Utility of Additive Manufacturing on Martian Analogs and Manned Mars Missions

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Abstract

A manufacturing capability is critical to a successful Mars mission. Breakdowns of important equipment are inevitable. The ability to manufacture replacement parts can reduce the number of spares required and therefor the cost of the mission. Unanticipated problems over the course of a long mission will require improvised solutions. A flexible manufacturing method like additive manufacturing allows the greatest variety of parts to be produced from the minimum of raw materials and equipment. This paper presents the results of an exploration of the potential utility of additive manufacturing, carried out during an eight-month Mars analog mission at the Hawai'i Space Exploration Analog and Simulation (HI-SEAS) habitat.

During the course of the mission more than 730 individual pieces were made, mostly based on the 60 or so parts designed by crew members. About 2/3 of these were practical parts (e.g. habitat repair/improvement, tools, scientific instruments) while the remaining 1/3 were fun parts (e.g. toys, presents for crew members, parts for games). In addition to the practical upsides there were less tangible benefits. Life during the mission was quite predictable and, surprises tended to be generally negative (e.g. systems breaking or not working properly). Especially during travel to and from Mars, monotony, boredom and depression have the potential to reduce team effectiveness/preparedness. The ability to manufacture presents and fun items (including ones made from digital files sent by family and friends on Earth) have the potential to increase moral. The ability to manufacture parts provided the crew with a sense of independence and satisfaction.

There are a few characteristics that make additive manufacturing well suited to this particular use. They produce minimal waste when compared to traditional subtractive manufacturing. The raw materials they require (generally filament, powder or pellets) tend to be easier to produce than the material required for subtractive manufacturing (larger blocks) as well, meaning local production or recycling of unneeded parts is more feasible.

The manufacturing was done on a consumer-level fused deposition modeling (FDM) type machine that can use a variety of plastics. While these materials were useful in a Mars analog, they aren't well suited to either the vacuum of space or the environment of the Martian surface due to extreme temperatures and low pressures. There are other types of additive manufacturing that can make parts out of metal powders which might be more appropriate.

Keywords: (HI-SEAS, Additive Manufacturing, 3D printing, In-Space Manufacturing, Mars, Analog)

Acronyms/Abbreviations

HI-SEAS – Hawai'i Space Exploration Analog and Simulation
EVA – Extravehicular Activity
ISM – In-Space Manufacturing
ISRU – In-Situ Resource Utilization
ISS – International Space Station
FDM – Fused Deposition Modeling
ABS – Acrylonitrile Butadiene Styrene
PET – Polyethylene Terephthalate
PLA – Polylactic Acid
SLS – Selective Laser Sintering
SMLS – Direct Metal Laser Sintering
SLM – Selective Laser Melting
PEI – Polyether Imide
PEEK – Polyether ether ketone

1 Introduction

As government and private industry begin to work toward long-term manned missions beyond low-Earth orbit, new capabilities must be developed to support humans beyond the range of physical support from Earth. One of these desired capabilities is a native manufacturing capability. During the course of a months or years long mission, systems will need repair. In a televised call in February 2012 NASA chief Charles Bolden asked the two American astronauts on board International Space Station (ISS) at the time, Dan Burbank and Don Pettit, about what astronauts need 20 to 30 years from now [1]. Burbank said:

> If we leave low earth orbit one of the key things, one of the most important things I think we need to have, is we need to have the capability to essentially cut the umbilical to be able to maintain spacecraft to the degree that if something breaks, you can replace a part outright. You need to be able to fabricate a part. You cannot bring with you all the pieces and parts that you might anticipate that might break over the course of a couple year mission.

The ability to manufacture replacement parts means a reduction in the number of spares required which reduces the up mass requirements and therefor the cost of the mission. Onsite manufacturing provides better capability to solve unanticipated problems as well. The types of manned Mars missions that are most typically discussed, conjunction class or “long stay missions” using chemical propulsion, would have a duration of approximately two and a half years with slightly less than a year and a half on the surface. During such a mission there will be no low energy launch opportunities for delivering additional supplies from Earth once the mission has departed Earth until around the time of its scheduled departure from Mars some two years later [2]. Even for a permanent Martian colony waiting for a part from Earth isn’t always going to be possible.

The purpose of this work was to explore the potential utility of additive manufacturing during future manned Mars mission by using it during an eight-month Mars analog mission at the Hawai‘i Space Exploration Analog and Simulation (HI-SEAS) habitat. The goal was to determine what types of items might be useful to an isolated crew.

2 Material and Methods

2.1 About HI-SEAS

Hawai‘i Space Exploration Analog and Simulation (HI-SEAS) is a NASA funded Mars analog run by principal investigator Dr. Kim Binsted, a professor from the Department of Information and Computer Sciences at the University of Hawai‘i Mānoa. The main goal of the study is to provide data about crew selection, cohesion and performance during long-duration, isolated missions. The crews are monitored using cameras, body movement trackers, proximity/environmental sensors, and surveys.

The habitat (Figure 1) is located at about 8000 feet on the slopes of Mauna Loa on the island of Hawai‘i. The habitat is made up of a 36-foot diameter geodesic dome and a 20-foot shipping container, for a total usable area of about 1500 square feet (Figure 2). All reasonable attempts are made to simulate Mars as closely as possible. Crew members have no live communication with the outside world. Email is delayed 20 minutes in each direction to simulate the signal travel time between Earth and Mars at opposition. Internet access is limited to a small number of permitted sites; news, social media and other frequently updated sites are forbidden. Food is shelf stable, mostly in the form of freeze dried or dehydrated ingredients that must be rehydrated and prepared into meals. Going outside the habitat is only permitted while wearing simulated space suits that isolate the wearer from the outside environment and approximates the awkward and cumbersome nature of a spacesuit. Crews are assigned geology tasks to approximate the activities that would be performed on the Martian surface.

Figure 1 – HI-SEAS habitat

Figure 2 – HI-SEAS habitat interior

Crews are made up of six members who are selected to be as astronaut-like as possible. As such they are generally engineers or scientists, mostly with advanced degrees. The selection committee's goal is to select a crew that is balanced with respect to skills, background and psychology

Four HI-SEAS missions have been completed so far. The first mission was a four months study investigating the palatability of shelf stable food, similar to what is likely to be used on long-duration space missions. Missions II-IV focused on crew cohesion and performance. Mission II was four months in length. The 3D printing work on which this paper is based took place during mission III, which ran for eight-months from October 2014 to June 2015. Mission IV ran from August 2015 to August 2016. Two additional eight-month long missions, V and VI, are scheduled to begin in January 2017 and January 2018 respectively.

In addition to the main study, six opportunistic studies run by other academic and industry groups were performed. These add-ons all focused on either psychology, group dynamics or some combination of the two. Generally they involved some kind of task or game and filling out surveys about mood and interactions with other crew members. In total about 40 tasks per week were required for these six studies. Most of these were short surveys taking just a few minutes though some tasks took up to half an hour.

Finally each crew member brought their own individual research. The purpose of these projects was to help keep the crew members occupied with tasks similar to those that astronauts would perform during a Mars mission. The goal of the individual research project carried out by the author of this paper was to explore the utility of additive manufacturing in an analog Mars mission and determine what lessons could be applied to a future manned mission to Mars (or missions to other destinations). Besides this investigation, the author also brought an Oculus Rift virtual reality system to the habitat in order to determine its utility in alleviating the feelings of confinement that might be expected in this environment. Other crew members' research areas were: Neil Scheibelhut – gut/skin microbiome, Allen Mirkadyrov – Earth-Mars transfer orbits, Martha Lenio – growing food indoors under LEDs, Jocelyn Dunn – investigating the correlation of cortisol/stress levels to exercise, sleep, eating habits, etc., Sophie Milam – STEM outreach and robotics.

A mission support team was on duty 12 hours per day during weekdays and eight-hours per day on weekends to be a point of contact for any issue occurring as well as to assist the crew in gathering any outside information they required.

As HI-SEAS is mostly an investigation of crew selection and dynamics rather than a study of Mars mission logistics and supply requirements, intermittent resupply occurs during the course of the mission (every two months for HI-SEAS mission III). Attempts were made to reduce resupply to the minimum level necessary but the habitat isn't equipped to store the necessary volume of supplies nor are all the systems robust enough to last the length of the mission with only locally stored spare parts.

2.2 In-Space Manufacturing (ISM)

NASA and private industry are currently working to develop the ISM technologies necessary for future manned missions [3]. Many of these technologies are based on existing additive manufacturing methods. Additive manufacturing is a general method by which the final product is built up bit by bit (most typically layer by layer but not exclusively). This contrasts with conventional manufacturing (milling, drilling, turning, etc.) which is subtractive. Additive manufacturing is often colloquially referred to as 3D printing. For the purposes of this paper the author will use 3D printing when referring to fused deposition modeling (FDM) which uses a CNC extruder to build up a plastic part layer by layer. This is the technology which makes up the vast majority of the consumer additive manufacturing market. All other methods will be referred to as additive manufacturing.

There are a few characteristics that make additive manufacturing well suited to ISM. It is incredibly flexible and can create a larger variety of geometries than any other single method. It generally produces minimal waste when compared to traditional subtractive manufacturing. The raw materials it requires (generally filament, powder or pellets) tend to be easier to produce than the material required for subtractive manufacturing (larger blocks) as well, meaning local production (in-situ resource utilization) or recycling of raw materials is more feasible. Finally additive manufacturing allows for manufacture of some parts that are impossible by conventional techniques such as ball bearing and ratcheting wrenches that require no assembly. This can allow greater flexibility in design.

The first 3D printer flown in space, the 3D Printing in Zero-G Technology Demonstration was built by Made in Space, Inc. of Mountain View, California and was launched to ISS onboard SpaceX CRS-4 in September 2014. It was installed in the Microgravity Science Glovebox in November 2014 and printed its first run of parts in November and December 2014 [4]. Made in Space has since launched a second printer (the Additive Manufacturing Facility) and an Italian built printer (pop3d - Portable 3D Printer on Board) has been launched as well [5] [6]. Results from mechanical tests comparing on-orbit printed and Earth printed parts showed significant differences in density, stiffness, strength and elasticity. The cause of these differences is not yet conclusively determined [7]. Further material characterization and process control studies will be required to understand performance of parts. Similar studies will be required for parts manufactured on Mars.

2.3 HI-SEAS Additive Manufacturing Work

Prior to the start of the mission the author contacted Made in Space to discuss potential collaboration. In a meeting they offered technical expertise on printer and filament selection and also agreed to provide ongoing technical help over the course of the mission.

The 3D printer recommended by Made in Space and selected for this work was an Up! Mini model manufactured by PP3DP. This is a fairly simple consumer level FDM type printer with a retail cost of approximately $600. It uses 1.75mm filament and can print a few types of plastic including ABS (Acrylonitrile butadiene styrene - the plastic used in Lego bricks), nylon, PET (Polyethylene terephthalate - the plastic used in soda bottles) and PLA (polylactic acid – a renewable biodegradable plastic). It offers a build volume of 120 x 120 x 120 mm (H x W x D) with an overall size of 350 x 240 x 350 mm. Layer thickness is variable between 0.20

and 0.40 mm. Max extruder temperature is 266° C and the heated bed reaches 51° C [8].

Spare printer parts/upgrades and additional feedstock were brought up during the mission resupply periods. All attempts were made to perform repairs on site and keep resupplies to a minimum to keep the mission as realistic as possible.

2.4 *Data Collection*

Over the course of the mission every run of the printer was tracked. Various characteristics of the models printed were tracked, this included: date, project, model description, part modeler, model name. In addition printer settings were recorded including: print temperature, material, print surface, raft or raftless, number of parts in run, extruder zero height and which extruder was used. Finally any comments about the resulting print were recorded as well. Photographs were generally taken of completed parts.

3 Results

3.1 *What Types of Parts Were Printed?*

Over the course of the eight-month mission more than 730 individual pieces were printed (Figure 3). The parts fall into two broad categories: practical or fun (Figure 4). The practical parts, which made up about 2/3 of the total part count, were further divided into subcategories: tools/scientific instruments, 3D printer parts, habitat repair/improvement, kitchen/office, test parts and outreach. The fun parts, which were the remaining 1/3 of the total parts, were subdivided into: toys, board games, presents and holidays/special events.

Figure 3 – A selection of the parts printed

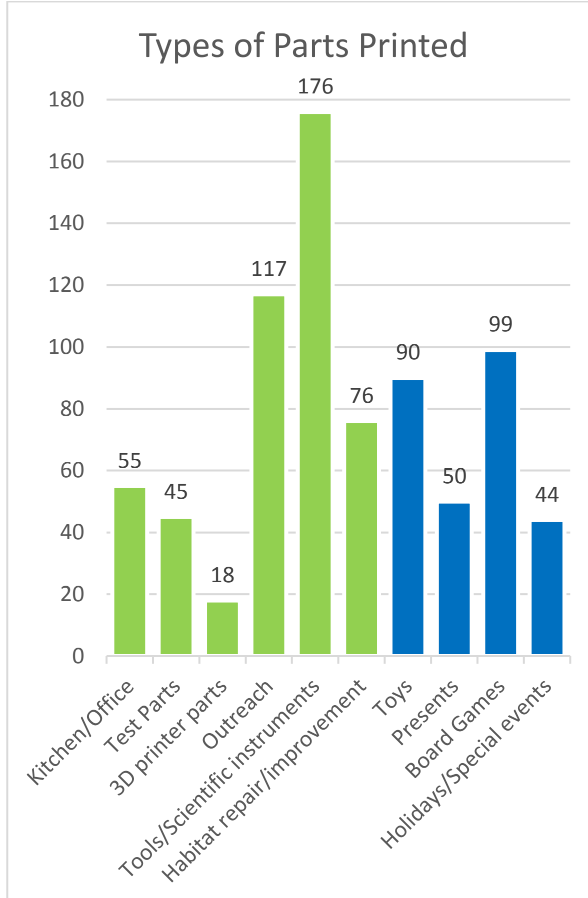

Figure 4 – Chart of types of parts printed

3.1.1 *Tools/Scientific instruments*

Tool and scientific instrument parts made up the largest single category of parts printed. Examples of parts that were printed successfully included: photoresistor holders to measure light levels in the the robotic garden, camera and Go-Pro tripod mounts, parts for a broken watch buckle (Figure 5), a helping hand soldering tool (Figure 6), the body for a spectrophotometer for measuring particulate in reclaimed water (Figure 7) and parts for a backup EVA helmet.

Figure 5 – Watch band replacement hasp

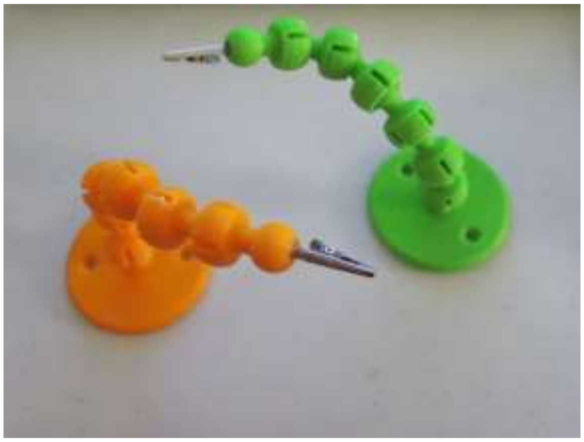

Figure 6 – Soldering helping hands

Figure 7 – Spectrophotometer

Sophie Milam, the crew roboticist investigated the possibility of a crew designed and manufactured rover to map lava tubes too small for human exploration. The goal was to design and manufacture a small rover built from a basic set of electronic and electromechanical components plus any parts that could be 3D printed. The ability to customize the design of the rover for the conditions that are encountered at the site is a potentially useful capability. An Arduino microcontroller was used to drive motors, servos and other electronics. The rover was approximately 20cm in length and was initially conceived to traverse small lava tubes and map them using an array of ultrasonic rangefinders. An initial prototype was completed and was capable of forward locomotion (Figure 8). Several revisions were made to the mechanical design but the motors available for this project weren't powerful enough for the task.

Figure 8 – 3D printed rover

Another capability that was explored was using 3D printing as a scientific visualization tool. The HI-SEAS crews were assigned a number of geology tasks. These tasks typically involved one or more extravehicular activities (EVAs) to investigate, take measurements or gather samples from a nearby geologic feature. For several of these tasks photogrammetry was utilized to create 3D computer models of the relevant features. Photogrammetry is a method for turning a number of still images of an object, taken at various angles, into a 3D model of that object. Autodesk Project Memento was used to create the models. These models could then be measured in ways that wouldn't be physically possible in real life (e.g. more accurate determination of irregular areas/volumes). It is also possible to 3D print these computer models and get a scale representation of the feature. This was successfully attempted but difficulties with cleaning up the model to print well prevented it from being used further. This remains a possible use for 3D printing.

3.1.2 3D Printer Parts

The printer experienced internment issues with the extruder feed mechanism not working, which required design and fabrication of new parts. The symptoms of this problem were that the printer would stop extruding plastic due to the feed gear grinding into the filament to the point that there was no longer enough material for the gear to grip and then it would stop feeding. This problem was isolated to a few rolls/brands of third-party filament but the design of the extruder meant it had poor ability to deal with diameter variations. The author designed a new filament feed mechanism to better accommodate undersized filament. The replacement part used a cantilever spring to replace the small bearing that was used to hold the filament against the feed gear (Figure 9). The spring design had a much larger tolerance to diameter variations. After several iterations the mechanism worked well in this regard but a secondary issue remained, since the material volume of the undersized filament is less than the nominally sized filament. It resulted in parts that had poor cohesion between layers. Due to the closed nature of the Up! 3D printer's software there was no way to rectify this issue.

In addition to this primary part a number of secondary parts were printed as well. These were upgrades or additions to the printer and included filament spool holders, a filament guide, and a temperature switch holder.

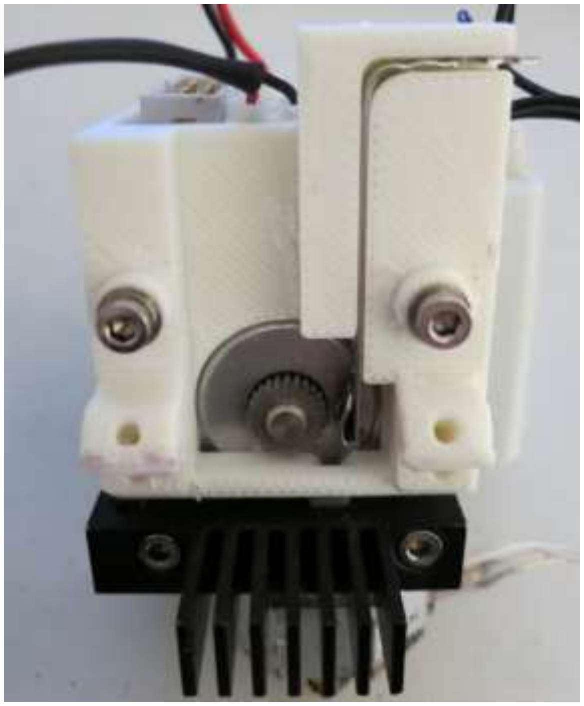

Figure 9 – Replacement extruder mechanism

3.1.3 Habitat repair/improvement

This includes parts to try to make life in the habitat a little easier. They generally fixed some inconvenience. Parts included docking stations for charging personal monitoring sensors (Figure 10), shelf/pegboard brackets and hooks, a holder for the shower timer, and iPad mounts for the stationary bike and for the wall (Figure 11).

Figure 10 – Sensor charging docks

Figure 11 – Habitat monitoring iPad wall mount

3.1.4 Kitchen and Office

Parts included food bag clips, cookie cutters and containers for pens/pencils.

3.1.5 Test Parts

Maximizing the capabilities of the printer required exploring the limits of what could be successfully printed. A number of test parts were printed to investigate minimum feature size, effect of temperature and other settings on the final product, and exploring printing of threads, gears (Figure 12) and a 3D printable alternative to Velcro (Figure 13).

Figure 12 – 3D printed square gears

Figure 13 – 3D printed velcro alternative

3.1.6 Outreach

The author created a 3D model of the HI-SEAS habitat and printed out a large number of them (117 including draft/test versions). These models (Figure 14) were distributed out as thankyou gifts to people associated with the HI-SEAS program as well as given out during subsequent STEM outreach programs.

Figure 14 – HI-SEAS habitat model

3.1.7 Toys, games, presents

The crew played a variety of different board games during their free time. The 3D printer was used to print additional game pieces, replace lost pieces, expand gameplay or allow for additional players. A variety of toys were printed though these were often also useful tests of printer capabilities. Examples include: parts for durability testing different materials (golf wiffle balls – Figure 15), parts with captive internal parts (Figure 16) and parts with a frequent filament color changes (Figure 16). Birthday presents for all crew members were printed. Items were also printed for holidays and other special occasions. These parts included: A star for the top of the Christmas tree (Figure 17), Easter eggs, a year charm for a graduation tassel for a crew member completing a degree and Halloween costume props.

Figure 15 – ABS and nylon wiffle balls for durability testing

Figure 16 – Captive part and color change test

Figure 17 – Christmas tree star

3.2 Number of Prints Over Time

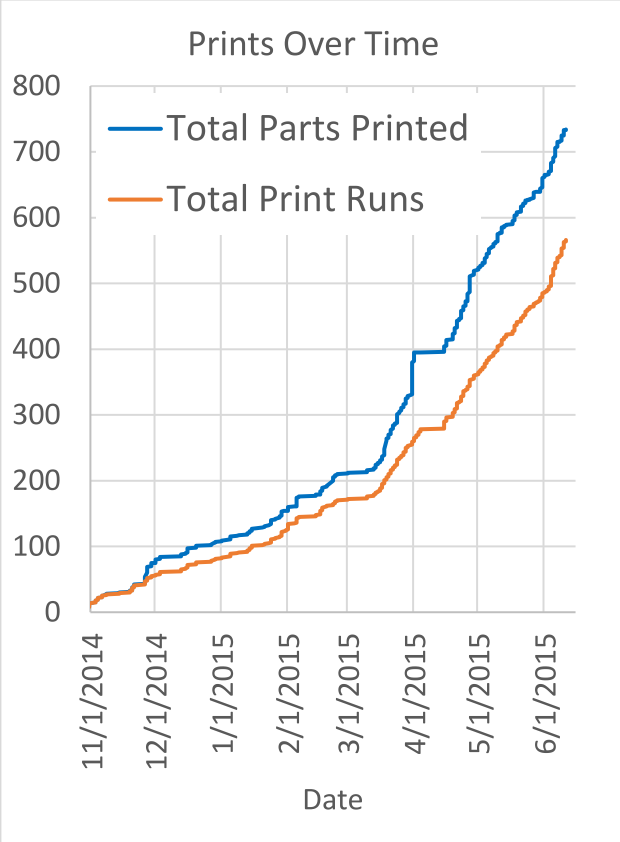

Figure 18 – Parts and print runs over time

The print rate accelerated over the course of the mission as skill levels improved. It was also a good way to remain busy to distract oneself from some of the stress and discomforts of the situation. Additionally around mid-March the author realized the mission was more than half over and there were still a large number of projects to be completed which contributed to a significant increase in print rate around that time. Several lulls in printing occurred, most notably several weeks in early April 2015 when no parts printed while awaiting a replacement for a broken extruder nozzle. Several large jumps in the number of parts printed occurred in short time spans when large numbers of small parts were printed in a single print run (several print runs with 20 individual parts were completed). The total number of print runs is also plotted to give a better sense of when this was the case (Figure 18). The average number of parts printed per run was 1.36 and more than 92% of runs had either only one or two parts (Figure 19). Zero part runs indicate that the run was stopped before it was completed. This was done if it became clear the part would not turn out as desired.

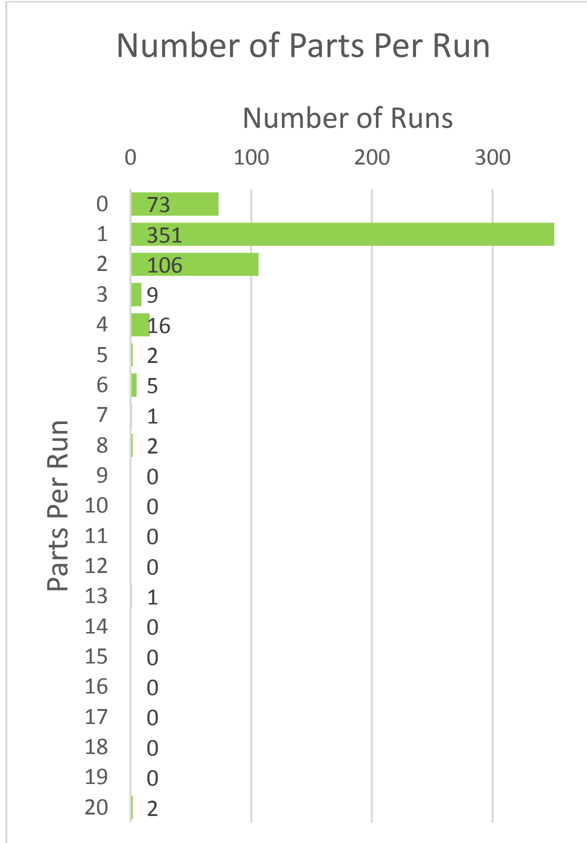

Figure 19 – Parts per print run

3.3 Part Designer

Of the 730 individual pieces printed during the mission 52% of these were based on the more than 50 parts that the author designed. Autodesk Inventor was the main CAD software used, although OpenSCAD, Meshlab, Netfabb basic, Meshmixer, Autodesk Memento and Solidworks were used for various tasks as well. Another 11% of the total parts were based on models that crewmember Sophie Milam designed (most of these were parts for the rover). The remainder of the parts were from other sources, mostly www.thingiverse.com and a smaller number from www.grabcad.com.

3.4 Amount of Material Used and Waste Generated

The 3D printer software tracks total material usage. The number tracked by the software includes all print jobs sent to the printer. It is not able to track when a print job is cancelled before it is completed and thus represents an upper bound on the amount of material used. This number was recorded monthly. In order to refine this number the following method was used: the total weight of material used during the mission was determined by subtracting the final weight of all filament spools from the initial weight. This gave a total actual mass of material used. The ratio of actual total material (5.76 kg) to software total material (9.65 kg) was 59.7%. The monthly material usage from the software was multiplied by this ratio to estimate actual monthly material usage. This is not an exact calculation as having a larger or smaller than average percentage of canceled prints during a given month would tend to skew this calculation, but it provides a better estimate of material usage. This adjusted amount is shown in Figure 20.

All waste material from stopped/failed prints as well as support material that was removed from satisfactory prints was collected and weighed once per month to determine waste from the previous month (Figure 20).

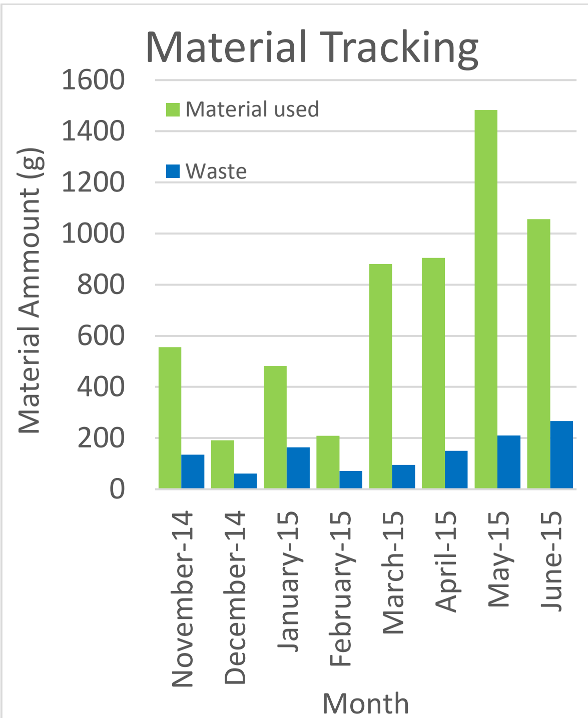

Figure 20 – Material used and waste generated

It should be noted that the mission ended June 15th, 2015 and so the rate of material use during that month is higher than the plot indicates and is actually the highest of any month.

The printing surface used was changed from the stock perforated plastic build tray (perfboard) to blue painters tape with a layer of water-soluble glue stick in mid-February 2015 and then to a glass build plate with a layer of water-soluble glue stick in mid-March 2015. Both of these later surfaces allow printing of parts without a raft which contributed to the reduction in the percentage of material wasted. A raft is a thin layer of material (a couple of mm thick) that is printed onto the build surface before the printer begins to print the actual part. It can help increase adhesion of the part to the build surface, but can be a significant percentage of the weight of the desired part depending on part geometry.

3.5 Materials Used

The parts printed were done almost exclusively in ABS. A small number of parts were printed with nylon or PET. The high stiffness and better surface finish of ABS made it more appropriate in most cases. Nylon was used mostly to provide increased strength and flexibility. 22 parts were printed in nylon including whiffle golf balls, a set of bushings for the rover and a carabiner. Only 6 PET parts were printed. There were difficulties with printing PET due to it being undersized at 1.55 to 1.60 mm undersized rather than the nominal 1.75mm.

4 Discussion

4.1 Useful Capabilities

4.1.1 Make Repairs, Improvements or Introduce New Capabilities

There were a number of items that were created as improvements or new capabilities to the habitat, these included: various hooks for hanging things, mounts/charging docks for tablets and other electronic items and camera tripod mounts. Based on crew feedback the most useful printed parts were items that got used every day and made life more convenient (this is discussed further in 4.1.5).

There were a limited number of opportunities to do genuine repairs to the habitat. Issues that did occur were often sensor or computer related that required electrical fixes.

4.1.2 Break Up Monotony/Create Surprises.

Life in the habitat was quite predictable. The few surprises that tended occur were generally negative, systems breaking or not working properly. Possibly as an attempt to counter this, the crew tended to make a big deal of holidays and special events. This involved things like dressing up for Halloween, cooking a full Thanksgiving dinner, putting up Christmas lights and a tree and hiding candy for Easter. Having a 3D printer helped to do some of these things when the supplies wouldn't have otherwise been available.

Crewmembers were requested to have their family and friends contact the author with ideas for presents for them over the course of the mission. The presents would then be designed, printed and presented to them. Only one person made contact and the print suggested (a spherical Mars topographic puzzle) was slightly beyond the ability of the software tools available. The author believes the idea remains a valid one, perhaps allowing for some connection with home while isolated from it.

4.1.3 Sense of Satisfaction/Independence

Living in such isolation is a combination of independence (crew members set their own schedules, mission support only gave long-term tasks who's competition was planned by the crew and no other people were ever seen in person) and utter dependence (outside help was required for something as simple as reading the news and resupply was required for food, water, fuel and other supplies). Future HI-SEAS missions will explore varying levels of crew autonomy over the course of the mission. The ability to solve problems/make improvements without the need to involve mission support was a welcome capability. Doing work that yields a physical product can also be quite satisfying. A 3D printer provides the ability to notice an issue and then design, manufacture and test a solution in a matter of hours.

4.1.4 Geology Task Visualization

As discussed in 3.1.1 crews at HI-SEAS were regularly assigned geology tasks. Computer models were built using photogrammetry and printed on the 3D printer. These models could be a useful visualization tool for future EVAs to the same areas, especially for crew members who haven't been there previously.

4.1.5 Crew Feedback

The crew was polled at the end of the mission to give their feedback about 3D printing and what were the most useful items that were printed. The crew was generally positive on 3D printing; no crew member expressed any negative feelings.

When asked about their favorite parts, crew members stated their favorites were either presents/toys printed for them or one of a few items that were used every day and generally considered most practical. These items included: an iPad wall mount that made crew members more aware of energy levels by constantly displaying power usage and battery levels, charging docks for personal proximity sensors that were worn during waking hours and a holder for the shower timer (shower time was limited). The need for some items of this type would be discovered during habitat and other pre-mission testing and wouldn't necessarily need to be printed during the mission but there had been previous crews in the HI-SEAS habitat for eight-months prior to the start of mission III and a large number of improvements were still made to general livability even so. Some of this is likely due to the personal preferences of the crew.

When asked about potential uses for additional capabilities suggestion included: printing O-rings for plumbing parts for the garden project out of printable elastomer, making more robust version of various parts out of metal (the rover in particular), printing integrated electromechanical parts if conductive materials were available. Additional printing capabilities will be discussed further in 4.6.5.

4.2 Hazards

While crew III didn't have this issue the previous crew complained of noxious fumes from the melted plastic. 3D printers are known to produce ultrafine aerosol particles that in an unvented or poorly filtered indoor environment can lodge in the lungs of people exposed to them [9]. Additionally polymers will offgas particularly when exposed to vacuum. Even in shirtsleeve environments materials should be chosen with minimal off gassing since these fumes will have to be dealt with by the life support filtering system. For space related uses the printer should be enclosed and equipped with an air filter while the life support system of the spacecraft/habitat should be designed to remove these particles and gases.

Extrusion based additive manufacturing uses an electrical resistance heater to melt the feedstock for extrusion. This necessarily generates high temperatures, 200°C - 250°C for ABS/PLA and up to 400°C for higher performance polymers such as Polyether Imide (PEI) and Polyether ether ketone (PEEK), which is both a fire hazard and a burn hazard.

The finely powdered materials used in powder bed additive manufacturing methods are a fire/explosion hazard when suspended in air. Suspensions of fine particles are more likely in the reduced gravity of Mars/the moon or the microgravity environment of Earth or transfer orbits (microgravity obviously presents other issues as well but they could potentially be overcome). Finely powdered metals, like those used in additive manufacturing, are the form of metal at the greatest risk for catching fire. Metal fires represent a special risk as they generally cannot be extinguished with commonly available fire extinguishers and require a special "class D" fire extinguisher. Filling the build volume with an inert gas would reduce the risk of fire/explosion and can also result in better quality final products.

4.3 Lessons Learned

4.3.1 Power Consumption Limitations

The HI-SEAS habitat operates primarily on a photovoltaic solar array (10kW) and battery storage system (20kWhr) with a secondary Hydrogen fuel cell system (10kW) and a tertiary gasoline electric generator (switched to propane for missions IV and after). The batteries were sized such that they would charge during the daylight hours, become fully charged in mid-afternoon, begin to discharge in the late afternoon/early evening and generally reach a low between 10% and 25% of capacity at sunrise. Cloudy days often meant that batteries never reached full charge and secondary or tertiary power systems had to be utilized. All reasonable efforts were made to reduce the need for these secondary or tertiary power systems since there were limited consumables on hand for them and depleting them would require resupply. Power usage of the 3D printer was measured with a Kill-A-Watt power meter and found to be 24 W in idle, a maximum of 96 W while preheating both the extruder and bed and an average of 53 W over the course of an hour-long print when starting cold. In comparison the first 3D printer aboard ISS, the 3D Printing in Zero-G Technology Demonstration, had a max power consumption of 176W [3] though it did not use a heated bed [4]. While the printer used was not a large consumer of power, its use was mostly limited to times when the batteries were fully or nearly fully charged to reduce the risk of running out of power.

4.3.2 Mechanical Problems with Printer

The 3D printer arrived at the habitat with one of the y-axis extruder head rail mounts broken from shipping. Made in Space provided 3D printed replacements and arranged for OEM parts to be shipped as well. This brings up a significant point: 3D printers are precise machines that require tight tolerances to operate properly. Any ISM device will have to be designed to tolerate launch (and potentially landing) loads while remaining functional.

Additional issues with a malfunctioning stage z-axis limit switch caused the software to not recognize the correct zero height and resulted in the print head crashing into the print bed. The problem was ultimately solved when it was determined that one of the switch's wires was poorly soldered.

An extruder failed when attempting to clean a clogged nozzle. The threads of the nozzle heater assembly sheared off. It required replacement of the nozzle heater assembly as the broken off threads were stuck in the heater block and the necessary tools to remove them weren't available. This is a known issue and the replacement nozzle heater uses a different design to prevent this issue.

4.3.3 Printer Upgrades

In addition to the upgrades that were printed during the mission (e.g. filament spool holder, filament guide, extruder body and temperature switch holder) some purchased upgrades were installed as well. The stock printer has two temperature settings (adjustable through software), one for ABS and another for PLA. This configuration works well with OEM filament, but in order to use other filament brands, materials besides ABS and PLA, and to give greater print control, an aftermarket temperature control was installed [10].

The Up! Mini uses perforated plastic build platforms. While they allow great adhesion between the build plate and print they are quite flexible and allow greater warping of parts. A stiffer alternative is glass build plates. Using a glass build plate requires more care to set the initial gap between the extrusion nozzle and build surface. A thin layer of glue is applied with a glue stick prior to printing to improve adhesion of the part. This allowed printing of almost all parts without a raft while maintaining (or improving) surface finish and reducing waste.

4.3.4 Design for Additive Manufacturing

Design for additive manufacturing is a specialized skill and requires a different thought process than subtractive manufacturing. Plastic parts made on an FDM printer have material properties that vary significantly based on direction. Parts are much stronger when loaded parallel to layers rather than normal to layers. Optimizing a part for this material anisotropy is one significant consideration.

Part build time is determined principally by part volume, layer thickness and number of layers. Solid parts may have an actual solid center (or as close as 3D printing can manufacture) or can be built with a less solid infill pattern that reduces material use and build time. Multiple parts can be manufactured in a single run of the printer and their arrangement can increase or reduce the build time per part depending on how the parts are packed onto the build plate. Additionally the machine control software will probably have settings for increased print head speed and the expense of quality.

When parts of an object overhang significantly additional support material is required (at least outside of microgravity). Typically minimizing this support material is desired though it may also be preferred to optimize for easy removal instead.

Design for these characteristics should be started during the initial brainstorming of the part. Optimizing the features is not generally a linear process; changing one factor will require reconsideration of the others so some knowledge of how changes will affect other characteristics is desirable.

Other additive manifesting process types may require other considerations. For example parts built using powder bed processes should have an escape passage to remove unconsolidated powder from enclosed volumes but they generally don't require support material for overhangs.

4.4 Part Finishing

The surface finish of parts straight off the printer was acceptable in many cases but we a finer finish was desired parts were smoothed with a combination of sandpaper and acetone (which dissolves ABS).

4.5 Designs from Mission Support

There were discussions with the mission support team about supporting 3D printing activities in the form of completed CAD models. The available mission support personnel didn't necessarily have the time, skill or desire to fulfill this role which left it to the crew. The other issue that this would have caused would be the need to integrate with a large number of existing parts of the habitat. After more than a year of crews living and working in the habitat there was no longer a complete inventory of the items there or the ad hoc modifications necessary to keep the systems functioning.

Having mission support take on this duty would be to free up astronaut time for activities that can only be performed by astronauts. In real life much of the design and prototyping would likely be done on the ground with only the final model file being sent to the crew to be manufactured. For probable failures (perhaps a significant portion of total failures) models could be designed and tested before the mission began while unanticipated issues would be dealt with as the came up [3]. Parts could even be designed from the outset to either be 3D printed or have 3D printed replacements if necessary.

4.6 Thoughts for future work

4.6.1 Recycling

While there was no shortage of raw material to print with during the mission that would certainly be a consideration during a true space mission. One of the advantages of having a 3D printer (or any native manufacturing capability) would be the potential reduction in weight by reducing the number of spares required. The reduction of raw material to an absolute minimum would further this goal. One possible method for this would be to recycle parts no longer needed and have the material reprinted into something useful at that stage of the mission. An example would be taking empty food packaging and printing it into containers for growing plants once the crew has reached the Martian surface. Packing material that will be needed to protect equipment during launch is another potential source of recycled raw material. This is also a good way to bring parts that are not critically needed but would be nice to have. The raw material can be brought in a useful form and then later used to create the part. There is currently work on recycling previous 3D prints and other materials occurring including Tether Unlimited's Refabricator planned for a launch to ISS in 2017 [11] and Made In Space's Material Recycler (R3DO)[12].

4.6.2 3D scanner

A 3D scanner might have been a useful capability. As discussed in 3.1.1 photogrammetry was used to create a number of models of geology features and printing of several was tried with moderate success. This method was also used to create models of small board game pieces but in general this technology isn't as well suited to creation of accurate 3D models as a dedicated scanner would be. The advantage of a 3D scanner would be the improved ability to interface new printed parts with existing parts with less work.

4.6.3 Parts Not Printed

The author kept a list of potential parts to design and print. At the end of the mission there was still a significant number of ideas that had not been completed. Reasons for not creating them varied and included: difficulties with certain features (e.g. threads), uncertainly if they were possible with available capabilities or simply lack of time.

A few potentially interesting ideas:

Garden plumbing parts – bucket spigot, ball valve and one-way check valve

Overhead light switch holder – for remote control

3D printing contest – outreach project where the most interesting ideas would be printed

Dome wall hooks – hooks for bolt ends exposed on habitat interior

Simulated spacesuit parts – ventilation and air diffuser parts

4.6.4 Fasteners

There are a number of options for fastening 3D printed parts together when necessary. The author used snap fits on a variety of parts and a slurry ABS chips dissolved in acetone to glue parts together. There are a number of other options as well including: various types of screws and threaded inserts that can be melted or pressed into parts [13].

4.6.5 Additional Printing Capabilities

A dual extruder printer with the capability to print multiple materials in a single part would have been welcome. Softer/more flexible materials can be co-printed along with standard materials. This allows for parts that include integrated bumpers, hinges and seals. This could be a useful capability for parts to direct air or water (plumbing and spacesuit parts as mentioned in 4.6.3).

The materials that were used during the mission were useful in the circumstances but they aren't necessarily well suited to either the vacuum of space or the environment of the Martian surface [14]. Materials in these environments may have to resist large temperature ranges, increased radiation (both electromagnetic and particle), corrosive atmosphere (atomic oxygen in low earth orbits) and vacuum or near vacuum conditions. There are some plastics better able to resist these conditions than the ABS used during the mission; examples include Ultem PEI, Kapton (polyimide) and PEEK. More expensive printers (that can reach higher temperatures) are required to use these high performance polymers.

Moving beyond FDM type printers to a powder bed fusion type machine which uses a heat source (most typically a laser) to melt powdered material. The laser melts the shape of the first layer into the powder, then another thin layer of powder is spread over the bed and the process repeats, building up the part layer by layer. This method is used for plastic using Selective Laser Sintering (SLS) or metal using Direct Metal Laser Sintering (SMLS) and Selective Laser Melting (SLM). Metal parts would have a far greater range of uses due to increased strength, stiffness, and ability to deal with harsh conditions when compared to polymers.

5 Conclusions

The purpose of this work was to explore the potential utility of additive manufacturing during future manned Mars mission by using it during an eight-month Mars analog mission. 3D printing was found to be a useful capability to have during HI-SEAS mission III. More than 730 parts were printed over the course of the mission. These parts ranged from practical to fun and simple with print times of a couple minutes to complex with print times of more than eight-hours.

A native manufacturing capability for a mission to Mars several years in length which would be without the ability to be resupplied is almost certainly needed. The alternative would require a combination of designing for extreme reliability and bringing spares for every possible failure and will still leave the crew with reduced ability to improvise solutions to unexpected issues.

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