ATHLETE as a Mobile ISRU and Regolith Construction Platform

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The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robotic mobility platform can provide precision positioning and mobility for site preparation and regolith construction needs. ATHLETE is a multi-use platform designed to use swap-out tools and implements that can be applied to any number of tasks that need precision limb manipulation or mobility. Major capabilities include off-loading habitats, transporting surface assets, robotically assembling outposts from multiple mission manifests, and supporting science and technology objectives. This paper describes conceptual approaches for supporting NASA regolith construction research, such as additive construction, modular brick and panel factory, and mobile ISRU platform.

Nomenclature

ATHLETE	=	All-Terrain Hex-Limbed Extra-Terrestrial Explorer robotic mobility system
FACS	=	Freeform Additive Construction System
ISRU	=	In-Situ Resource Utilization
JPL	=	NASA / Caltech Jet Propulsion Laboratory

I. Introduction

THE most significant cost for space missions comes from lifting materials out of Earth's gravity well. The use of in situ resources gathered and processed at the destination can significantly reduce the amount of mass that must be brought from Earth. The Jet Propulsion Laboratory (JPL) has been supporting a team of NASA multi-centers, universities, and private corporations to develop technologies for regolith construction and In-Situ Resource Utilization (ISRU) in lunar, Mars, and asteroid surface environments. JPL's contribution has been expertise in remote robotic construction concepts and development of mobility platform concepts and prototypes.

Robotic planetary surface construction concepts include precision assembly using the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robotic mobility system as a construction platform (Figure 1). ATHLETE will off-load large payloads from landers and transport the elements to the outpost site (Howe & Wilcox 2016). Pressurized habitation modules can be set on the surface singly as they arrive (Figure 2), where subsequent modules can be assembled together as they arrive to make up the final outpost configuration (Figure 3). ATHLETE has been discussed as a cargo handling platform (Wilcox, et al, 2007), exploration work platform (Wilcox 2012), and assembler of planetary outposts (Howe, et al, 2010).

With its capacity to convert from wheeled mobility into precision limb manipulation, we have proposed the use of ATHLETE as a precision positioning tool for additive construction, where native regolith can be set down in thin layers and melted or sintered into place to construct large-scale structures much the same way plastic deposition "3D printers" create three-dimensional plastic parts. We have discussed the ATHLETE-based Freeform Additive Construction System (FACS) control, mechanical systems, operational capacities, print range, and binding technologies (Howe, Wilcox, et al, 2013), and various construction scenarios (Howe, Wilcox, et al, 2014). This paper expands on the FACS concept, proposing ATHLETE as a support for ISRU volatiles processes (propellant and oxygen production, etc), platform for brick or prefabricated panel manufacturing and placement, and various tools for minor local regolith manipulation.

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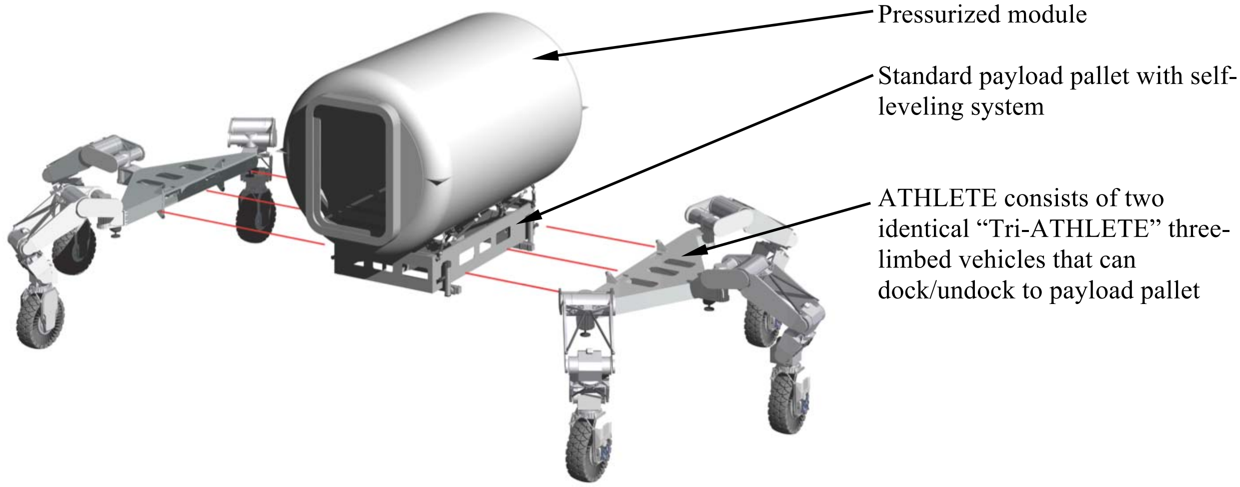

Figure 1: ATHLETE as a robotic constructor for planetary surfaces

Figure 2: Robotic construction field testing: docking and undocking of habitat payloads

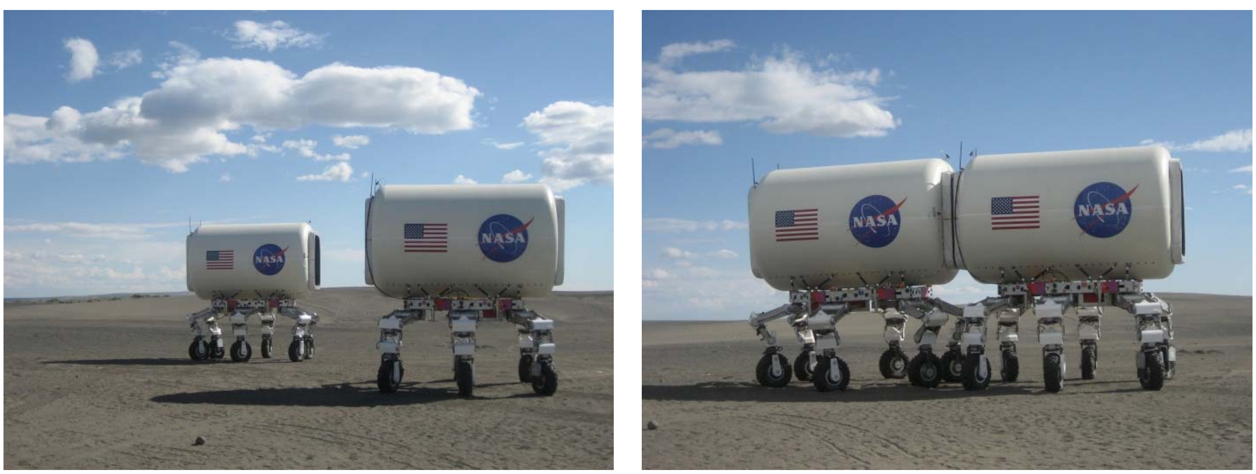

Figure 3: Robotic construction field testing: assembling an outpost from multiple elements

II. Mobile ISRU Platform

For any particular destination, mission planners should not expect to find all the materials needed in a single location. In situ resources are frequently very diffuse, and thus a great deal of area must be covered to harvest a significant amount of the desired resource. On planetary bodies such as Mars and the Moon, scattered resources call for a mobile In Situ Resource Utilization (ISRU) plant, which can move over the surface to prospect for and locate useful resources, and then "bring the process to the resource" instead of "bringing the resource to the process." The fundamental reasoning is that, at low gravity planetary bodies, mobility is relatively low-cost compared to Earth. For example, an off-road vehicle that can carry its own weight in payload on Earth can carry ~11 times its own weight on the moon and >4 times its own weight on Mars. For ISRU to be attractive, the mass of material processed must be many times the mass of the ISRU plant itself. Thus, moving the plant is advantageous compared to moving all the material to be processed, especially when one considers all the round-trips that haulers have to take.

Recent research has shown the high value of lunar ice, in particular, to be processed into propellant for human missions to Mars (Ho, et al. 2014). An example of this is volatiles in the lunar polar craters. From orbital neutron spectrometer data, it is expected that hydrogen exists in roughly the top half-meter of lunar polar regolith. It is presumed that this hydrogen is bound in the form of water, which is perhaps the most valuable space resource.

Microwave hardware can be mounted to an ATHLETE to extract and concentrate water as a mobile ISRU system that can move across the lunar surface (in particular hydrated minerals and ice at the polar craters) and "cook out" the volatiles in the regolith. It has previously been demonstrated that microwaves can efficiently heat regolith (Barmatz, et al 1995; Barmatz, et al 2013; Barmatz, et al 2014). Most of the earlier studies used a microwave resonant system to heat the regolith. An alternative more practical approach for space applications is to radiate the microwave energy directly onto the regolith surface. One approach for doing this is the use of a microwave horn emitting device (Figure 4) that would capture most volatiles as it is swept across the surface by an ATHLETE limb. The heating device can also be body-mounted on a vehicle with a perimeter skirt for capturing volatiles. Another efficient device could extract volatiles using one or more microwave coax cables radiating on excavated regolith moving along a belt or other material handling device (Figure 5). These approaches can use a fixed frequency magnetron tuned to the absorption band of water (similar to microwave ovens on Earth) to heat water-rich regolith to boil off the water vapor. Figure 6 shows a microwave horn extracting volatiles from an excavated hole in the regolith. Microwaves penetrate dry regolith and are absorbed by water, effectively heating only the material to be harvested. Volatiles, and other resources, can also be extracted from excavated regolith.

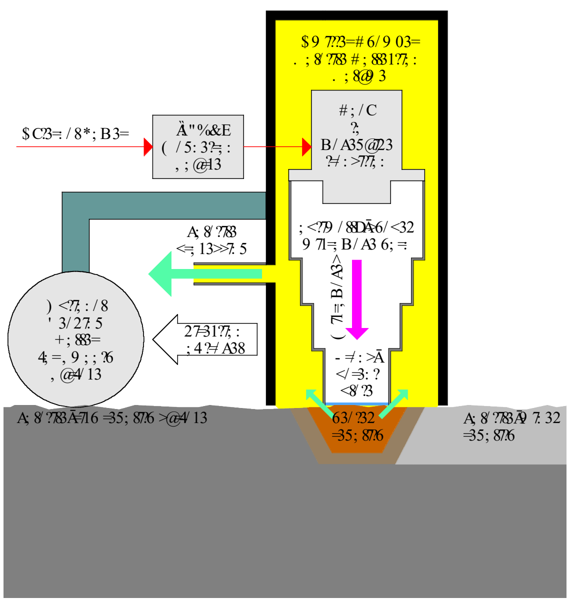

Figure 4: Using microwaves to extract volatiles from regolith on the surface ("lawn mower style") with optimally-shaped microwave horn

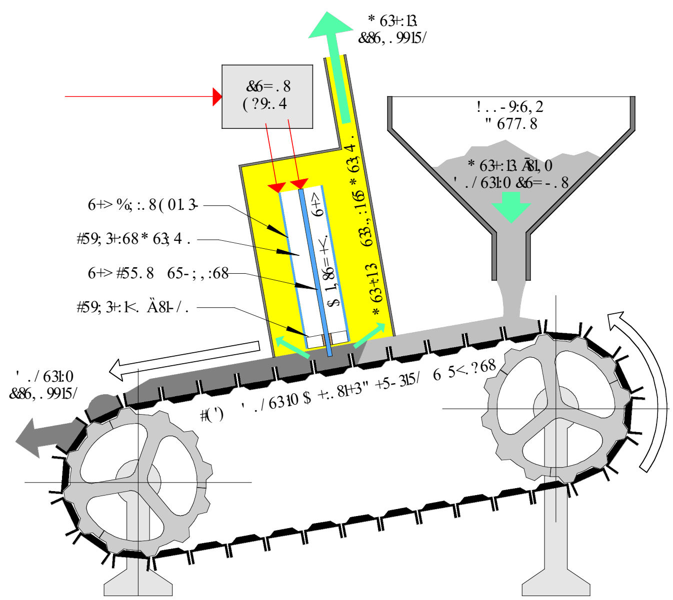

Figure 5: Using microwave coax to extract volatiles from regolith during material handling

If the vehicle were ~10 m across and the volatiles are driven out from several centimeters deep, most of the volatiles that escape the heating chamber in near vacuum would be captured by the skirt. Volatiles from the chamber and skirt would make their way into a cold trap that condenses and concentrates them. The cold trap would stay cold by radiating to the dark sky. The skirt would not need to "seal" particularly well against the terrain because the pressures would never get high enough for the molecules to hit each other; instead, each water molecule would bounce freely around under the skirt until it hit the cold trap, where it would condense.

In a proposed flight system, power for the microwave emitters could come from a solar power plant or solar concentrators, temporarily set on the rim of the lunar polar crater, to beam power directly (Shapiro 2002; Mankins

2009; JAXA 2015) or as reflected sunlight (Nakamura & Smith 2011) to the vehicle as it works in shaded areas (which would just reflect the energy vertically downward through the transparent top of the skirt).

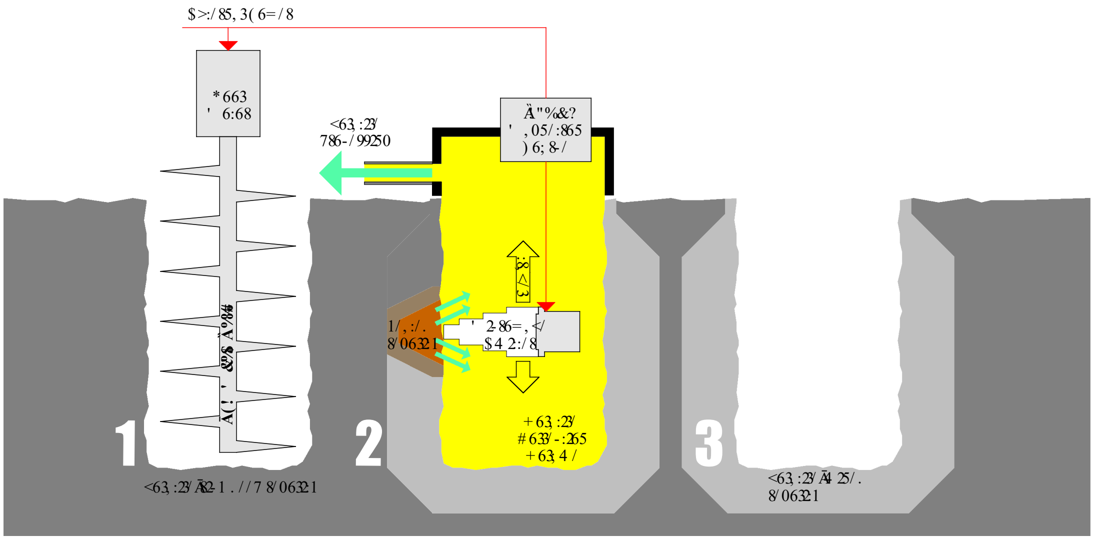

Figure 6: Using microwaves to extract volatiles from below the surface, by "painting" sides with a microwave emitter horn

Bench top test systems have been assembled at Jet Propulsion Laboratory by the authors for the purpose of developing advanced methods for extracting volatiles from regolith. Figure 7, left, shows a resonant microwave cavity connected to a volatile condensation system. Figure 7, right, shows a new test apparatus consisting of a vacuum chamber containing a regolith simulant. This particular arrangement shows a coax microwave emitter inserted along the axis of the chamber that will extract volatiles from the regolith simulant. Those volatiles will be pumped out and sent to the volatile condensation system shown in Figure 7, left.

Figure 7: Bench top test apparatus for extracting volatiles from regolith simulants (left), with regolith vacuum chamber (right)

Mars is known to possess two major sources of accessible water: (1) at high latitudes, subsurface ice is present at depths of a few meters or less (Figure 8); and (2) hydrated minerals at the surface have been detected from orbit at a large number of locations (Figure 9). While it requires less energy to extract ice that is mixed with regolith but not chemically bound as compared to extracting water from hydrated minerals, the hydrated minerals are located at the surface and thus require less energy to excavate. It is not clear which of these two sources will prove most accessible on Mars – indeed it may depend on the location of the selected landing site. In both cases, the data acquired from orbit averages over large areas, while the distribution on the surface (and subsurface) is expected to be heterogeneous at much smaller spatial scales than can be mapped from orbit. Accessible water on Mars is key to a sustained presence on Mars, and knowledge of such deposits is critical to the location, design, and sustainment of a Mars settlement. Thus the ability to prospect may be required, or at the least would greatly improve the efficiency for a mobile ISRU plant.

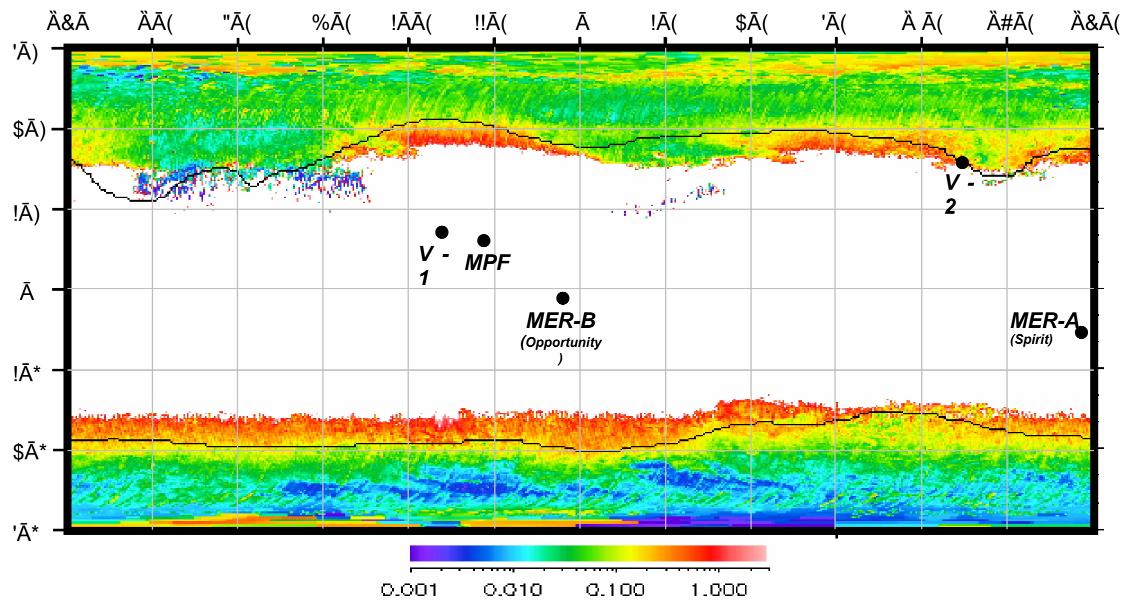

Figure 8: Ice table depth (scale in meters) measured by the Gamma Ray Spectrometer (GRS) instrument on Mars Odyssey (Mellon & Feldman 2006)

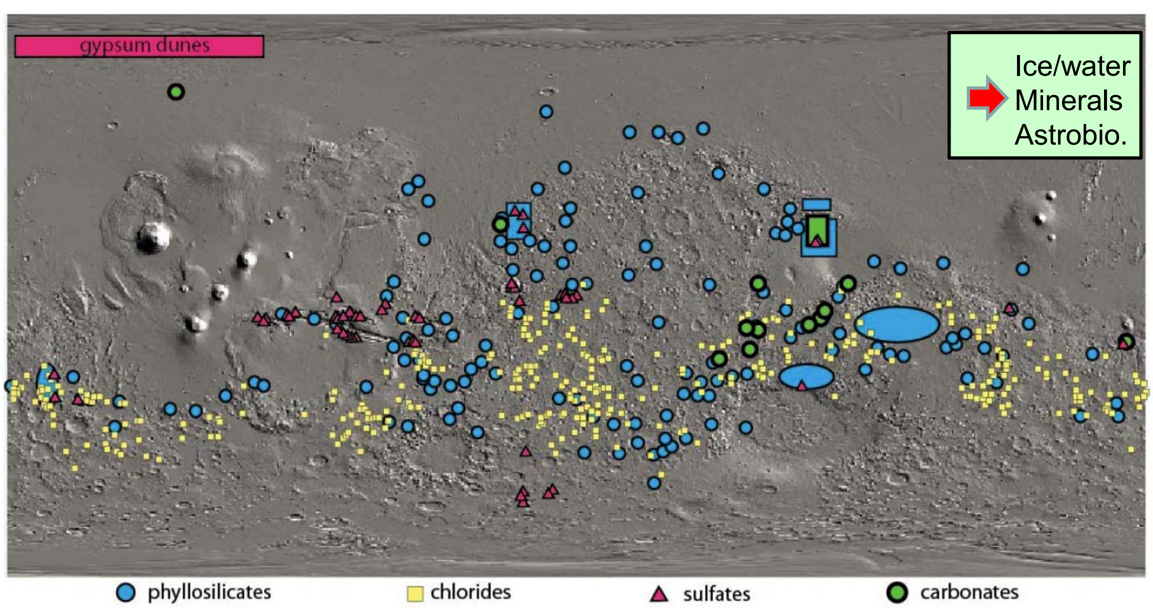

Figure 9: Detections of hydrated minerals on Mars (Ehlmann et al, 2012). These are phyllosilicates, sulfates, and carbonates formed in liquid water environments, and they contain as much as ~13% water

For the case of subsurface ice, the ISRU plant on Mars could prospect using Ground-Penetrating Radar (GPR) that will be integrated on the proposed prototype. GPR will discover shallow subsurface features not exposed to surface (Kim et al, 2006). Through characterization of subsurface stratigraphy, GPR can guide a rover to positions where the layer is closest to the surface for easy sampling. It will also show the extent of the homogeneity of the layer, thus the utility of sampling depth.

GPR data will also show relative dielectric constant contrasts and the phase of the reflected wavelets from each layer. One can obtain constraints on subsurface materials of the layer, including presence of water ice or hydrate minerals, e.g., gypsum ($CaSO_4 \bullet 2H_2O$), kieserite ($MgSO_4 \bullet H_2O$), that can be heated to extract water. Figure 10 shows ATHLETE fitted with GPR on a field test at Dumont Dunes, California. To prospect for hydrated minerals, the system would use the same proven technology used to detect the presence of hydrated minerals from orbit: infrared imaging spectroscopy. An example of an imaging spectrometer designed for use from a Mars rover is shown in Figure 11.

A concept for an ATHLETE modular pallet (Figure 13) can be dedicated for a portable regolith ISRU separation plant, including liquefaction and storage of water and cryogenic fluids, and Sabatier Reactor for the separation of volatiles that have been collected for future use as propellant, crew cabin atmosphere, and water (Figure 12).

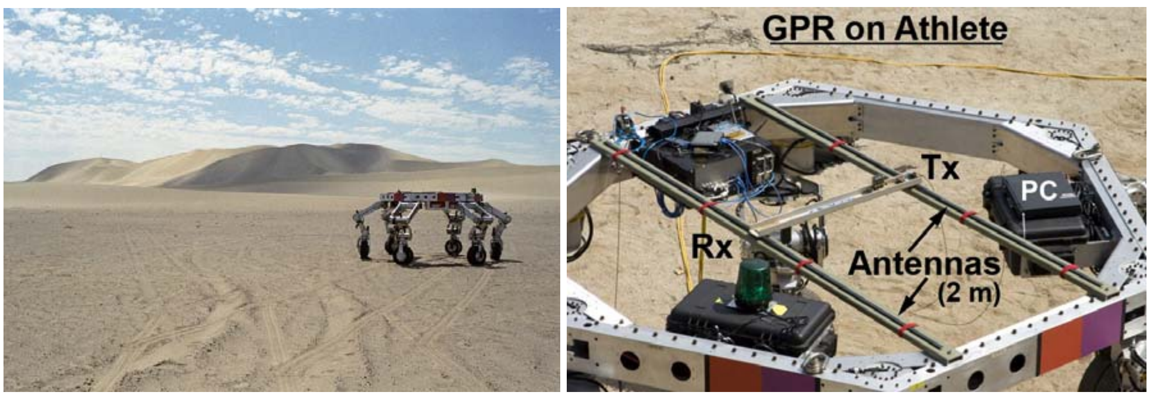

Figure 10: Athlete Rover deployed in Dumont Dunes, California (left), GPR antenna and electronics mounted on the Athlete rover (right)

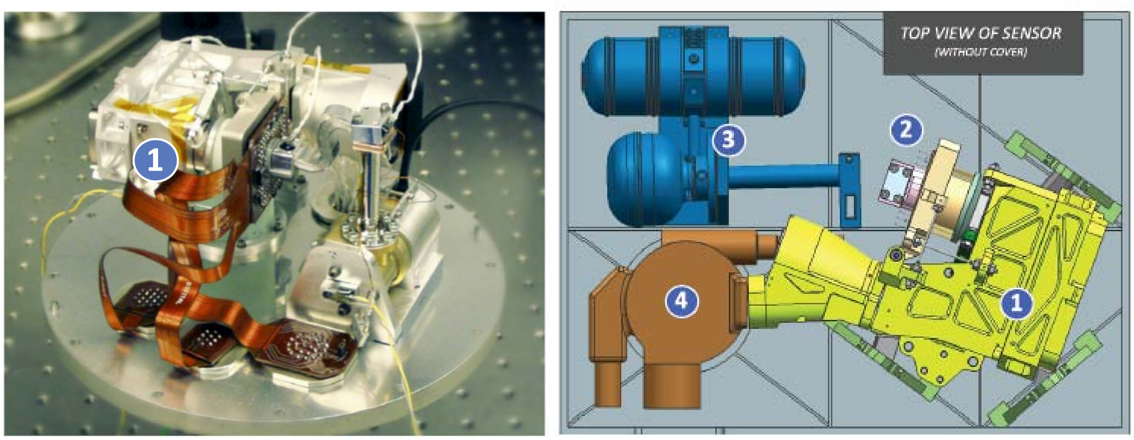

Figure 11: (1) Prototype Ultra-Compact Imaging Spectrometer (UCIS) developed at JPL; (2) Infrared focal-plane array with heritage from the Moon Mineralogy Mapper; (3) Pulse-tube microcooler; (4) Calibration subsystem. Mass is 3kg for the sensor head and 1.4kg for command and data-handling electronics (not shown)

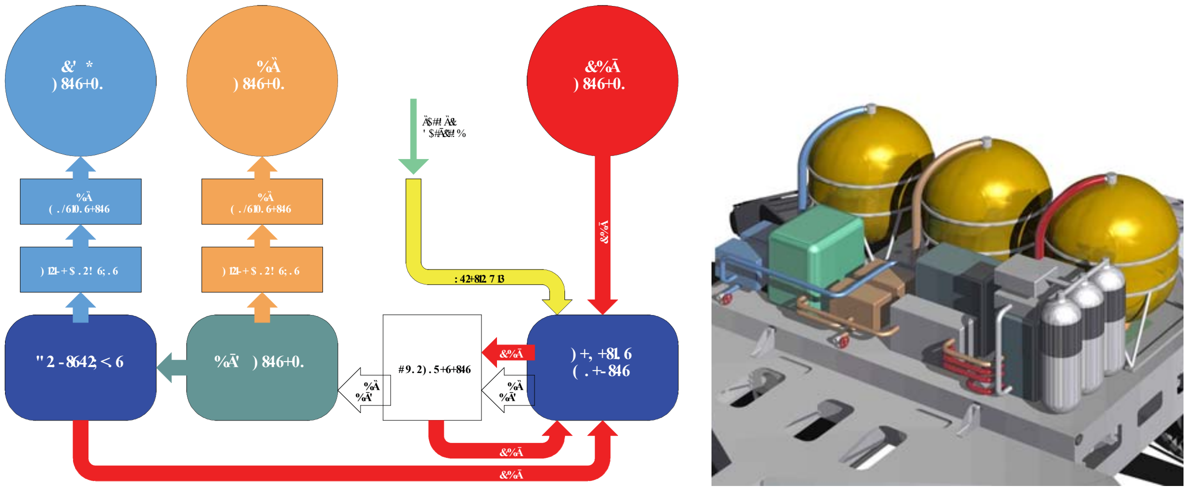

Figure 12: Volatiles that are separated from regolith are processed into fuel, water, and atmosphere gases (left); the processing plant is shown conceptually on ATHLETE (right)

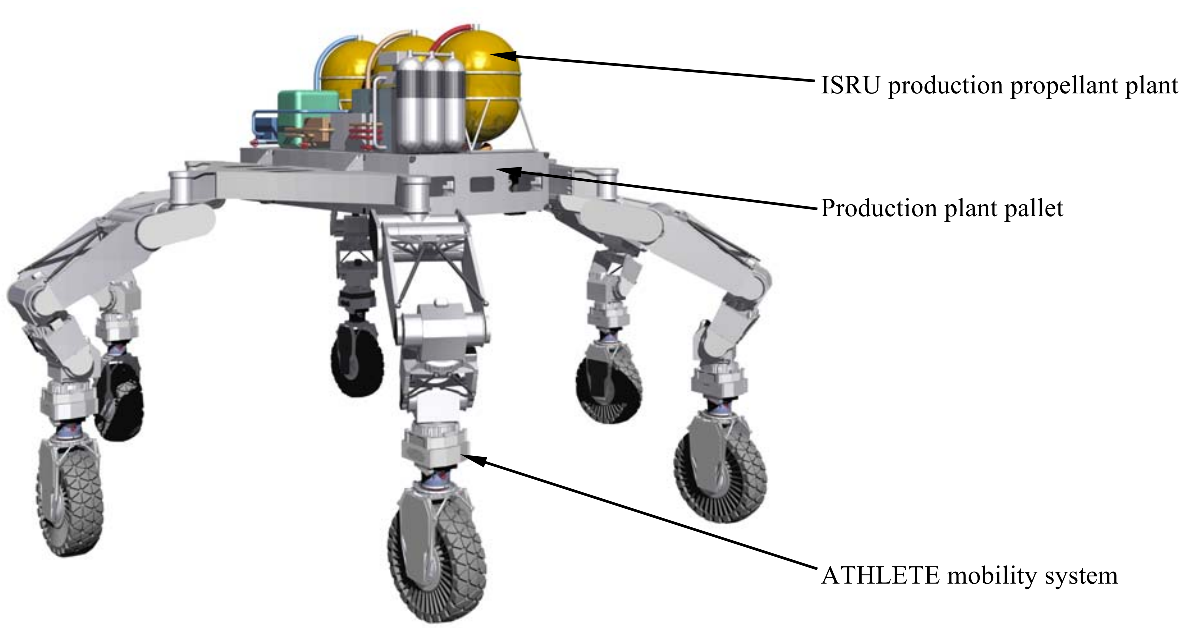

Figure 13: Conceptual ATHLETE-based Mobile ISRU propellant production plant

III. In-situ Regolith Construction Platform

Large-scale structures can also be 3D printed using native regolith material. Low-resolution structures that need to be created for an outpost (e.g., radiation, micrometeorite and ejecta shields and landing pad paving) can be very large and require mobile vehicles to construct. For radiation shielding, these structures may need to be meters thick. Regolith material can be excavated near the planned structure location using a vehicle similar to NASA Kennedy Space Center's Regolith Advanced Surface Systems Operations Robot (RASSOR) excavator robot (Mueller & King 2008). An ATHLETE based Freeform Additive Construction System (FACS) can then stabilize surfaces and rigidize extruded regolith into the desired shapes using microwave sintering or melting (Figure 14 and Figure 15), or through liquid extruded material such as that used by the Contour Crafting method (Khoshnevis et al, 2005).

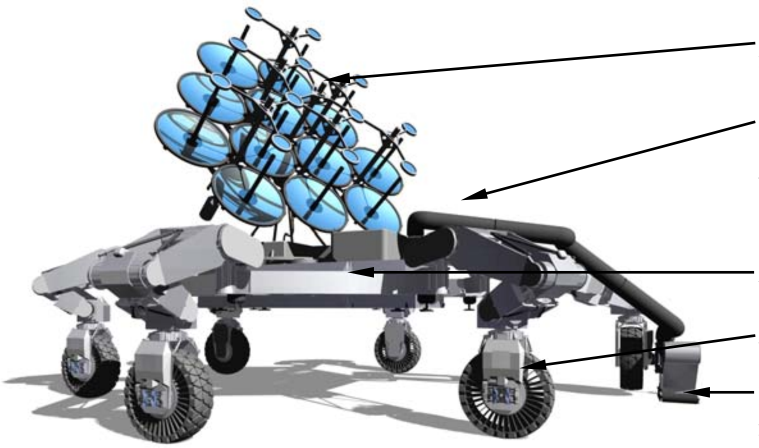

Figure 14: Solar concentrator power system: solar concentrator parabolas (Nakamura & Smith 2011) can be mounted on ATHLETE or the overlooking crater rim, with power beamed back to ATHLETE or location

A. FACS Additive Construction System

A Freeform Additive Construction System (FACS) would 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 (Howe et al, 2013; Howe et al, 2014). The FACS system is an additive manufacturing system that would be 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. A microwave printhead concept could use powder regolith fed through a material handling system, where volatiles can be extracted at the same time as the regolith is being heated for additive construction purposes (Figure 16).

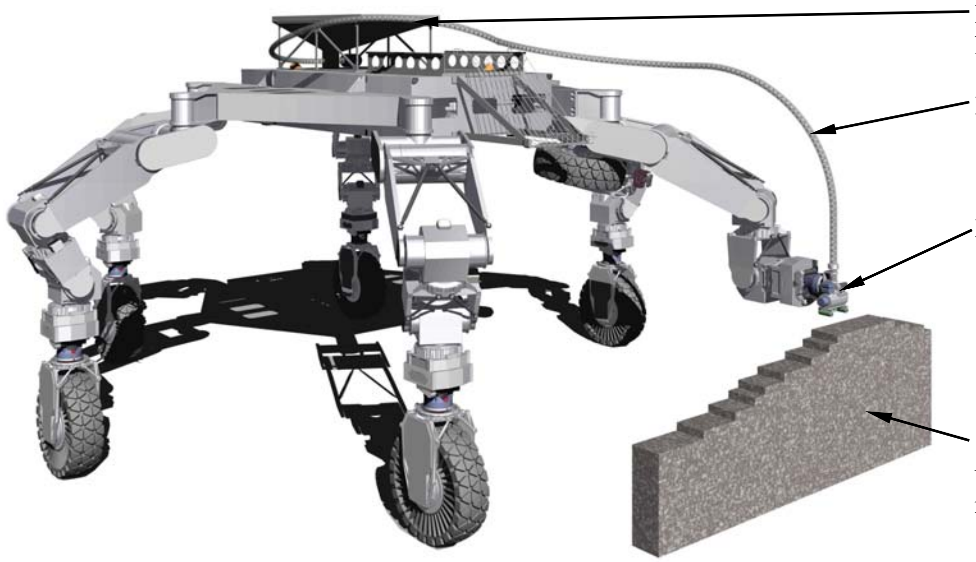

Figure 15: Freeform Additive Construction System (FACS)

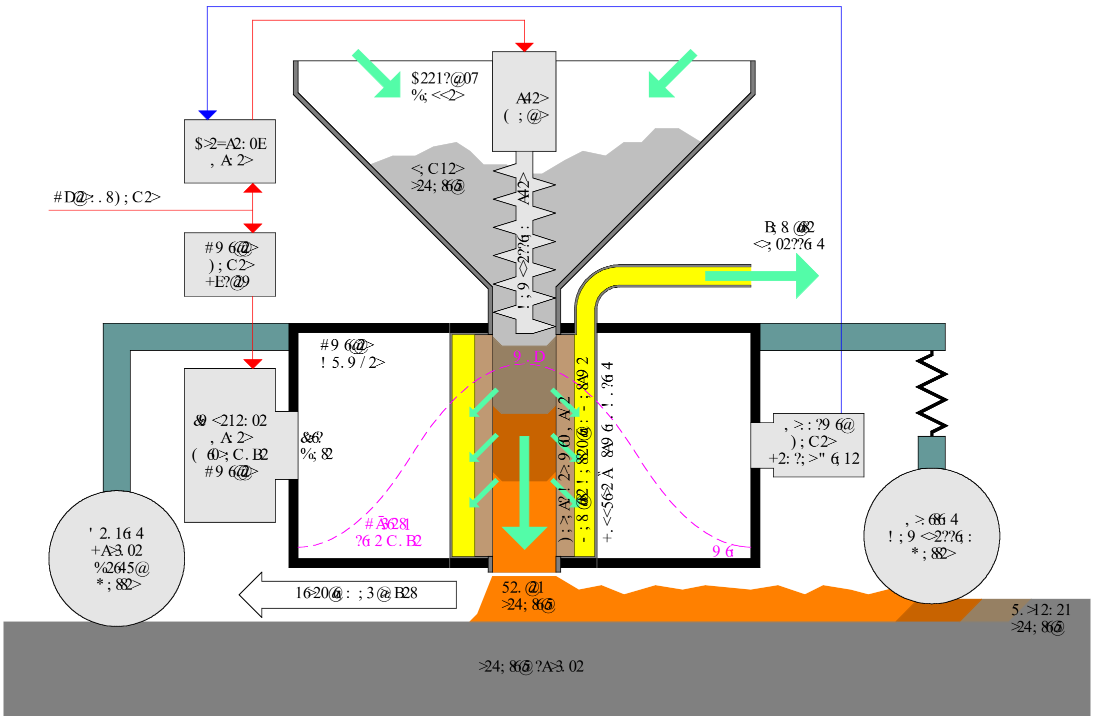

Figure 16: Microwave print head for large-scale 3D regolith structures: regolith is heated/melted in a tube while at the same time volatiles are collected through porous ceramic for further processing; Heated regolith can be deposited in layers for paving or "printed" as large-scale structures such as walls or berms

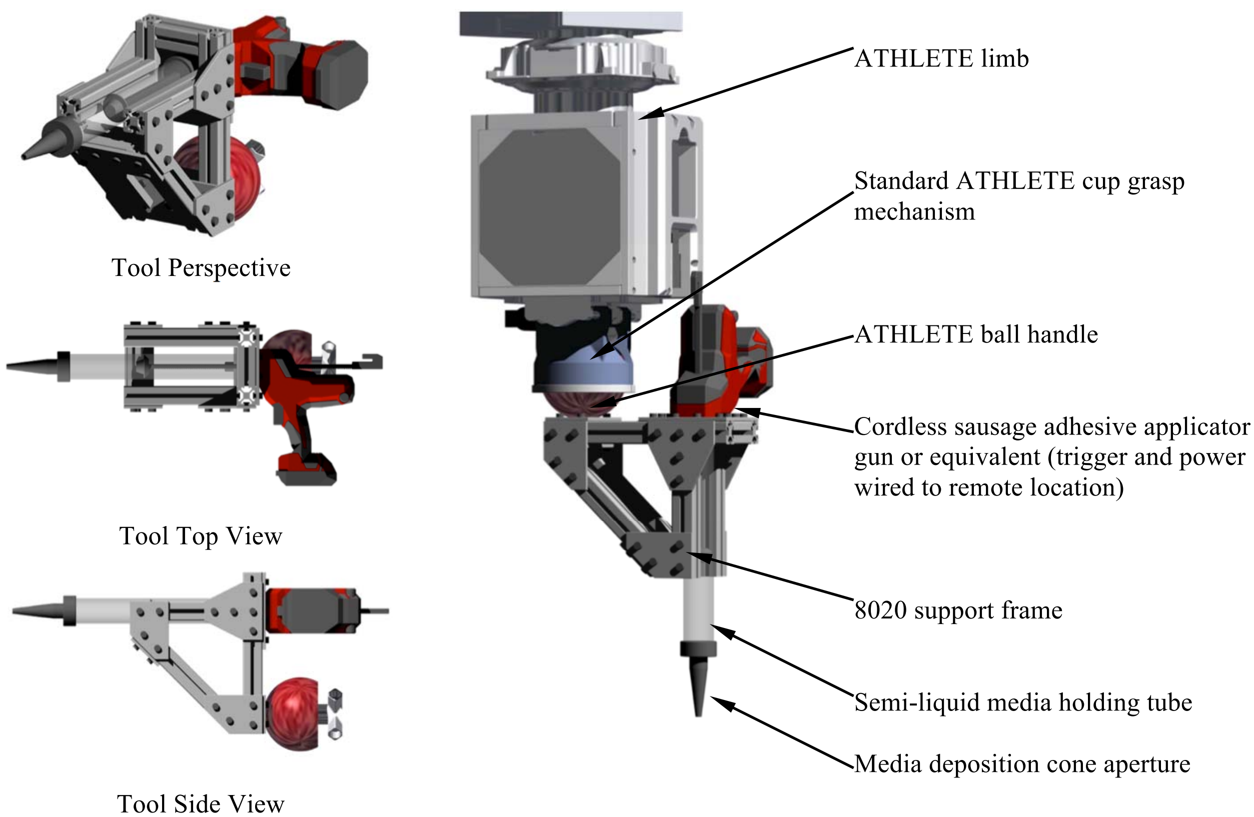

Figure 17: Design for a "Fountain Pen" printhead using simple off-the-shelf parts

A demonstration printing system was devised that uses a dip, charge, and apply cycle similar to how a fountain pen is recharged from an ink well. Preliminary designs for a working prototype called for a cordless sausage adhesive applicator gun to be attached via standard ATHLETE cup grasp mechanism to an ATHLETE limb (Figure 17 and Figure 18). The operational scenario is for ATHLETE to move the limb into a media tank "ink well", suck up material into the "fountain pen", then move over to the proposed structure location and start depositing material. The cycle would repeat itself until many layers of material are built up into the target structure. The media tank could be replenished periodically as needed.

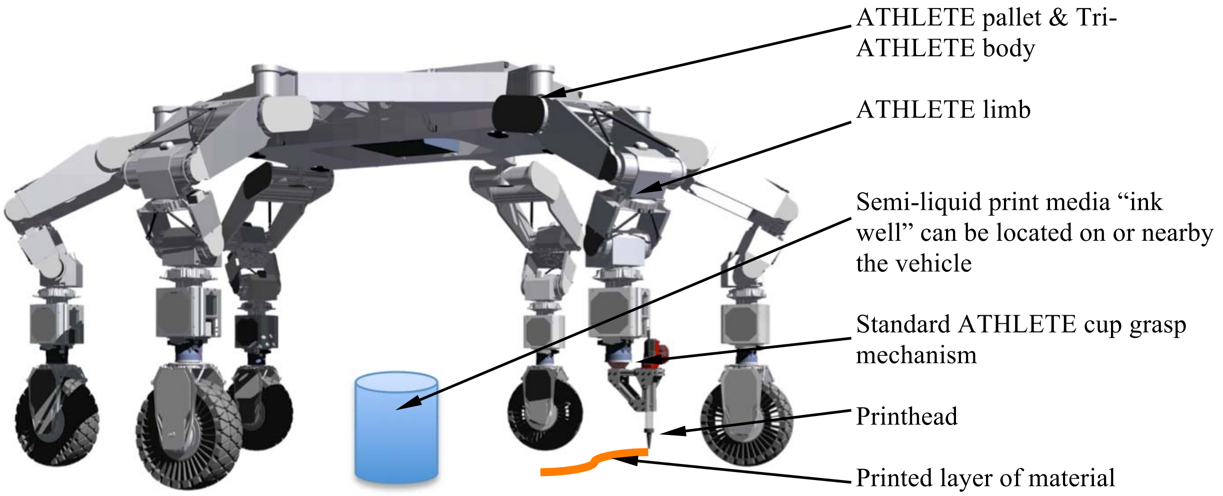

Figure 18: Diagram showing ATHLETE "fountain pen" printhead with media tank "ink well"

The actual implementation of the ATHLETE "Founten Pen" printhead demonstration occurred in August 2015 during a Keck Institute for Space Studies workshop, with all workshop attendees present. Figure 19 is a view of ATHLETE printing concrete material (see inset of Figure 19) on a simulated lunar landscape.

Figure 19: Demonstration of ATHLETE as a large scale 3D printer using a "fountain pen" printhead

B. ISRU Prefabricated Panel Factory

A modular prefabricated panel factory concept has been conceived for an ATHLETE portable robotic constructor.

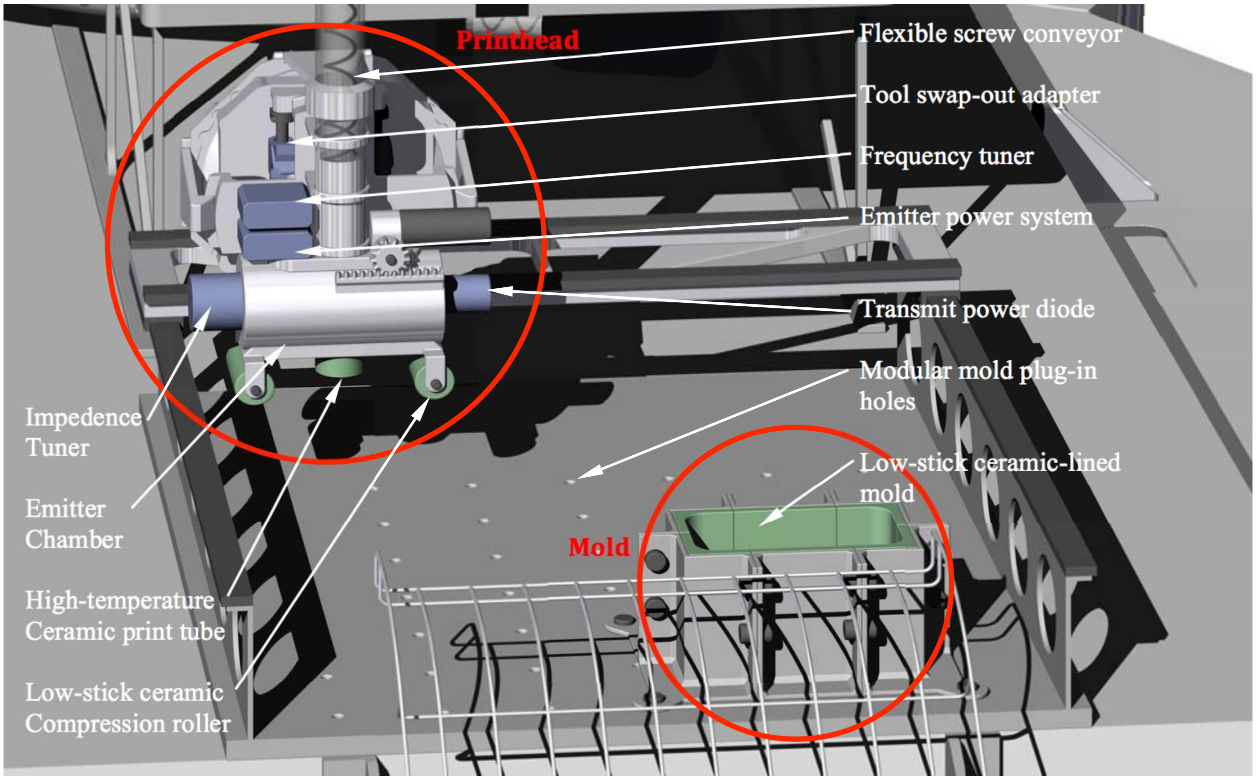

Figure 20: ISRU panel factory components

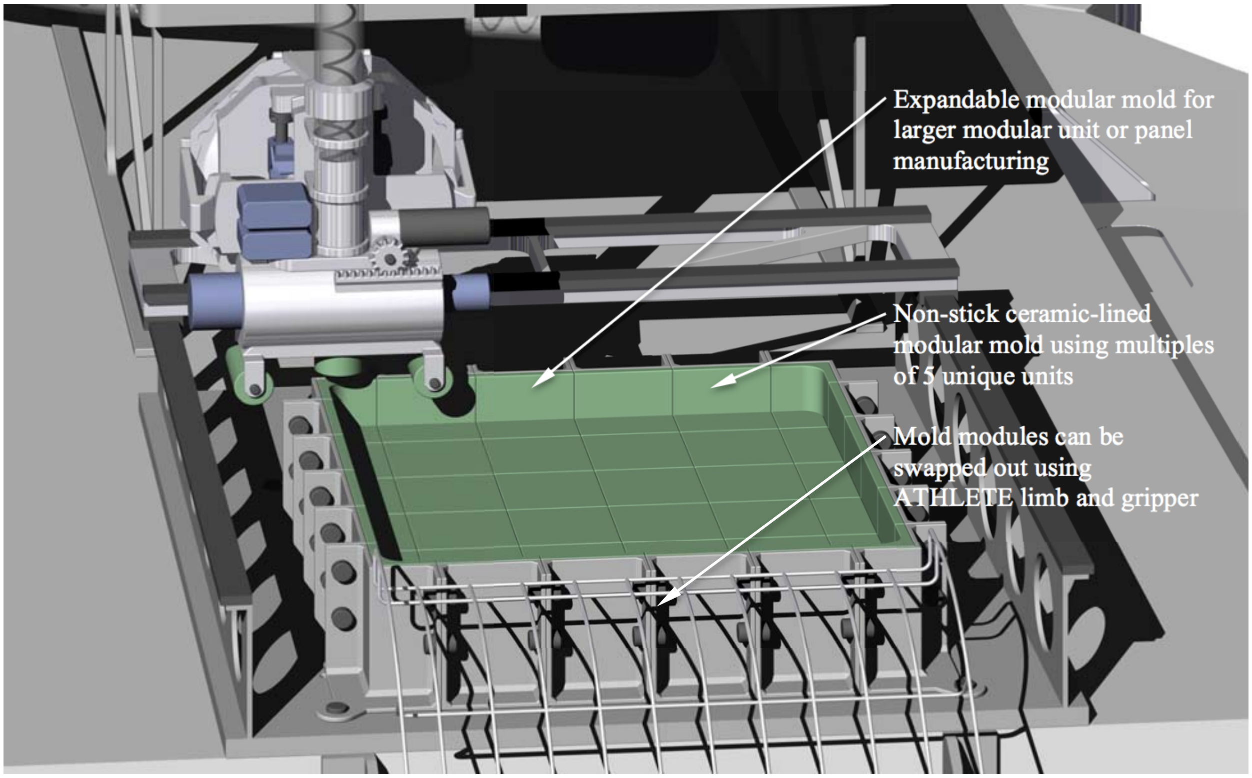

Figure 21: Modular brick / panel mold system

The factory consists of an ATHLETE limb fitted with a manipulator or gripper, factory apparatus, and wire rack receiver (Figure 22). The factory apparatus consists of a modular mold with plug-in holes, low-stick alumina or ceramic-lined mold modules, mold base actuator, printhead (microwave, solar concentrator, or liquid extrusion), and flexible screw conveyor for material handling (Figure 20). X-translation is achieved by the printhead actuated on a rail, Y-translation has the rail moving perpendicular, and Z-translation consists of a vertically actuated mold bottom.

Modular mold units include corner, edge, and field pieces, where ATHLETE's gripper can select among multiple modules to plug into the base and create small brick-sized, or larger panel-sized molds (Figure 21). The operation of the panel factory would begin with the placement of the mold pieces and the mold bottom raised to the top. The printhead would lay down material in a uniform layer on the mold bottom. Once a layer has been set down, the vertical actuators lower the mold bottom incrementally to allow for another layer. The process repeats itself until a sufficient number of layers have been set into place the the panel is complete. Next the vertical actuator raises the mold bottom again until the panel is entirely above the mold walls. The printhead then breaks the panel loose from the mold bottom, sending it sliding down the wire rack receiver (Figure 22). Finally, as a new panel is being printed, the ATHLETE gripper or manipulator takes the panel out of the rack and places it in its target location. Figure 23 shows ATHLETE placing a small printed modular unit onto a wall.

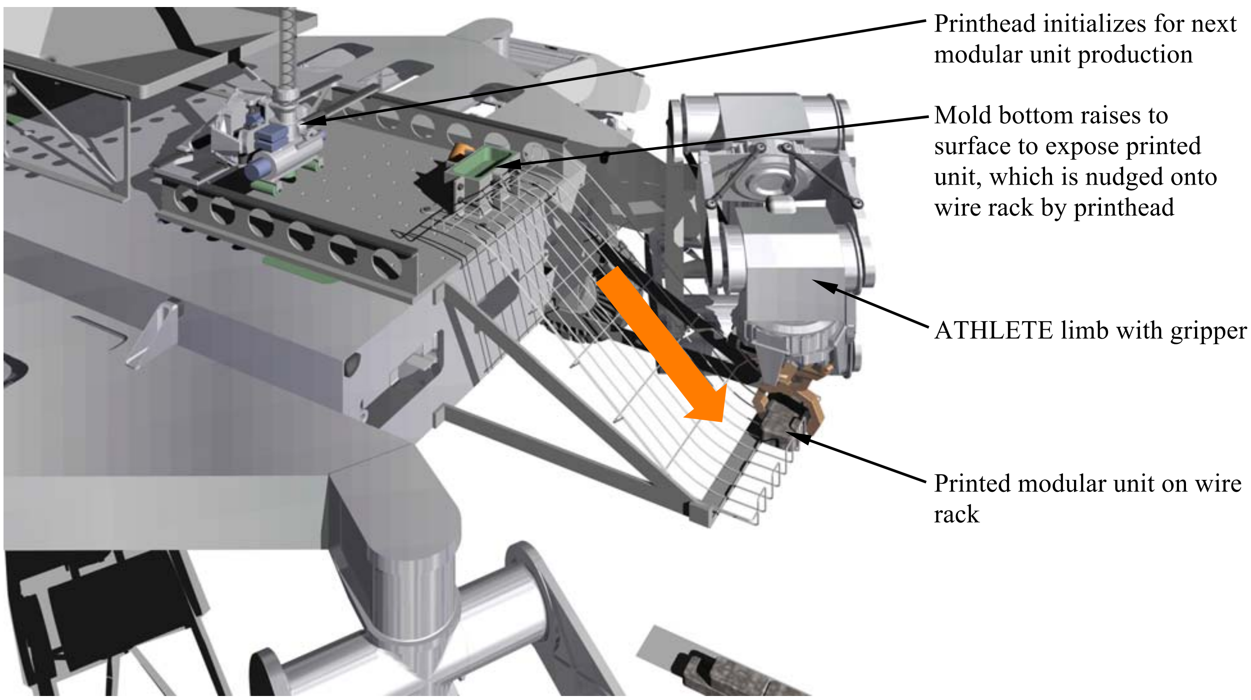

Figure 22: Panel manufacture process

The additive printing of modular units provides a quick way of using native soils and materials for the construction of outpost infrastructure. Modular units can function as foundational compressive structures that can be configured into surface paving, walls, berms, and can also be used for the construction of vaults, domes, and roofed structures. Since additive manufacture of building panels can be done in advance, structures can be assembled quickly and additional regolith loosely piled on top for radiation shielding.

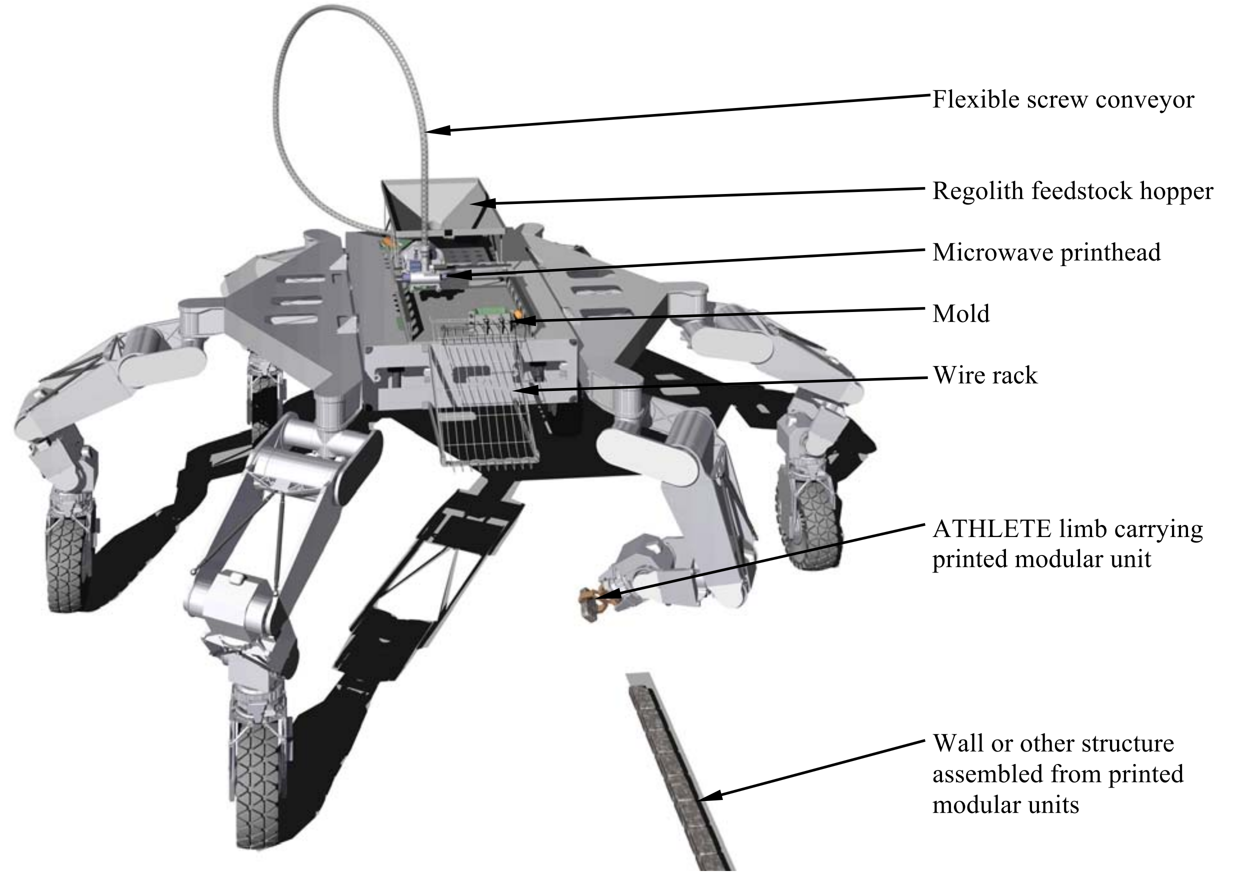

Figure 23: Brick / panel placement

C. Simple Additive Regolith Construction Functions

A variety of tools have been conceived that would be useful for ATHLETE as a remote construction vehicle. Multiple tools can be stowed on a "tool belt" (Wilcox et al, 2007; Wilcox 2012) where each tool is accessible via an ATHLETE limb. Figure 24 shows an ATHLETE limb stowing the mobility wheel underneath itself, with tool belt mounted with smaller tools.

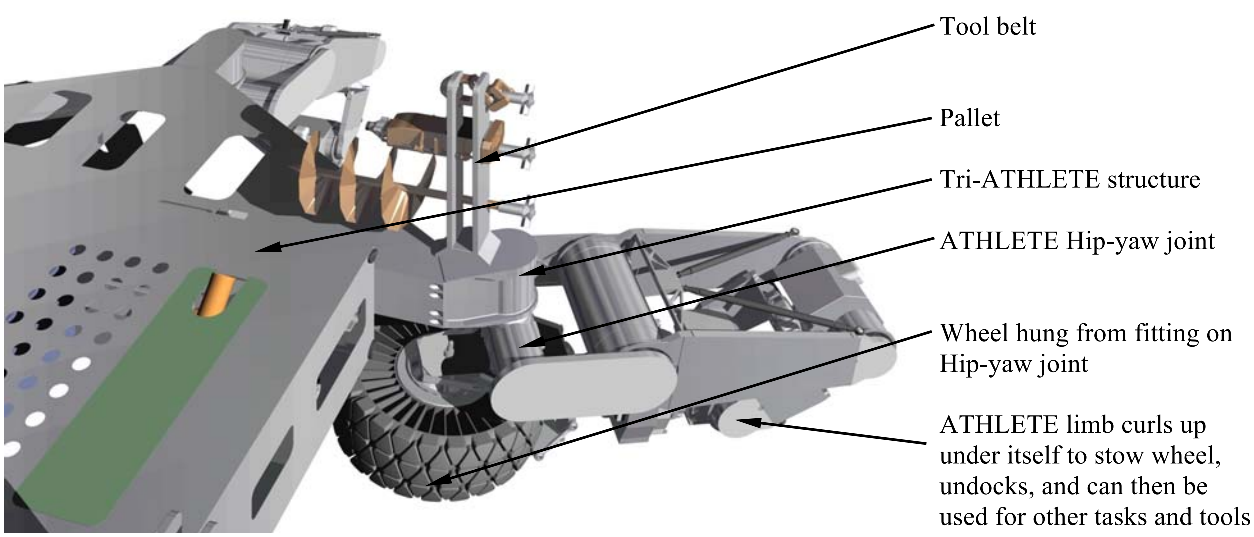

Figure 24: ATHLETE wheel stow for tool manipulation

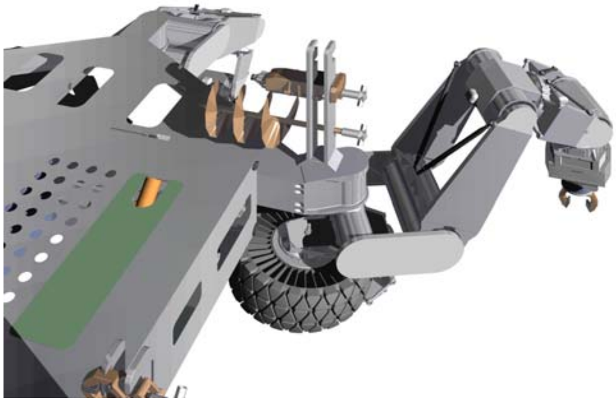

Figure 25: ATHLETE gripper / manipulator tool

Figure 26: ATHLETE auger drill tool

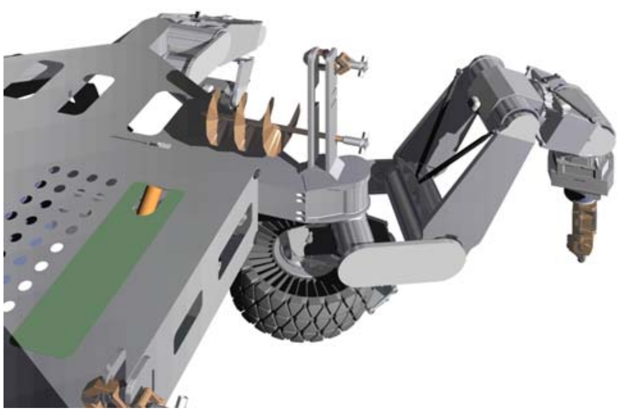

Figure 27: ATHLETE impact drill tool

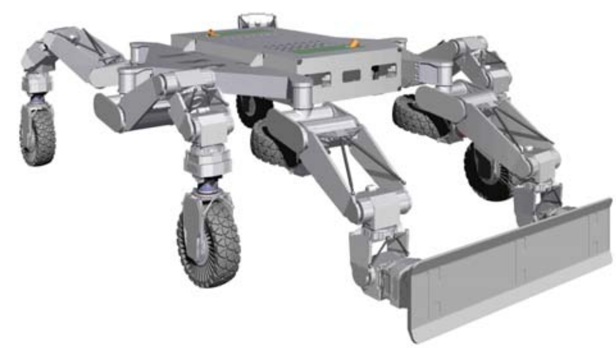

Figure 28: ATHLETE dozer blade can be set on the surface near the outpost to be retrieved when needed. Note wheels stowed underneath body

Figure 29: ATHLETE backhoe shovel can be stowed on Tri-ATHLETE frame or set on the surface for future retrieval

Figure 30: Simple regolith moving tool -- the "snow blower" uses an internal high-speed auger to throw regolith on top of structures

ATHLETE self retrieves a gripper (Figure 25), auger drill bit (Figure 26), and impact drill tool (Figure 27). In addition, a dozer blade can be manipulated by a pair of ATHLETE limbs (Figure 28) leaving four limbs for mobility, and Figure 29 shows a backhoe shovel attachment.

Unpressurized garages can be constructed using prefabricated panels either manufactured on board ATHLETE or on the ground using tilt-up construction techniques (Howe et al, 2014). Once these hard structures are in place, the balance of thick regolith needed for radiation shielding can be scooped up on top of the garage. One tool that might be helpful in loading loose regolith up onto a heap might be a “snow blower” tool, shown in Figure 30 as a high-speed auger in a cylindrical casing (other designs are possible and would need further design and testing to see if there is an efficient design that can take advantage of powder material in low gravity.

IV. Future Considerations

The number and types of tools that can be manipulated by an ATHLETE limb are limitless, depending on the operational scenario that they would be needed. Also, specialty pallets (the ATHLETE rectangular body) can be designed for a variety of purposes including ISRU plant, construction truck, and 3D additive construction platform. Using modular drop-off sub-pallets, ATHLETE can carry relay power stations for beamed power that it can drop off in the sunlight to allow it to work in a dark crater. Additional pallets fitted with nuclear fission power plants and cables can be carried to a remote location – on the way out ATHLETE digs a shallow trench using a backhoe device, then drops the pallet behind a ridge from where the target outpost will be located, and buries the trench on the way back. A mobile ISRU / construction function will be a critical piece of equipment needed for the construction of long-term infrastructures, outposts, and science installations.

Acknowledgments

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