

Zero Launch Mass Three Dimensional Print Head

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ABSTRACT

NASA's strategic goal is to put humans on Mars in the 2030's. The NASA Human Spaceflight Architecture Team (HAT) and NASA Mars Design Reference Architecture (DRA) 5.0 has determined that in-situ resource utilization (ISRU) is an essential technology to accomplish this mission. Additive construction technology using in-situ materials from planetary surfaces will reduce launch mass, allow structures to be three dimensionally (3D) printed on demand, and will allow building designs to be transmitted digitally from Earth and printed in space. This will ultimately lead to elimination of reliance on structural materials launched from Earth (zero launch mass of construction consumables). The zero launch mass (ZLM) 3D print head project addressed this need by developing a system that 3D prints using a mixture of in-situ regolith and polymer as feedstock, determining the optimum mixture ratio and regolith particle size distribution, developing software to convert g-code into motion instructions for a FANUC robotic arm, printing test samples, performing materials testing, and printing a reduced scale habitable structure concept. This paper will focus on the ZLM 3D Print Head design, materials selection, software development, and lessons learned from operating the system in the NASA KSC Swamp Works Granular Mechanics & Regolith Operations (GMRO) Laboratory.

INTRODUCTION & BACKGROUND

Shelter is a fundamental need for humans and equipment operating in extreme environments. The space environment on solar system bodies such as the Moon, Mars and asteroids is harsh and unforgiving, requiring special measures to be taken above and beyond what is typically required in extreme environments on Earth, such as at the polar regions, deserts and high altitudes. In space, vacuum, radiation, large thermal swings, micrometeorites, rocket plume blast effects at launch/landing, night conditions, dust storms, levitated dust, Mars weather, and topography are just some of the extreme factors that must be mitigated to ensure successful long term human and robotic operations.

Construction of appropriate structures such as landing pads, blast protection berms, roads, dust free lots, shade walls/structures, hangars and habitats will be necessary for a long term and sustainable presence in space which will ultimately lead to the

expansion of human civilization into the solar system. Due to the high level of logistics needed and the high cost of launching mass out of Earth's gravity well, it will not be practical to bring the materials from Earth. However, if we take advantage of the vast amounts of indigenous resources as construction materials, it will be possible to build the necessary infrastructure to provide shelter and other mitigations to the extreme environments with substantially reduced logistics and affordable costs. Since technological solutions based on robotics and advanced materials are being developed, the indigenous construction materials can be emplaced with automation and eventually even autonomy. One example of the radically improved technologies that are emerging is three dimensional automated additive construction (3DAAC) also known as 3D printing with concrete, mortar and basalt or other rock based composite types of materials.

This paper describes a NASA proof of concept project at the Kennedy Space Center Swamp Works laboratory which developed regolith based polymer concrete composite materials and robotic terrestrial laboratory prototypes which will eventually enable 3DAAC on solar system bodies that have regolith readily available in granular form at the surface. Specifically, it focuses on the development of a 3D print head mechanism that can be attached to a robotic positioning device such as a robot arm or a gantry system. The term zero launch mass (ZLM) is used to indicate that all feedstock materials used shall be indigenous, therefore requiring zero launch mass for construction materials from Earth, after the initial delivery of the 3DAAC system.

ADDITIVE CONSTRUCTION WITH MOBILE EMPLACEMENT (ACME)

NASA shares many requirements with the US Army Corps of Engineers (USACE) regarding shelter required for troops in forward bases and astronauts living on another planetary surface. Habitation is provided for the troops in the form of rectangular barracks structures measuring 32 feet long by 16 feet wide and 8.5 feet high. Each barrack is known as a "B-hut" and can house up to 16 soldiers at a time – primarily for sleeping at night and shelter from the weather elements. Currently the B-huts are constructed of plywood and are demolished and burned when the forward base is no longer needed. All construction materials must be flown in from the United States resulting in high costs and substantial logistics. The USACE has a goal of providing better shelter for the troops, with increased insulation values, higher resistance to incoming projectiles, rapid construction and long term value by either re-purposing the B-huts into schools, hospitals, community centers and other useful infrastructure or by recycling the materials to be used in printing more B-huts or other useful structures. The USACE desire is to use indigenous materials to avoid long range transportation of the construction materials.

These needs are similar to the needs of astronaut crews working in space, so in a joint project with the USACE, NASA has developed a deployable robotic gantry system to prove feasibility of the 3DAAC concept on Earth, which will lead to 3DAAC solutions in space, Mueller (2017). The system is known at NASA as Additive Construction with Mobile Emplacement (ACME) or at the USACE as Automated Construction of

Expeditionary Structures (ACES), and it uses an ordinary Portland cement (OPC) concrete slurry to 3D print with a pump, hose and a nozzle that is positioned by a robotic gantry with three degrees of freedom. The OPC concrete is extruded through the nozzle and emplaced in successive horizontal layers under computer control from a 3D digital model to build a structure. It is not impossible, but difficult to make OPC concrete on planetary surfaces (Moon, Mars), since it requires many ingredients and water which is a precious commodity in the inner solar system. An alternative is to use waterless thermoplastic polymer concrete composites, which can be printed on demand with reduced logistics compared to OPC concrete. The thermoplastic binder can be synthesized from resources in space or recycled from available mission materials such as packaging while the aggregate consists of regolith. The ZLM print head can be retro-fitted onto the ACME gantry robot to show how it could 3D print large structures in space. Initial testing has focused on the use of the ZLM print head on a commercially available robotic arm at the KSC Swamp Works GMRO laboratory.

ZLM PRINT HEAD GOALS

The goal of the ZLM project is to demonstrate the concept of 3D printing habitable structures using ISRU (mostly regolith) materials by 3D printing a proof of concept, structurally sound, one piece, one meter diameter dome using no support structure. In order to accomplish the print, a 3D printing system was developed using a commercially available industrial robot arm. The print head which is required to extrude a polymer composite concrete material is not commercially available, so it was developed in house at the NASA KSC Swamp Works. This paper focuses on the ZLM 3D Print Head design, materials selection, software development, and lessons learned from operating the system in the Swamp Works GMRO laboratory.

ZLM PRINT HEAD REQUIRMENTS & KEY PERFORMANCE PARAMETERS

Table 1 provides the requirements for the ZLM Print Head.

Table 1. ZLM Print Head Requirements

Number	Description	Specification	Rationale
ZLM-01-001	Printed structure shape	The printed structure shall be a one-piece, one meter diameter, half meter tall dome using no support structure.	Demonstrate the capability to build habitable structures.
ZLM-01-002	Printed structure strength	The printed structure shall be self-supporting.	A structure is not useful if it is easily collapsible. It requires a certain reasonable level of strength.
ZLM-02-001	Material composition	Printing material shall consist of at least 70% ISRU materials.	To fulfill the claim to be zero launch mass, the majority of the material needs to be ISRU, with only a small amount being derived from items

			that are already being flown on the mission (such as trash).
ZLM-02-002	Material additives	Printing feedstock must consist of materials that can be derived from in-situ resources which includes but is not limited to trash.	To fulfill the claim to be zero launch mass, the majority of the material needs to be ISRU, with only a small amount being derived from items that are already being flown on the mission (such as trash).
ZLM-02-003	Regolith simulant	The regolith printing material shall be Black Point-1 (BP-1) basalt lunar regolith simulant.	BP-1 is a high fidelity physical regolith simulant that is readily available in the Swamp Works Lab.
ZLM-03-001	Automation	The print process shall be fully automated.	Demonstrates the concept of printing habitats without human involvement.
ZLM-03-002	Robot arm	The print head shall mount to the FANUC robot arm to perform the printing.	Allows for printing automation demonstration with a robot arm readily available in the Swamp Works Lab.
ZLM-04-001	Print head	The print head hopper can be refilled by a batch process.	The print head needs to be able to build a significant structure without operator action other than refilling the hopper.
ZLM-04-002	Extrusion tube heating temp	The print head shall have the capability of printing with the following polymer additives: LDPE, HDPE & PET.	There are useful applications with these different polymers and will be most beneficial to test them all with this print head rather than creating new ones.

Table 2 provides the Key Performance Parameters for the ZLM Print Head.

Table 2. ZLM Print Head Key Performance Parameters (KPP)

Performance Parameter	State of the Art	Threshold Value	Project Goal
ISRU printing material from extraterrestrial bodies	None	Successful 3D printing with a material that is at least 70% ISRU	100% ISRU material made of 85% regolith & 15% PE
3D printing overhangs	Utilize support material	Print a one piece, one meter ogive without support material	Print a one piece, one meter dome with no support material

ZLM PRINT HEAD DESIGN

The ZLM Print Head was designed to hold and extrude a regolith/polymer mixture in a Fused Deposition Modeling (FDM) additive manufacturing process (Mueller, 2015). The print head interfaces with a FANUC M-410iC/185 robotic arm which provides four degrees of freedom (X, Y, Z, and rotation about Z) to move the print head around the print volume. The maximum print height is 5.5'. Figure 1 shows Computer Aided Design (CAD) renderings of the print head, print head cross section, and print head integrated onto the FANUC robotic arm. Figure 2 shows images of the ZLM print head. The print head has five major components; structure, a feeding and conveying system, a heater, a fume extractor and a dry air purge system. The system was designed in accordance with NASA STD 5005D.

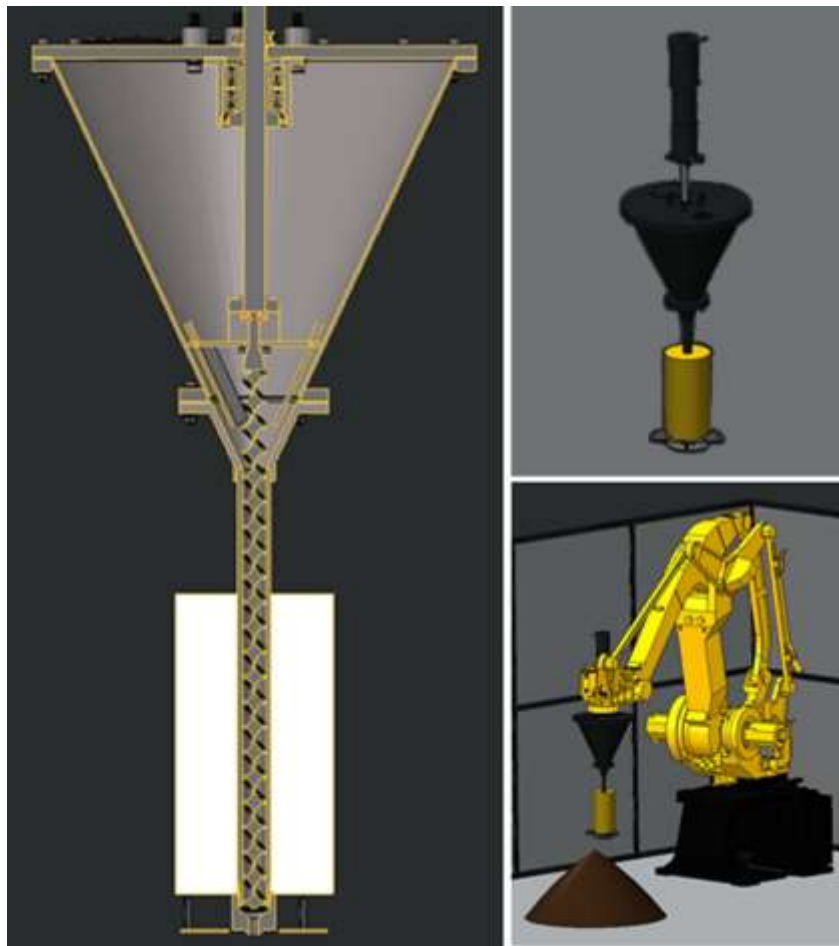


Figure 1. ZLM Print Head CAD Renderings

The print head structure consists of a hopper, a barrel, and a nozzle.

The hopper is designed to hold the raw materials and assist in supplying the feeding and conveying system. The hopper interfaces with the robotic arm via a bolted connection between the hopper upper plate and the wrist joint. The hopper upper plate has a sealable access port for supplying raw materials and a HEPA filter vent. The

conical section of the hopper has a bolted interface with the upper plate and was designed at a 65 degree slope angle which is greater than the angle of repose for the primary raw material, BP-1. The lower portion of the hopper interfaces with the barrel via a bolt hole pattern.



Figure 2. ZLM Print Head

The barrel has a small cone with an upper flange for bolting to the hopper. The cone has a steel schedule 80 pipe welded to the bottom. The pipe has a heated zone in which the raw materials are melted and mixed as they progress towards the nozzle via the feeding action of a feed screw running down the inside of the pipe. The bottom of the pipe has a threaded 1" NPT male interface.

The print head has several nozzles of varying diameter from $\frac{1}{4}$ " to $\frac{15}{16}$ ". The nozzles were made by modifying 1" NPT steel pipe caps to have a hole along the central axis and an internal and external chamfer. Additionally, there is a threaded bolt hole pattern

on the nozzle which interfaces with a bracket that holds ventilation system tubes and cooling fans.

The feeding and conveying system is designed to move raw materials from the hopper, through the heating and mixing zone in the barrel, and out of the nozzle. The feeding and conveying system is powered by a Midwest Motions motor/gearbox with an Elmo SimplIQ Cello motor controller providing closed loop velocity control and over current protection. The motor/gearbox is coupled to a drive shaft that runs through the pass through hole in the center of the FANUC wrist joint and into the hopper. There are angular contact ball bearings pressed into a housing that is bolted to the upper hopper plate that react thrust and radial loading of the shaft. The housing is sealed so that BP-1 does not contaminate the bearings. A flange is welded to the bottom of the shaft which interfaces with a shaft adapter and an agitator with a bolted connection. The agitator consists of two paddles that rotate with the shaft and fluidizes the bulk material at the bottom of the hopper. The feed screw interfaces with the drive shaft via female and male hex features on the shaft adapter and feed screw. As the feed screw rotates, bulk material flows into the flutes and is conveyed down the barrel. The material reaches the heated zone on the barrel which melts and mixes the bulk materials. The material continues to be driven downward by the feed screw and is deposited into a cavity above the nozzle. The continuous flow of material fills up the cavity and forces the material out of the nozzle.

The heating system has resistive heating wires wrapped around the bottom ~12" of the barrel. Four thermocouples are located along the length of the heat zone between the heating wires and barrel. The heat zone is wrapped in furnace batting insulation. The temperature is controlled via a Watlow heater controller.

The fume extraction system is used to exhaust any fumes produced during the extrusion process to the outdoor environment for personnel safety reasons. Three two inch air hoses are attached near the nozzle opening and run up the structure to a manifold that combines the hoses into one four inch hose. The hose is routed along the arm and then outside to an exhaust chimney. Two duct boost fans are used to provide air flow through the tubes.

The dry air purge system is used to eliminate moisture in the air inside the hopper. It is only used when polyethylene terephthalate (PET) based pellets are used as the raw material to prevent moisture absorption into the pellets. A high efficiency particulate air (HEPA) filter vent built into the hopper exhausts the air into the lab environment. Cleaned and dried facility shop air is flowed into the hopper to provide a continuous supply of dry air at no greater than five psi. The shop air is regulated at the facility port.

ZLM CONSTRUCTION MATERIALS

Previous efforts at the KSC Swamp Works have focused on using 100 % regolith materials in a sintering process (Mueller, 2014). In this research, the team investigated

using polymer concrete composite materials. The ZLM print head uses two types of materials for printing, one is a mixture of BP-1 regolith simulant and High Density Polyethylene (HDPE) powders. The other is pelletized basalt glass fibers and Polyethylene Terephthalate Glycol (PETG). Initially, the team focused on BP-1 and HDPE powder because regolith is readily available on planetary surfaces and HDPE can be synthesized from resources in space (especially Mars) using the Fischer-Tropsch method or re-cycled from available mission materials such as packaging. Eventually the project refocused on the use of the PETG/basalt glass fiber pellets because of numerous advantages including better material properties and processing characteristics. Additional information on the benefits of pelletized basalt glass fibers and PETG is provided in the lessons learned section of this paper.



Figure 3. BP-1/HDPE Powders (Left) and Basalt Fibers/PETG Pellets (Right) Feedstocks and Typical ZLM Print Head Extrusions

ZLM ROBOTIC SYSTEM FOR LAB TESTING

The robot used to position the ZLM Print Head is a commercially available FANUC M-410iC/185 palletizing robot. It is an industrial robot designed for high volume production to palletize heavy products fast and efficiently. It has four axes and a payload capacity of 185 Kg (407 lbs.). The three major axes (X, Y, and Z) can be moved at speeds up to 140°/s and the rotation axis at the wrist can move at 305°/s. The maximum reach height of the robot is 3143mm (124 inches). The control system is a Fanuc R-30iB A-Cabinet Controller with a graphic iPendant.

During development activities, the limited number of axes of this robot was a project drawback as it constrained the print head motion to a horizontal plane which hindered development of unsupported 3D printing and other innovative project approaches. The

eventual goal is to be able to 3D print in any plane and direction which would require six degrees of freedom for positioning the ZLM nozzle

ZLM SYSTEM SOFTWARE

One major objective of additive construction processes is to provide a universal manufacturing process for a variety of parts and structures. In order for the 3D printer to be an effective tool it must be able to print files generated by industry standard CAD software. The current industry accepted process to do this is to export your part or model as a Standard Tessellation Language (.stl) file and use a “slicer” to generate a numerical control programming language g-code file. Many open source and commercial software packages exist to “Slice” a model. Slicer software divides a 3D model into 2D cross sectional “slices” of the model at a given interval. Each cross section is taken at a configured layer height and a toolpath is generated for the 3D printing system to follow as it extrudes the layer. Each layer’s toolpath is then concatenated into one final program and formatted as a g-code program that is accepted by 3D printer machine drivers.

Since the ZLM Print Head is attached to an industrial robot, custom software, control systems, and work flows were required to provide a method of driving the robot with an adequate and accurate toolpath.

The open source software package called “Slic3r” was used for this project. Custom configuration files were made to parameterize the print and extrusion characteristics. The key slicer configuration settings are outlined below.

Table 3. Key Slicer Settings

extrusion_width	18 mm
layer_height	5 mm
nozzle_diameter	9.5 mm

Since the FANUC R-30iB industrial robot controller cannot interpret g-code, a method of translating g-code into usable commands for the robot was required. There are many options for driving the FANUC industrial robot. Each method had pros and cons, but none are well suited to additive manufacturing. The following two methods were investigated:

1. Teach Pendant Program - FANUC Teach Pendant programs are the simplest programming option for the robot. These programs can be manually taught using a handhold teach pendant controller or saved as a list of teach pendant commands to a file and loaded to the robot. Teach Pendant (TP) commands offer a few advantages. First, they automatically make use of a FANUC “look ahead” feature. When executing a movement command, the FANUC will consider subsequent commands and the current motion parameters to plan the motion in an optimal way. When tuned properly, this feature can help create smooth, constant velocity toolpaths for the print head. TP programs also give

easy access to the robot controller's input/output (I/O) capability, which is used to control the print head's extrusion motor. They also allow for easy timing and synchronization of motion and I/O control.

The major disadvantage to TP programs is their use of robot controller memory. In order to execute a TP program, the entire program must be loaded to the r30ib controller. The controller has limited memory size of 2 Mega Bytes (MB), imposing a substantial constraint to the size of a print. Additionally, prints involving a significant amount of curved geometry will use up more memory as curves are broken into many small line segments in the g-code.

2. Socket Messaging/ ROS Driver - The Robot Operating System (ROS) Industrial Consortium has developed an open source ROS driver for FANUC robots. The driver consists of a custom KAREL program that is loaded and run on the FANUC robot controller. The program makes use of the "Socket Messaging" option that can be installed on the robot controller. The driver accepts messages over the robot controller's network connection. Each message contains a robot pose message, a list of joint positions in radians. The KAREL driver parses this message and creates a Position Register in the robot's memory. It then calls a standard teach pendant program to initiate a joint movement to the angles stored in the position register. The ROS industrial consortium supported the project by modifying the open source ROS FANUC driver to add a capability of messaging Cartesian coordinates to the robot. The modified driver accepts messages containing XYZ coordinates and uses the robots built in motion commands and kinematics to move to the position.

This method provided the benefit of being able to stream points in real time to the robot, circumventing the memory limitations on the robot controller. However, suitable motion was unachievable with this driver setup for a number of reasons. First, the driver can no longer make use of FANUC's look ahead function, which was essential to achieving smooth motion and constant velocity. Additionally, the driver architecture introduced timing difficulties when attempting to synchronize commands being streamed in real time.

After testing several configurations, it was determined that using Teach Pendant programs were the only feasible way to meet the project goals within the required project timeline. Making use of the look ahead function and finely tuned motion parameters, smooth motion and constant velocity were possible. Without these features, the robot was forced to comply with an acceleration/deceleration limit between each point, making for a very inconsistent speed and causing jerky motion and vibration when moving through fine point segments. By using the termination type called "corner radius" and an appropriate linear motion command, the robot could move through points without having to fully stop or decelerate at each coordinate in a line segment. This created a constant velocity toolpath and smooth motion.

In order to preserve a seamless workflow of printing any sliceable model, custom software was developed to parse g-code files and compile an equivalent Teach Pendant program with the optimized motion commands. The software had the following functions:

1. Provide a GUI for all operation and configuration of the software tool.
2. Parse the g-code and extract G1 commands containing motion or extrusion into a toolpath array.
3. Allow the user to shift the print to the appropriate robot tool frame, placing the print in any location in the robots workable area.
4. Do a safety check to ensure that the print does not exceed a defined work area
5. Allow a user to configure the following parameters:
 - a. X,Y,Z center
 - b. Print speed (mm/sec)
 - c. Movement speed between extrusion (mm/sec)
 - d. Termination type of motion
 - e. Acceleration value (mm/sec²)
 - f. Feed system motor speed (rpm)
 - g. Pause times when starting and stopping extrusion
 - h. Enable/disable extrusion control
6. Provide an option to display a 3D plot of the compiled toolpath.
7. Generate appropriate analog output values and pause commands to control extrusion.
8. Compile the resulting program into a valid TP program.
9. Allow the user to save and load configurations for later use.
10. Display total print size and estimated print time.



Figure 4. FANUC TP G-Code Compiler GUI

In order to control extrusion speed and allow the starting and stopping of extrusion during the print, additional control hardware was required. The Analog Output Module (ADA02A) was purchased and installed in the FANUC controller. Each teach pendant program includes commands that control the voltage output on the analog output module. This signal is connected to an analog input on the Elmo motor controller. The motor controller is set to analog velocity control mode, and the voltage range is mapped to a corresponding motor speed. By changing the analog output value during each print program the extrusion speed can be controlled.

ZLM PROJECT RESULTS

The ZLM print head project successfully met the KPP. A one meter diameter ogive was printed without any additional support material using feedstock that was at least 70% ISRU derived. The maximum overhang angle of the ogive was 35 degrees from horizontal. It has been shown that flatter overhang angles, including printing horizontally, are possible without support material when using cooling fans. Further development needs to be completed to identify the optimum parameters for horizontal printing and incorporate cooling fan control algorithms. Completion of this development work will enable the printing of a dome and virtually any other part with overhangs.



Figure 5. Printed One Meter Diameter Ogive

ZLM PROJECT LESSONS LEARNED

A number of issues arose during the ZLM project leading to lessons learned:

1. **Eliminating Moisture In Raw Materials** – Both the BP-1/HDPE and basalt glass fiber/PETG feed stocks suffered issues with moisture absorption affecting the performance of the system. In the BP-1/HDPE powdered feed stock, BP-1 is hygroscopic. During the extrusion process, as the BP-1 heats up, the moisture is liberated and flows to the cooler regolith above the heated zone. The buildup of moisture causes changes the characteristics of the raw materials and makes it more cohesive which tends to block the flow of material down the feed screw. This leads to inconsistent extrusion rates.

The basalt glass fiber/PETG pelletized feed stock readily absorbs water which can lead to steam pockets forming in the heated zone of the extruder. The steam pockets lead to the extrusion rate becoming inconsistent. Additionally, PETG will hydrolyze when melted in the presence of moisture, this will yield a more brittle extrudate.

Thorough pre-drying of the raw materials and maintaining a dry environment while printing is sufficient to eliminate issues with moisture in the raw materials.

Reducing Friction in the Feed Screw – The ZLM print head feed screw motor experienced much greater torque requirements than anticipated with certain feed screw styles. This led to extruder jamming. Although this issue was never fully understood, single flight feed screws with greater flight thicknesses tended to generate more friction than dual flight screws with thinner flights. A commercial off the shelf (COTS) thin dual flight feed screw was used to reduce the friction in the system, but a custom design feed screw is being developed by an experienced vendor to create better mixing and extrusion performance.

Controlling Nozzle Temperature – Small changes in nozzle temperatures dramatically changed the surface characteristics of the extrudate. The nozzle was susceptible to changes in temperature from a number of sources including the heat zone temperature, extrusion rate, environmental temperature, air flow over the nozzle, insulation position, and extrudate buildup on the nozzle. The temperature variations produced three typical conditions of the system: nozzle too cold - material freezes in the nozzle and reduces the effective nozzle diameter; nozzle too hot - the extrudate adheres to the nozzle as it flows through creating a rough extrusion; and nozzle temperature just right – the extrudate flows with a smooth surface finish and consistent diameter. A second closed loop controlled heating zone will be added to the nozzle to eliminate temperature fluctuations.

2. Eliminating Warping and Cracking – When using the BP-1/HDPE feed stock printed structures tended to warp, crack and curl off of the built plate. This is a result of the relatively high thermal shrinkage ratio of HDPE.

PET has a much smaller shrinkage ratio and was used instead of HDPE to eliminate the issue. Further research should be completed in this area because it is possible to print HDPE structures in a thermally controlled environment. Furthermore, printing HDPE in a vacuum, like the surface of the Moon, may mitigate the warping and cracking issues, due to the very different heat transfer types in a high vacuum (mainly radiation heat loss), which slows it down.

3. Feedstock Form – Initially, the ZLM print head project focused on the use of powder feedstock. It was thought that using a powdered form of the materials would skip the compounding and pelletizing steps and provide a simplifying advantage. During the project a number of factors shifted the focus from powders to the use of compounded pellets:

- a. Pellets are the industry standard for plastics processing. Many forms of processing equipment already exists for pellets and can be purchased directly or leveraged for new designs
- b. Powdered polymers are hazardous due to explosion risks (on Earth)
- c. Finely powdered polymers and regolith can be the source of human respiratory hazards
- d. Quality and consistency of extrusions from compounded pellets is better than mixed powders
- e. Production of powdered HDPE is costly, time consuming and requires use of specialized equipment
- f. Handling of pellets is simpler and cleaner because mixing is no longer required.

4. Robotics Software and Drivers – The use of the lab’s existing FANUC industrial robot was required to stay within project budget. After testing and researching the available options to program and communicate with the robot, it was determined that the system was not ideal for the additive manufacturing use case. The robots lack of Application Programming Interfaces (API) and direct control options made it very difficult to tune and develop the system. Additionally, the low controller memory size imposed a limit on the size and detail of printing. Alternative industrial robot systems were investigated, and

Alternative industrial robots should be investigated. Important factors when looking for an appropriate system would be: increased degrees of freedom for more advanced additive construction techniques; a robust API and communications options for driving the robot; and low level access to robot functionality.

Controlling Tool Paths –Slic3r was very useful in many regards, however, it does not provide direct control or editing of the tool paths it generates. The Slic3r algorithms tended to produce irregularities in the toolpath and unnecessary start/stop extrusion points. This reduced the quality of the printed parts and introduced difficulties when printing at extreme overhangs. Alternatives to Slic3r should be investigated to provide greater control over the tool path.

ZLM FUTURE DIRECTION

The goal of the ZLM print head project was to create a “proof of concept” prototype print head to establish feasibility of 3D printing with polymer concrete composites derived from indigenous materials. The project started at technology readiness level (TRL) 2: technology concept and/or application formulated and is currently at TRL 3: analytical and experimental critical function and/or characteristic proof of concept established. The authors intend to keep advancing the TRL until the technology is a candidate for a space mission demonstration at TRL 6: system/sub-system model or prototype demonstration in an operational environment.

CONCLUSION

The ZLM print head prototype development is a sub-system under the NASA ACME and USACE ACES projects with the goal of proving that indigenous materials could be used in space and in theater to be deployed in forward bases. A ZLM print head was designed, fabricated and tested in the KSC Swamp Works GMRO laboratory using a specially developed polymer concrete composite material. Initial results indicate that it is feasible to 3D print infrastructure and shelters using a PETG / Basalt glass fiber material in pelletized feedstock form. This was proven by printing a one meter diameter ogive structure using the ZLM print head mounted on a FANUC M-410iC/185 industrial robot arm. Other material combinations using LDPE, HDPE, PETG and basalt regolith powder blended pellets feedstocks are planned but have not been implemented yet. The primary lessons learned are documented in this paper and will be addressed in the next generation ZLM print head design. The ZLM print head can be mounted on any suitable robotic positioning mechanism, such as the ACES 3 gantry 3DAAC robotic system, on other commercially available robot arms or gantry systems and innovative systems developed at other research labs.

Current development and testing results indicate a high level of promise for this technology which may provide mission planners with enabling new options for the construction of infrastructure in space. In addition there are substantial opportunities for terrestrial applications of 3DAAC which have the potential to reduce the cost of shelter and infrastructure on Earth, with rapid deployment.

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