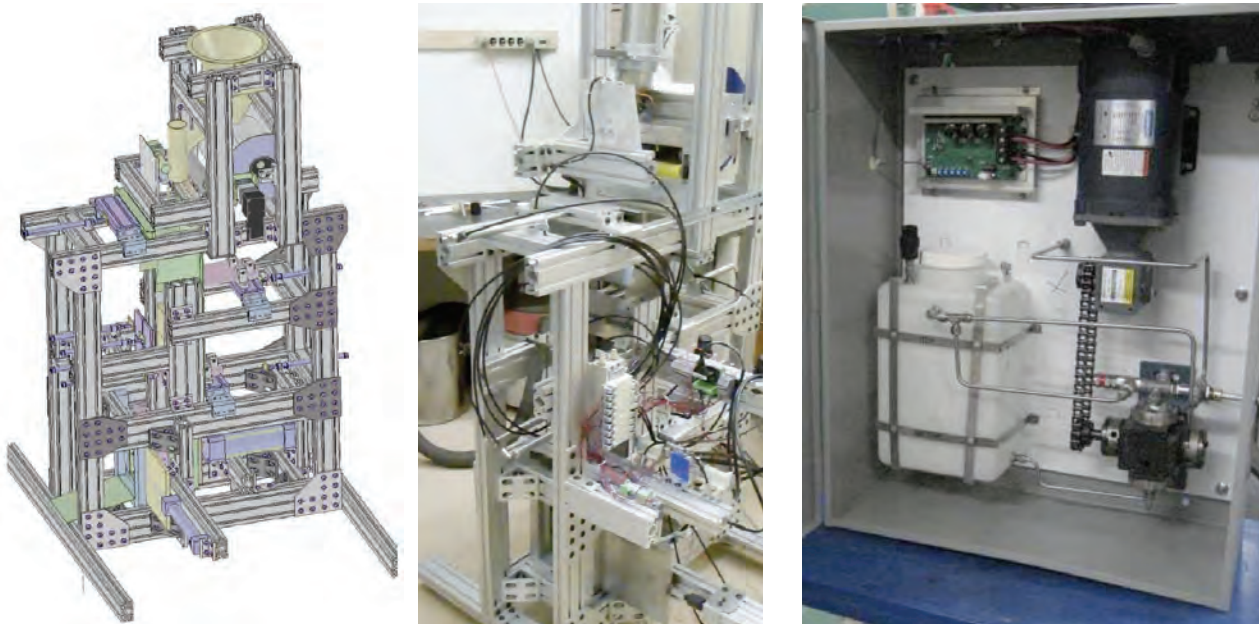
Figure 19: Regolith stabilization demonstration for brick-making (left & center) using urethan resin binder, and demonstration spray unit (right), courtesy of Adherent Technologies, Inc

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Adherent Technologies also produced a spray system (Figure 19, right) that could apply the polysol and isocyanate parts in a controlled manner in a vacuum for possible paving and soil stabilization.

It is proposed that Adherent's multi-part binder technology could be adapted for controlled mixture and material handling to a custom print head for layered application as a large-scale 3D additive printer (Figure 18).

D. Material Handling

The FACS system described in this paper consists of a precision robotic mobility and positioning platform (the ATHLETE system), carrying limited material processing and handling from a reservoir to the print head. Though it might be possible for ATHLETE to also perform some of the mining, excavation, and gathering of regolith, it is proposed that more specialized equipment, such as those described by Mueller & King (2008) in Figure 21, or the Kennedy Space Center Swamp Works Regolith Advanced Surface Systems Operations Robot (RASSOR). Excavation equipment would mine and gather regolith and perform limited material processing (crushing, filtering, etc), and deposit the material into a receiver hopper on the top of ATHLETE.

The print head nominally rests in a holster on the end of the pallet, with umbilical in a stowed configuration. All six ATHLETE limbs can be used for mobility when the print head is stowed in the holster. When the printing activity is required, one of the ATHLETE limbs adjacent to the holster will reach up and grasp the print head and carry it to the start position. In this way, print ranges can be doubled when the print head is returned to the holster by the first limb, and then grasped again by the neighboring limb 'switching hands' to extend the work without having to relocate the entire ATHLETE platform (Figure 11).

An internal material processing and handling system would then be customized for the target printing technology – material would be transported through either a 7 Degree Of Freedom (DOF) umbilical or a 3 DOF conveyor belt to the print head. The FACS material handling chain is shown in Figure 20 (3 DOF articulated conveyor belt shown), where material is delivered at the orange arrow and passed to the print head.
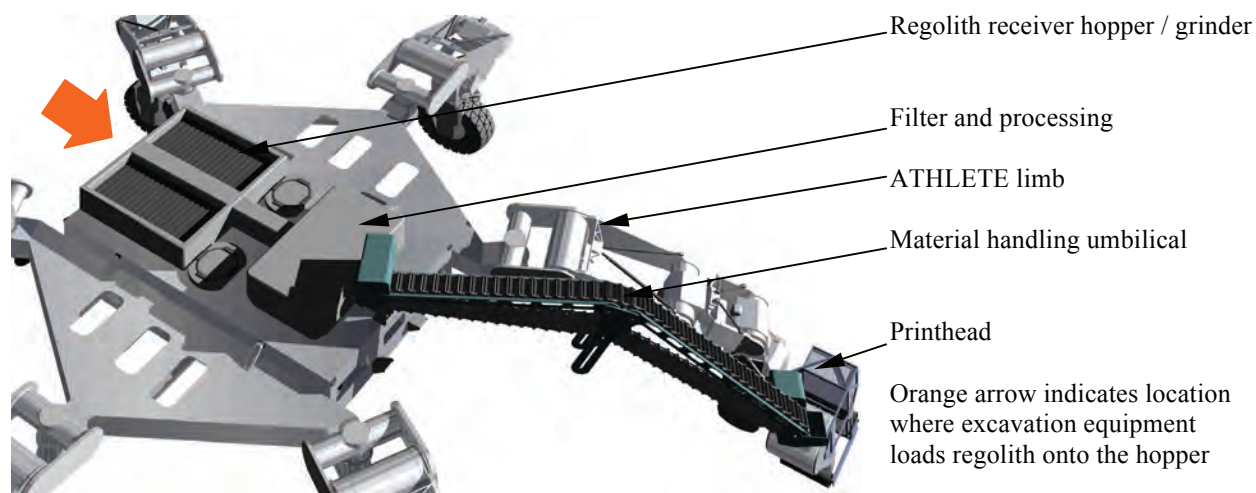

Regolith receiver hopper / grinder

Filter and processing

ATHLETE limb

Material handling umbilical

Printhead

Orange arrow indicates location where excavation equipment loads regolith onto the hopper

Figure 20: In-situ regolith material handling chain
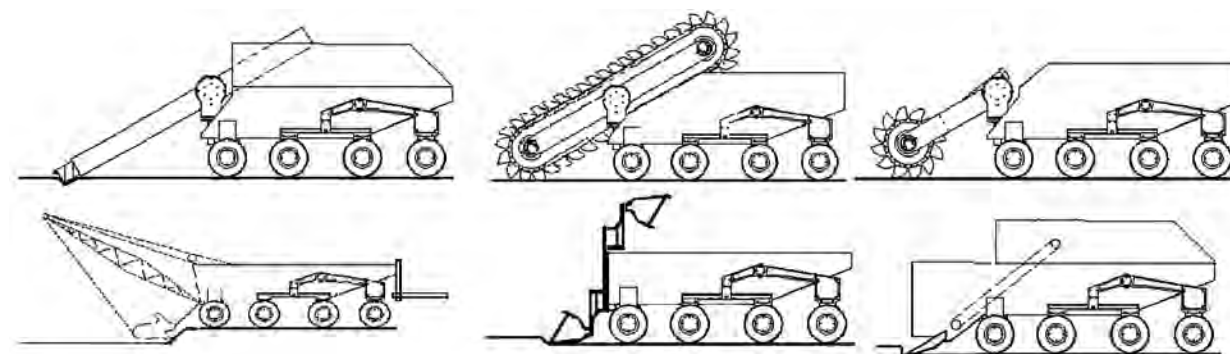
Figure 21: Excavator types for regolith material handling and delivery (Mueller, King 2008)

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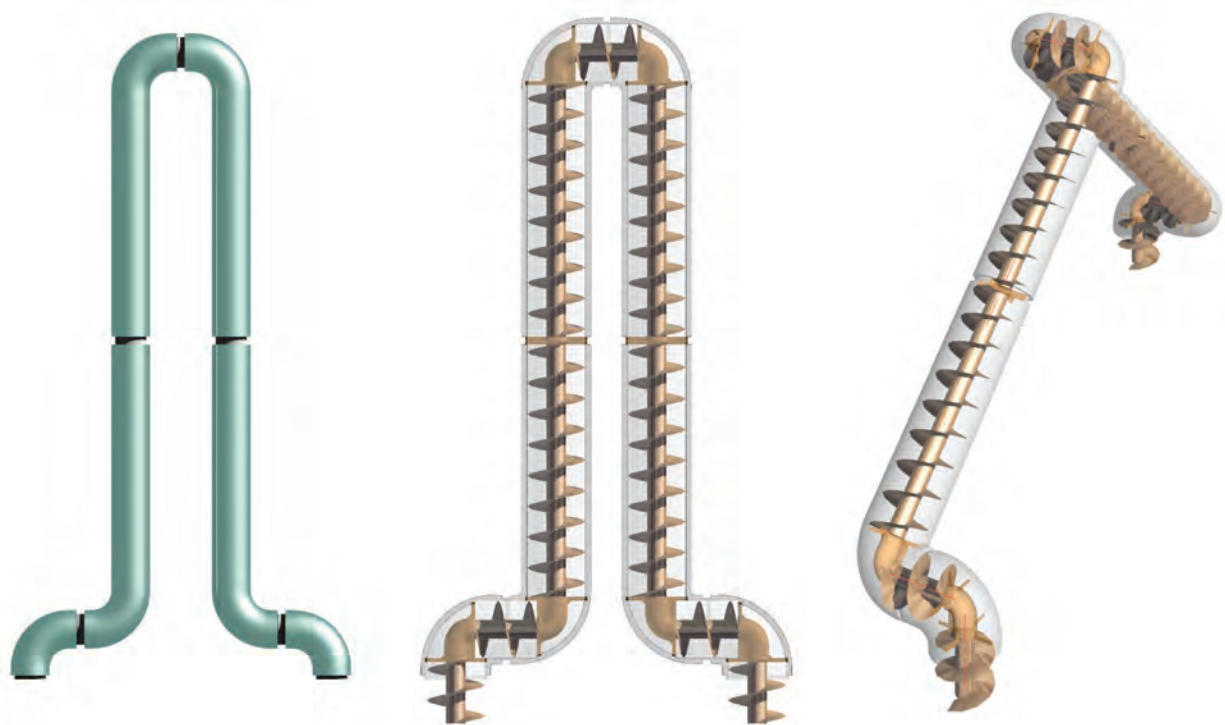
Figure 22: 7 DOF passive umbilical conduit (left) for cables or fiberoptics, and Archimedes Screw (middle, right) for transport of regolith powders to the printhead. Archimedes Screw shafts can be hollow for carrying cables and fiberoptics

Articulated central hub

Spring-loaded belt return

Conveyor belt with deep bucket pockets

Regolith powder feedstock insertion

Regolith powder feedstock to printhead
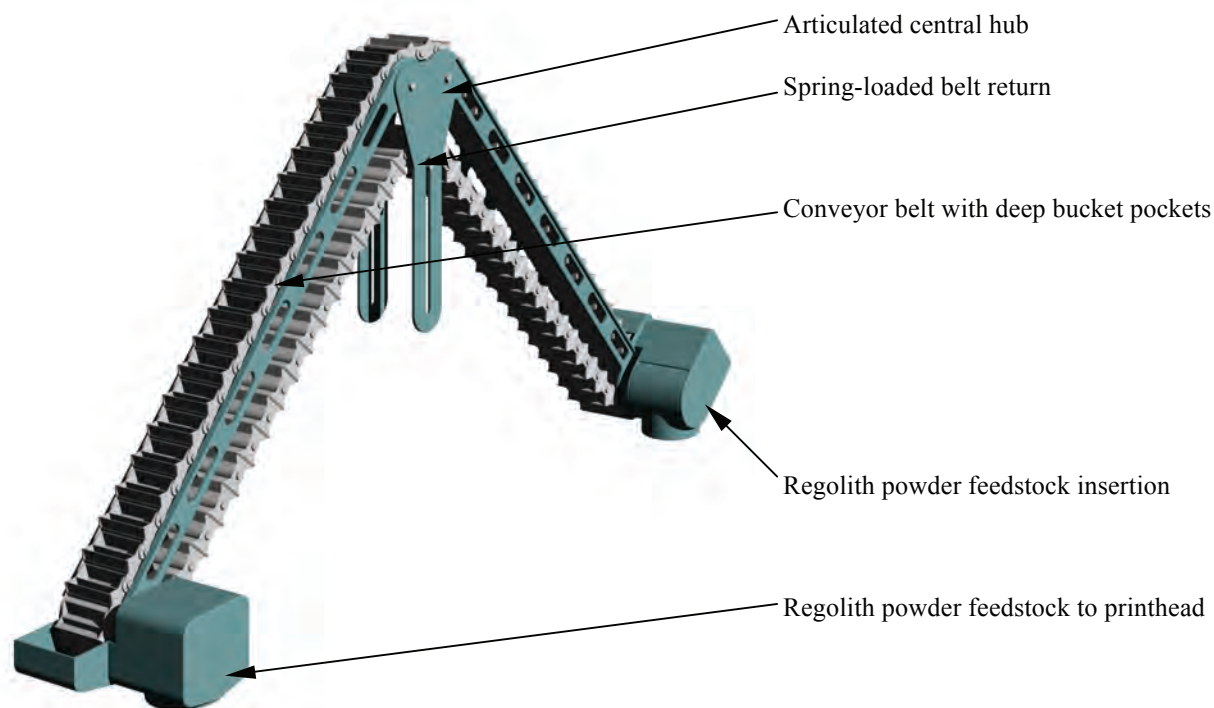
Figure 23: 3 DOF articulated conveyor belt umbilical

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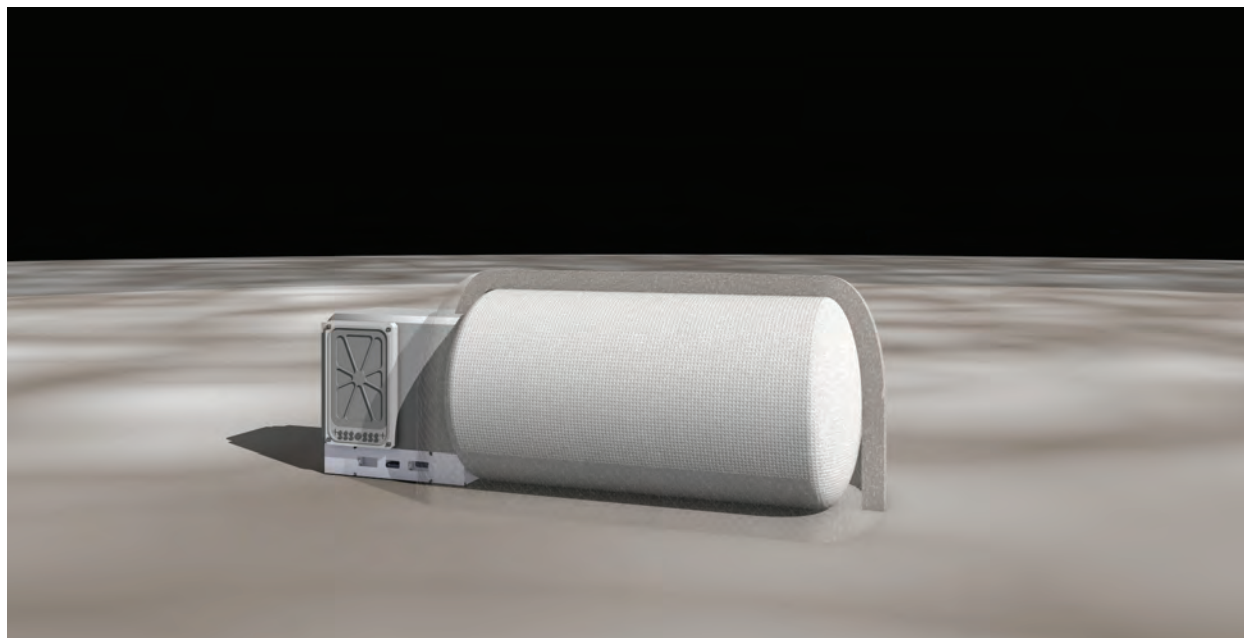
1. 7 DOF Passive Umbilical

A seven degree of freedom passive umbilical has been conceived, with rotating passive joints, that can bring material either pumped through a conduit (Figure 22, left) or through a powered Archimedes Screw (Figure 22, middle and right). The Archimedes screw, with gear boxes at the joints, can be powered from either end such as the ATHLETE power take-off or via a pallet-based motor. The 7 DOF passive umbilical mounts to the ATHLETE pallet at one end and the print head fixture on the other. One ATHLETE limb will grasp the print head from its holster, and move it into position for the additive printing activity, whereupon the 7 DOF umbilical can follow at most any position driven by the ATHLETE limb. At this stage, a complete analysis of the proposed workspace of the 7 DOF umbilical and any potential conflicts with the environment (including ATHLETE limbs, pallet, and other equipment) has not been undertaken, since it is quite early in the design. However, preliminary studies on passive flexibility where both ends of the umbilical are constrained vertically have been completed to support known print ranges (Figure 9, Figure 10, Figure 11).

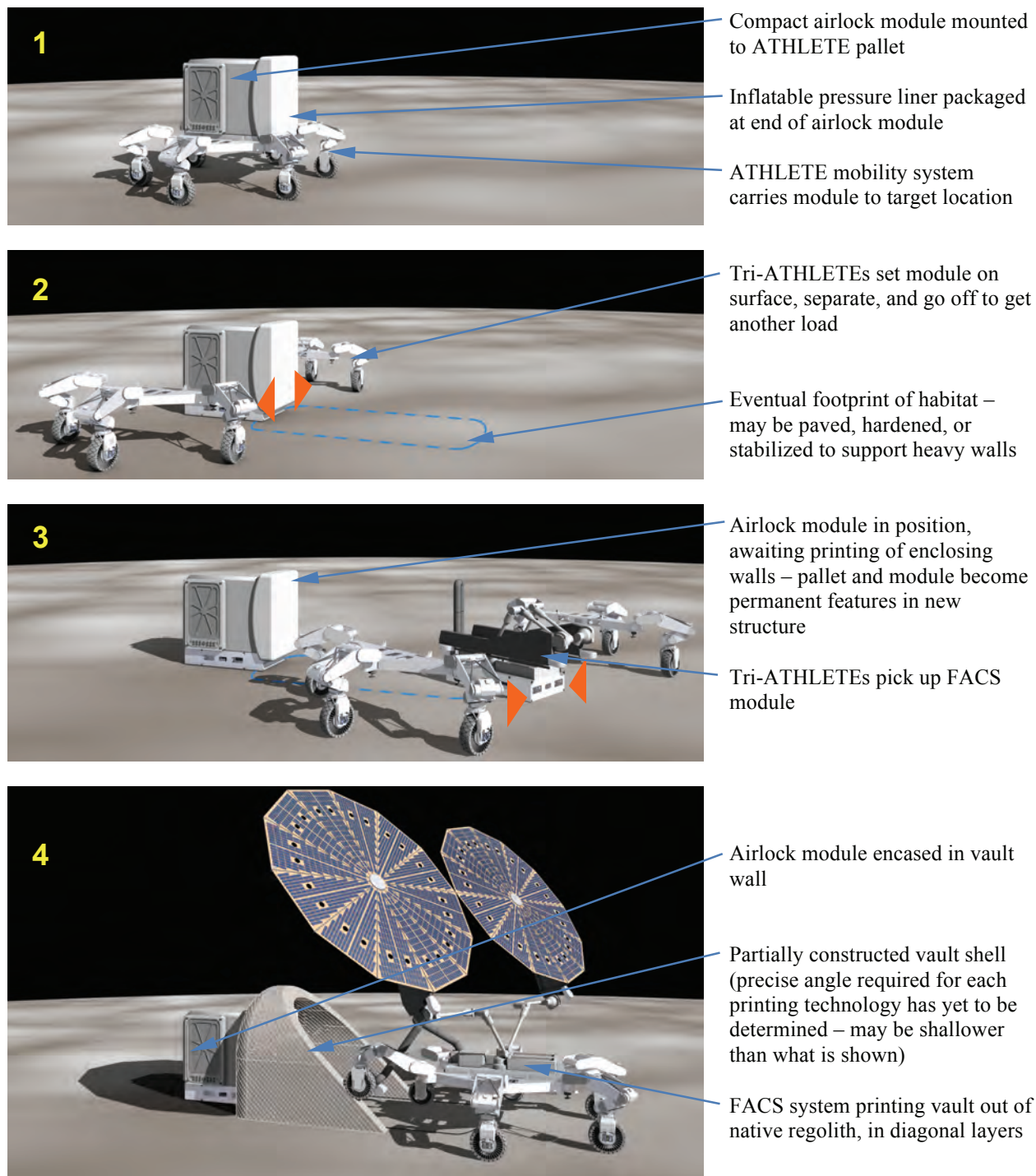### 2. 3 DOF Articulated Conveyor Umbilical

Alternatively, a three degree of freedom articulated conveyor umbilical has also been devised, that can be used if both ends of the conveyor are mounted vertically (Figure 23). The articulated conveyor has deep buckets for material handling of regolith powders and grains, and can be folded or stretched using a spring-loaded tensioner to keep the belt in place. The 3 DOF conveyor has several conflicts with the environment that limits its workspace as compared with the 7 DOF umbilical. One ATHLETE limb will grasp the print head from its holster and move it into position for the additive printing activity, followed in a constrained manner by the 3 DOF umbilical. As with the 7 DOF, complete kinematic analysis and conflicts analysis have not been completed as of this writing.

IV. FACS Application for Planetary Construction

The FACS system can be used in a variety of applications, such as paving, surface stabilization, berm / trench wall stabilization, and to print walls and overhangs. An example of printing a large-scale vaulted shell enclosure, using techniques pioneered by the University of Southern California Contour Crafting team, is shown in Figure 25. In this example, an ATHLETE mobility platform carries a compact airlock module into place and positions the pallet in the target location on hardened ground. An inflatable liner is packed at one end of the module. The Tri-ATHLETE halves undock and go pick up the FACS pallet, then begin the printing process, using an angled layering pattern. The angle allows for the printing of overhead vaults and ceilings without the need for support or scaffolding. Once the shell is printed, the inflatable liner can be autonomously inflated in place to create a pressurized cabin waiting for crew to arrive (Figure 24). Multiple pressure hatches in the airlock module can allow docking of pressurized rovers or 'ganging' up of multiple modules into a complex or outpost.


Figure 24: Example in-situ derived habitat showing cutaway and inflatable liner

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1 — Compact airlock module mounted to ATHLETE pallet

Inflatable pressure liner packaged at end of airlock module

ATHLETE mobility system carries module to target location

2 — Tri-ATHLETEs set module on surface, separate, and go off to get another load

Eventual footprint of habitat – may be paved, hardened, or stabilized to support heavy walls

3 — Airlock module in position, awaiting printing of enclosing walls – pallet and module become permanent features in new structure

Tri-ATHLETEs pick up FACS module

4 — Airlock module encased in vault wall

Partially constructed vault shell (precise angle required for each printing technology has yet to be determined – may be shallower than what is shown)

FACS system printing vault out of native regolith, in diagonal layers

Figure 25: Example printing process of a large-scale vaulted shell enclosure with inflatable pressure liner: (1) ATHLETE carries airlock module to target location; (2) Tri-ATHLETEs place module and go off for another load; (3) Tri-ATHLETEs dock with FACS module; (4) FACS system prints hard shell vault over target footprint; (5 not shown) pressure liner inflates inside printed shell (see Figure 24)
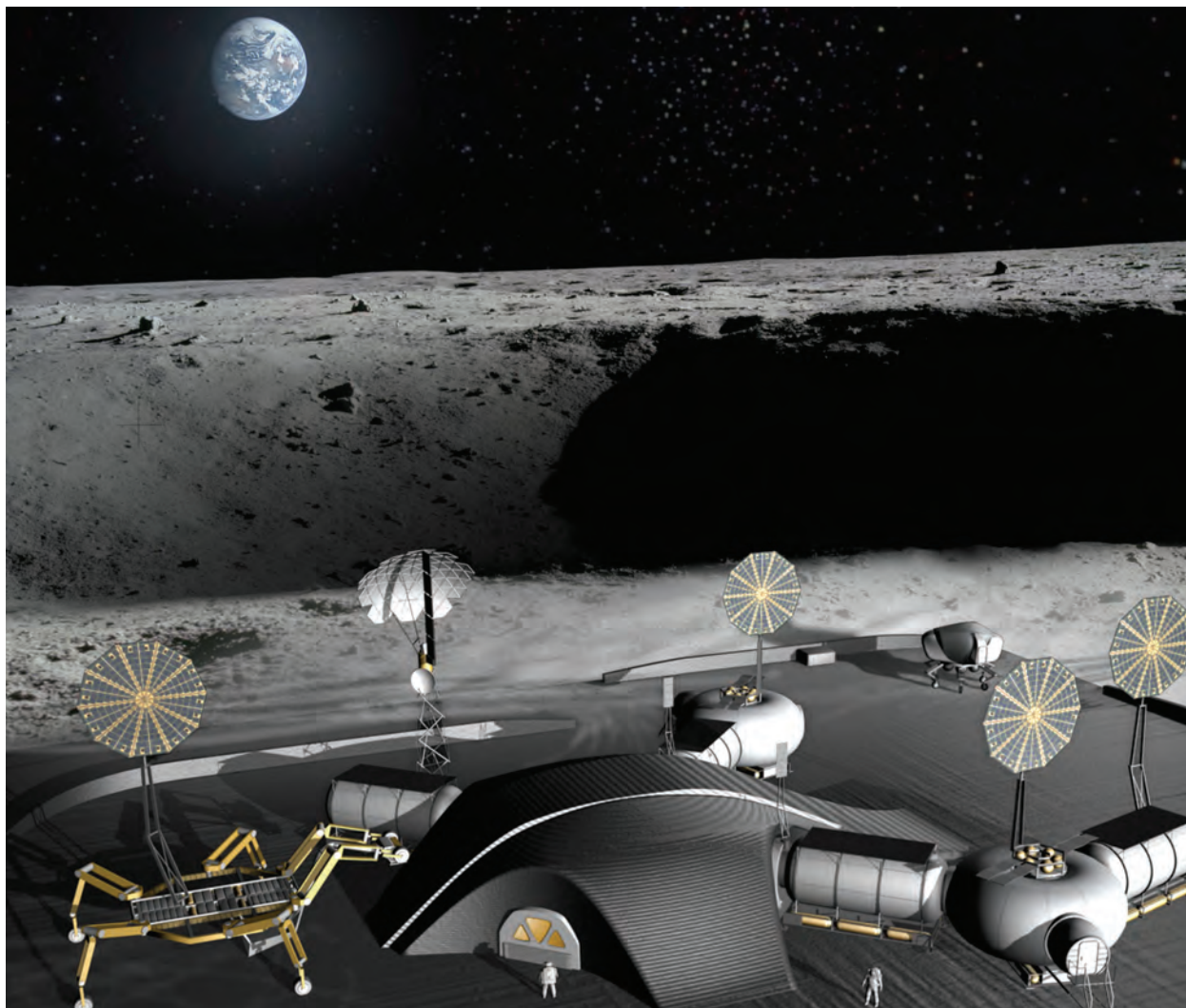
Figure 26: SinterHab constructed on a paved surface, showing an earlier version of ATHLETE (lower left) as a large-scale 3D printer (Rousek, Eriksson, Doule 2012)
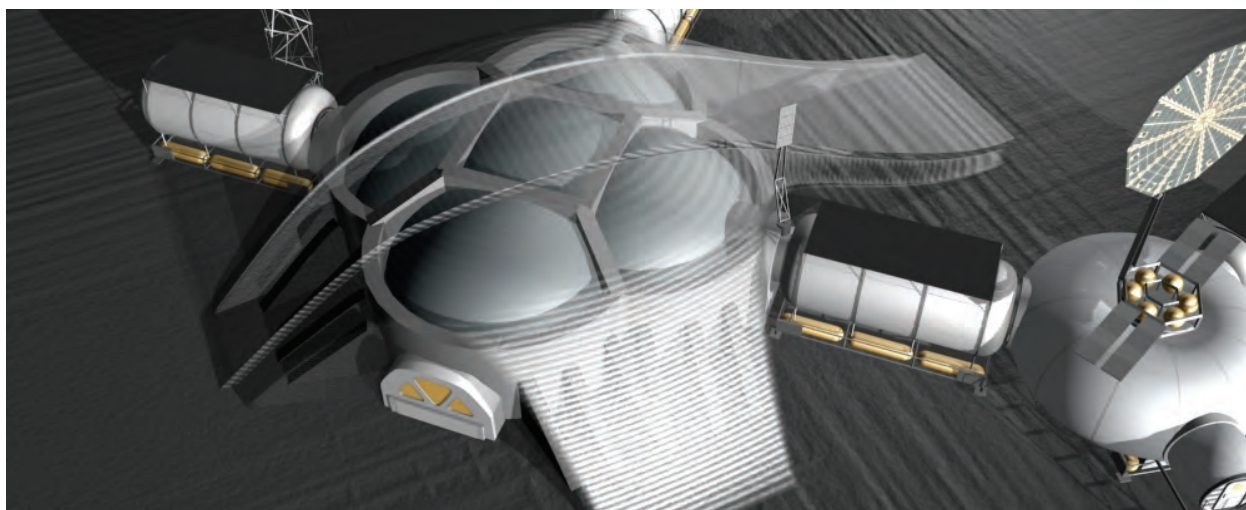
Figure 27: SinterHab consists of hollow chambers with post-inflatable air bladders, interfacing with early sortie mission pressurized modules (Rousek, Eriksson, Doule 2012)

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Several advanced studies of 3D printed lunar outposts have been proposed. The SinterHab outpost (Figure 26) uses ATHLETE with a "Sinterator" print head (described earlier) to gradually build up a solid radiation resistant shell around previously located modules (Rousek, Eriksson, Doule 2012). Initial sorties and limited scale outposts characterized by single pressurized modules can be scavenged as core cabin volume, whereupon printed compression structures can be constructed to enclose larger volumes to supplement the original (Figure 27).

V. Conclusion

Combining current research, four additive manufacturing technologies have been identified that can be mounted to an ATHLETE mobility system for the in-situ construction of walls, berms, paving, vaults, domes, and other compressive structures that do not need precision tolerances. Rough in-situ structures can be combined with precision manufactured imported modules and equipment to significantly reduce launch mass, stabilize surfaces, and provide radiation shielding. Using ATHLETE, structures can be prepared well in advance of crew arrival, to create pressure vessel shells, garages, and site structures needed in a planetary outpost.

Considering four different printing technologies, each with strengths of their own, it has been determined that a demonstration solar concentrator paver could be assembled together within a few months using an operational ATHLETE and existing concentrator collectors. Building upon the ATHLETE positional accuracy, further research on material handling, sintering, binding, and in-situ concrete are well within our reach.

Acknowledgments

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