TOWARD A MULTIMATERIAL FABRICATION LABORATORY
In-Space Manufacturing as an Enabling Technology for Long-Endurance Human Space Flight

TRACIE PRATER PhD, NIKI WERKHEISER PhD and FRANK LEDBETTER PhD
NASA Marshall Space Flight Center, Huntsville, Alabama, 35812 USA; Wheelhouse Consulting, Huntsville, Alabama, USA

email tracie.j.prater@nasa.gov

Human space exploration has not ventured beyond low earth orbit and the moon. It is understood that a suite of manufacturing capabilities will be needed on long duration, long endurance missions to reduce logistics and enhance crew safety, enabling rapid response to unforeseen situations. The International Space Station provides a unique opportunity for NASA and commercial partners to test out the manufacturing technologies needed on missions humanity will undertake in the post-ISS era. The in-space manufacturing (ISM) project at NASA and numerous commercial companies funded under this program are working to develop the manufacturing systems, skill sets, materials and techniques needed to support these future exploration missions. This paper provides an overview of technologies developed or in development under the helm of the ISM project that stand to change historical paradigms for human spaceflight and approaches to mission planning. Categories and activities on the ISM roadmap are also discussed. In the near term, these activities lead to the development of a multimaterial fabrication laboratory for the International Space Station, a unit capable of processing multiple materials and performing part inspection. In the long term, they represent a key foundational step on the path to reducing dependence on earth and making humanity a space-faring species.

Keywords: Manufacturing in space, Additive manufacturing, International Space Station, 3D printing, Advanced manufacturing

1 INTRODUCTION

The goal of NASA’s In-Space Manufacturing (ISM) project is to identify, develop, and implement manufacturing solutions to support fabrication and repair of components on-orbit. ISM uses the International Space Station (ISS), an orbiting and continuously crewed laboratory located approximately 200 miles above the earth in low earth orbit, as a testbed for development of the manufacturing technologies needed to support long duration, long endurance missions (such as a 500 day Mars campaign), where cargo resupply is not readily available and the amount of mass launched from earth to support desired levels of system reliability may be prohibitive. ISM has undertaken (in conjunction with the Evolvable Mars Campaign) several top-down quantitative analyses of ISM benefits to crew time, cost, mass and reliability on such missions [1]. Based on historical space station data, approximately 13,000 kg of spares are maintained on orbit (not including packaging or carrier mass) to support operations. An accompanying 18,000 kg of spares is maintained on the ground, ready to fly on demand. Every year, 3,000 additional spares are upmassed to support corrective maintenance and consumables. This extensive suite of spares is needed since it is not possible to predict with any degree of certainty what spares will be needed and when. Even after years of continuous ISS operations, unanticipated system issues still appear. It is not difficult to see how this logistics model, pictured in Fig. 1 overleaf, would be difficult to sustain for long duration, long endurance spaceflight.

In-space manufacturing refers to any manufacturing process...
which operates in the microgravity environment. The roadmap for the in-space manufacturing project is focused on developing a suite of capabilities, from 3D printing of plastics to non-destructive evaluation, which offer an alternative to traditional logistics approaches and mission planning. These key capabilities include: additive manufacturing of polymers, additive manufacturing of metals, recycling, manufacturing of electronics, and inspection. These capabilities collectively enhance crew safety, enabling a rapid response, just in time manufacturing capability to respond to the “unknown unknowns” of human spaceflight operations.

While ISM began with 3D printing of plastics in 2014, the roadmap is focused on expanding its portfolio to include a diverse array of technologies needed to support crewed exploration missions NASA will undertake in the post-station era. The future of ISM beyond 2024 is uncertain. At that time, NASA and private companies developing space habitats must be poised to take advantage of in-space manufacturing capabilities (developed using ISS as a testbed) to support their operations. The benefits of ISS in these scenarios stand to revolutionize and uniquely enable human spaceflight. A diverse suite of ISM processes could enable manufacturing of large scale structures not constrained by launch requirements of payload fairings, dramatically decreasing the mass of spares, and provide a capability to adapt to unanticipated circumstances. ISM also can facilitate use of local resources and, with the development of “common use” materials (such as a packaging, which are designed to be reused), recycling.

2 MANUFACTURING OF POLYMERS

NASA’s in-space manufacturing project traces its origins to a small business contract with Made in Space, Inc. of Mountain View, California, to develop and operate the first 3D printer designed specifically for the International Space Station. This printer, which used fused deposition modeling (FDM) to manufacture parts of ABS plastic, was deployed on ISS in September 2014 and completed its first phase of operations in November and December 2014 of that year. FDM heats plastic wire feedstock to its glass transition temperature and extrudes it layer by layer. The raster movements of the bed the material is deposited on and/or the movement of the extruder head dispensing material is precisely controlled to build up a specific geometry. Comparative analysis of samples produced on board ISS with samples printed on the ground with the same printer prior to its launch to ISS exhibited some variation in properties likely due to process variability, but showed no substantive evidence of microgravity effects on material quality/outcomes or deposition mechanisms [2,3,4]. Additional phase II operations of the printer provided additional statistical sampling for material property data and allowed a more focused look at isolating the microgravity variable through careful control of the manufacturing process [2]. Subsequent ground analyses of specimens produced with a flight-equivalent printer and results of multi-physics modeling also substantiated experimental findings that operation in microgravity does not significantly impact material outcomes for FDM [5].

While the first printer from the technology demonstration mission was intended to serve as the technical proof of concept for FDM in a microgravity environment, the second printer, a commercial facility developed by Made in Space and known as the Additive Manufacturing Facility (AMF), currently serves in a utilization capacity for ISS. AMF has a larger build volume than the technology demonstration mission printer and has an expanded material envelope which includes high density polyethylene and ULTEM 9085 in addition to ABS [6]. NASA is using this printer for additional materials characterization work, specifically development of baseline design values. To date several functional parts have been produced using the system: a tow hitch to join two spheres from the Synchronized Position Hold Engage and Reorient (SpherEES) payload, used to evaluate guidance, navigation, and control algorithms in microgravity on ISS; and Oxygen Generation System (OGS) adapter that mounts a velocibale probe to monitor airflow and health of the OGS; a critical piece of environmental control and life support hardware on station; and, a Radiation Exposure Monitor (REM) shield enclosure for the Bigelow Expandable Activity Modules (BEAM) [7, 8]. The OGS adapter is shown in Fig. 3.

3 RECYCLING

Recycling is critical to solving the logistics problems of long duration, long endurance missions, as it provides an opportunity to transform otherwise nuisance materials (which may represent thousands of pounds of upmass) into usable feedstock to support manufacturing. ISM will explore the potential for recycling through its second payload, the ReFabricator, developed by Tethers Unlimited, Inc. (TUI) under a Small Business Innovative Research (SBIR) contract. ReFabricator is an integrated printer/recycler which can melt a 3D printed part and re-extrude it into filament feedstock for further printing [9]. Operational on ISS in fall 2018, data from the ReFabricator mission will provide important information about degradation of thermoplastic materials with recycling in a microgravity environment. Results will provide some indication of life limits for parts based on their use scenario and number of recycling cycles. An assessment of the degree to which recycling introduces material contamination (from non-feedstock materials) into the feedstock will also be obtained from this data.

The recycling roadmap for ISM also includes complementary development of materials for packaging that are designed to be recycled, referred to as common use materials. Currently the packaging materials for ISS are highly diverse. To make maximum use of these materials (which would otherwise be downsized in cargo ships which burn up in the earth’s atmosphere on re-entry), common materials used across all packaging systems need to be developed. Cornerstone Research Group developed reversible copolymer materials under a phase II SBIR [10]. These materials have strength and modulus values commensurate with the base thermoplastic materials, yet maintain a depressed viscosity which enables them to be extruded through the FDM process. FDM prints with this material are shown in Fig. 4. In parallel with the ReFabricator payload, TUI is also developing a 3D printable and recyclable foam packaging – Customizable Recyclable ISS Packaging (CRISP), shown in Fig. 5. CRISP can be fabricated with custom infill profiles to enable specific properties (such as vibration characteristics) such as the addition of thread for guidance, navigation, and control algorithms in microgravity on ISS; and Oxygen Generation System (OGS) adapter that mounts a velocibale probe to monitor airflow and health of the OGS; a critical piece of environmental control and life support hardware on station; and, a Radiation Exposure Monitor (REM) shield enclosure for the Bigelow Expandable Activity Modules (BEAM) [7, 8]. The OGS adapter is shown in Fig. 3.

3 RECYCLING

Recycling is critical to solving the logistics problems of long duration, long endurance missions, as it provides an opportunity to transform otherwise nuisance materials (which may represent thousands of pounds of upmass) into usable feedstock to support manufacturing. ISM will explore the potential for recycling through its second payload, the ReFabricator, developed by Tethers Unlimited, Inc. (TUI) under a Small Business Innovative Research (SBIR) contract. ReFabricator is an integrated printer/recycler which can melt a 3D printed part and re-extrude it into filament feedstock for further printing [9]. Operational on ISS in fall 2018, data from the ReFabricator mission will provide important information about degradation of thermoplastic materials with recycling in a microgravity environment. Results will provide some indication of life limits for parts based on their use scenario and number of recycling cycles. An assessment of the degree to which recycling introduces material contamination (from non-feedstock materials) into the feedstock will also be obtained from this data.

The recycling roadmap for ISM also includes complementary development of materials for packaging that are designed to be recycled, referred to as common use materials. Currently the packaging materials for ISS are highly diverse. To make maximum use of these materials (which would otherwise be downsized in cargo ships which burn up in the earth’s atmosphere on re-entry), common materials used across all packaging systems need to be developed. Cornerstone Research Group developed reversible copolymer materials under a phase II SBIR [10]. These materials have strength and modulus values commensurate with the base thermoplastic materials, yet maintain a depressed viscosity which enables them to be extruded through the FDM process. FDM prints with this material are shown in Fig. 4. In parallel with the ReFabricator payload, TUI is also developing a 3D printable and recyclable foam packaging – Customizable Recyclable ISS Packaging (CRISP), shown in Fig. 5. CRISP can be fabricated with custom infill profiles to enable specific properties (such as vibration characteristics)
Also under a phase II SBIR, UltraTech Machinery is-
made in Space is developing the Vulcan Hybrid Manu-
tethers Unlimited is also developing the MAMBA (Meta-

lated supplies and equipment [12]. Sterilization is critical for
long duration missions, as research indicates that bacteria
and viruses become more virulent in a microgravity environment,
while crew member's immune systems may become compro-
mised, potentially due to synergistic effects of radiation and
microgravity. Funded under a phase II SBIR, ERASMUS com-
bines the results from the Refabricator payload with a dry heat
sterilizer and UV sanitation routine that will enable reuse of
consumables/supplies or consumables manufactured from re-
cycled material. Reuse of medical equipment/consumables also
has important earth-based applications in waste reduction and
scenarios (such as remote medicine and army field operations)
where supplies may be scarce. Fig. 6 shows several biomedical
consumables manufactured with the ERASMUS capability.

NASA is also exploring biologically derived filaments which
can be manufactured from inedible plant waste. These fila-
ments would be produced from raw plant mass extrac-
trahers (such as cellulose or lignin) in combination with other
additives for use in FDM. Some biologically derived filaments
are already commercially available (PLA, PHA, etc.). In a small
project in partnership with ISM, the synthetic biology group at
Ames Research Center and the VEGGIE payload at Kennedy
Space Center were able to germinate wheat grass and radish
seeds in 3D printed lattice structures. These structures, which
were made of PLA, PHA, or even potato starch derived fil-
ament, can be optimized to facilitate nutrient absorption and
water delivery (Fig. 7). Plant growth is made possible by the
addition of a moisture retainer starch polymer and microbial
cellulose. While the project initially used commercially avail-
able filaments, further work in this area by stakeholders may
demonstrate an end to end process for utilizing raw plant mass
to produce filament feedstock, which can then be used to make
structures to support further crop growth. Achieving sustaina-
bility in food sources for deep space exploration is an ongoing
research area at NASA and a manufacturing/recycling capabil-
ity could provide an important piece of this puzzle.

4 METALS MANUFACTURING

Work under the SBIR program is also focused on development
of a metallic manufacturing capability for ISS to complement
polymeric manufacturing processes such as FDM. While there
is work underway to develop higher strength polymers com-
patible with the FDM process, metal parts remain the status
quo for parts in high performance systems such as environ-
mental control and life support systems, which typically re-
quire the greatest amount of spares. Ground based metal sys-
tems for 3D printing of precision components typically rely on
selective laser melting (SLM) processes, where a bed of powder
based metallic material (15-100 microns in thickness for each
layer) is selectively fused by a laser. Powder bed fusion pro-
cesses such as SLM yield high resolution parts of good materi-
al quality and enable unique design features (such as complex
flow passages for fluids) which may be difficult or impossible
with conventional manufacturing techniques. Powder systems,
however, provide an immense challenge for the microgravity
environment. One challenge is scalability, as these systems have
large footprints and require higher power than what is typically
possible for ISS payloads. Safety hazards associated with use of
lasers, combustible nature and toxicity of the raw powders,
and difficulty controlling the movement of the powders in
microgravity present additional challenges. Given these consid-
erations, wire-fed systems are favored for initial development
and deployment in a crewed environment. Parallel work under
this technology area is being pursued by four companies:

- Techshot, Inc. has developed the Sintered Inductive Metal
  Printer with Laser Exposure (SIMPLE). This desktop sized unit
  uses a wire feed typically in the form of a ferromagnetic metal
  wire. The wire is inductively heated as it is extruded [13]. A
  low-powered laser Positioned near the extruder completes the
  melt. The test unit for this project, now in phase II funding, is
  shown in Fig. 8.

- Also under a phase II SBIR, UltraTech Machinery is work-
ing to scale the ultrasonic additive manufacturing (UAM) process
and assess its feasibility for use on ISS. Developed by

- MAMBA forms virgin or scrap metal into ingots which then
  undergo finish machining with a CNC [16]. MAMBA builds
  the Positrusion process (used to recycle plastic in the ReFab-
  ricator system) to metals, while extending the capabilities of
  manufacturing in space by exploring the unique challenges
  posed by traditional subtractive manufacturing processes in
  the zero-gravity environment (Fig. 11).

The UAM process is being explored on several other pro-
grams at NASA including:

- 3D printing of heat exchangers with a full suite of qualifi-
cation tests
- Embedding sensors in metal components for digital twin
  and health monitoring
- Production of metal matrix composites for selective rein-
  forcement and fatigue mitigation
- Made in Space is developing the Vulcan Hybrid Manu-
  facturing unit under a phase I NASA SBIR. Now in phase II
  funding, Vulcan represents a multimaterial, hybrid manufac-
  turing capability for ISS. The system will include fused fila-
  ment fabrication (FFF), an additive manufacturing process for
  metal fabrication, a CNC mill for processing, and an automat-
ed robot for movement of the part between subsystems
  [15]. Phase I consisted of extensive trade studies for the sys-
  tem and its manufacturing processes/materials, initial materi-
  al evaluations, and demonstrations of constituent subsystems,
  including a chip capture system for debris generated during
  the manufacturing process. Fig. 10 shows a piece made using
  the Vulcan system.

In phase 1, UltraTech successfully reduced the UAM pro-
cess's footprint (i.e. power and volume requirements) by de-
signing and implementing a higher frequency sonotrode. Early
tests of the new design have shown quality welds in 6061 T6 and
7075 T6 at significantly lower power and lower force than the
larger production system. Force reductions will drive down overall
system size and weight as the machine structure will have
reduced forces to react. Similarly lower forces will require
less energy from the motion system while the smaller head re-
quires less welding energy. Scaling of the system also has impli-
cations for robotics and use of the process for freeform fabri-
cation. Current UAM machines made by UltraTech are hybrid
systems (additive + subtractive), so a potential flight unit de-
veloped as part of phase II would incorporate a CNC mill head to
enable finish machining of metal parts in the same unit.

Tethers Unlimited is also developing the MAMBA (Met-
al Advanced Manufacturing Bot-Assisted Assembly) system.
MAMBA forms virgin or scrap metal into ingots which then
undergo finishing machining with a CNC [16]. MAMBA builds
directly on the work of the Refabricator payload by extending
the Postnurbs process (used to recycle plastic in the ReFab-
ricator system) to metals, while extending the capabilities of
manufacturing in space by exploring the unique challenges
posed by traditional subtractive manufacturing processes in
the zero-gravity environment (Fig. 11).

Systems such as these under development which integrate
an additive and subtractive manufacturing capability into the
same system are known as hybrid manufacturing processes.
Work on automated tool changeout for metal AM tech-
ologies in tool wear in dry machining processes, feedstock
management, and ensuring crew safety during operation of these
potential payloads is also part of the development effort for
metals manufacturing in space.

5 ELECTRONICS MANUFACTURING

While it is impossible to predict what components and subsys-
tems on a space mission will fail and when such failures will
occur, many of the historical failures on space station during
its operational life have been electronic in nature. A manufac-
turing capability for electronics is thus seen as a key capability

Fig. 6 Examples of 3D printed biomedical consumables.

Fig. 7 Printing of plant substrates with biologically derived (COTS)
filament. Germination of wheatgrass achieved with a retainer
starch polymer and microbially-produced cellulose.

Fig. 8 SIMPLE (small metal 3D printer) developed by Techshot
under an SBIR.

Fig. 9 Illustration of the ultrasonic additive manufacturing
process.

Fig. 10 Example of Aluminum part made by Vulcan during
prototype testing.

Fig. 11 Tin Ingot formed using the New Postnurbs-Plus Design at
250C, Cross-Section and Tensile Bars that were machined from it.
for long duration, long endurance crewed spaceflight. Much
of the electronics development work for in-space manufactur-
ing is in-house, as the Materials & Processes Laboratory and Space Systems Development at NASA Marshall Space Flight
Center are using the nScrypt platform (a machine for fabrica-
tion of electronics using additive manufacturing techniques)
to explore use scenarios and pursue accompanying materials
development work.

The nScrypt is a multi-head, modular system which can
precisely print polymer substrates, dispense electronic inks,
align layers, and pick and place electronic components. NASA
Marshall is pursuing development of metallic, dielectric, and
other electronic inks with this system and exploring the use
of additive manufacturing of electronics to support high-value
ISM applications. The system has been used to develop a wire-
less sensor archetype which uses an ink with a sensitivity to
temperature, pressure, humidity, or other some stimuli. Chang-
es in the stimuli produce an accompanying change in resist-
ance or capacitance that in turn alters the output voltage of the
circuit in a detectable manner. Wireless sensing networks are
an important area for space technology development, as these
sensors can potentially to reduce mass associated with wiring,
connectors, brackets and other mechanical parts.

In the last decade, thin film transistors, memory devices,
chemical, biological and physical sensors, and many others
have been fabricated on flexible substrates. The early attempts
involved fabricating of the desired device on a conventional
rigid substrate such as silicon, followed by some type of trans-
fer process to a flexible polymer substrate. More recently, the
technology has evolved to the direct fabrication on flexible
substrates such as paper, textile and plastics. This was primarily
enabled by printing processes such as inkjet printing and
droplet jet printing that allow printing a wide variety of
different materials – semiconducting, dielectric – to create the
aforementioned devices.

It is desirable for NASA to adapt these emerging technol-
gies for producing antennas, gas sensors, biosensors, energy
storage devices including batteries and supercapacitors on de-
mand in the ISS. Most of these devices have limited lifetime
and fail unexpectedly and thus, are suitable for in space man-
facturing as and when needed. Our work addresses the above
needs through two avenues: tool development and application
development, both of which are described here briefly. A de-
tailed discussion on nanosensors and devices for aerospace
needs can be found in [17].

The most common printing techniques mentioned above
typically require a sintering or annealing step at temperatures of
200 – 400 deg. C after the deposition is completed in or-
der to get the consolidated thin film with desired morphology.
This sintering step precludes the use of delicate substrates
or thin layers of ink. The sintering step is typically required
for high-performance antennas and new materials is that
they can be printed on a variety of flexible and variable surfac-
es using additive manufacturing processes. A sample printed
antenna is shown in Fig. 14.

Fig. 14 Love profile wideband antenna with reconfigurable
radiation patterns.

The ISS crew cabin air quality monitoring requires sensors for
CO, CO2, ammonia, NO2, formaldehyde and humidity and
these sensors can be readily printed on flexible substrates
[19-21]. For example, ammonia sensors printed on cellulose
paper and cotton textile show sensing capabilities down to 1
ppm (part per million). It is also possible to print biosensors
for crew health monitoring [22] and physical sensors to detect
incidents on solid structures [23]. Finally, many of these print-
ed sensors require only low level of power for operation and
this power can be locally generated from vibrations and other
movements through triboelectric power generation. An entire
triboelectric power generator has been demonstrated as well
[24, 25], thus enabling self-powered sensors for de-
ploing in the ISS.

Sensors fabricated to date at MSFC with additive technol-
gies include a wireless humidity sensor printed with MS-
FC-developed silver and dielectric inks (pictured in Fig. 13),
a wireless humidity sensor for use in a structural health monitor-
aplication for the Space Launch System launch vehicle, and a
capacitive haptic sensor. On space missions, a customization
availability for sensors could enable crew to respond to specific
needs for health monitoring of systems or undertake repair/
fabrication of sensors on demand.

There is additional work in polymer-ceramic-carbon nano-
tube composite materials, which have piezoelectric, pyroemet-
ric, and flexoelectric responses that can be used for many sens-
ing applications. New research on incorporating these novel
sensor technologies into spacecraft systems has centered on the develop-
ment of wireless antenna designs to be printed directly onto the
sensors. Through various collaboration efforts of MSFC sci-
entists with universities, optimized wideband antennas which
are printed with silver inks developed at MSFC. The advantage
of these devices is that they can be printed on a variety of flexible and variable surfac-
es using additive manufacturing processes. A sample printed
antenna is shown in Fig. 14.

6 THE MULTIMATERIAL FABRICATION LABORATORY

While it is difficult to extrapolate what manufacturing capa-
bilities will be available when humanity is ready to venture
far beyond earth, the multimaterial fabrication laboratory and
activities under NASA’s in-space manufacturing project rep-
resent the first steps on the journey to earth independence. In
2017, the in-space manufacturing project issued a Broad Ara
Announcement (BAA) for a multimaterial, multiprocess fab-
rification laboratory to operate onboard the International Space
Station in the 2021 timeframe [26]. The announcement was
phased, with the first phase a flight demonstration of a scal-
able ground-based prototype of a Fab Lab sys-

tem. Phase B will further mature the technologies developed
in phase A to a unit that is packaged for flight. Phase C re-
presents a flight demonstration of the system onboard ISS. A
phased approach provides natural pivot points, enabling the
ISM program to maintain a flexible approach and revere-
tor FabLab capabilities to the highest potential technologies
developed under phases A and B. Companies working under
phase A are required to participate in subsequent phases of the Fabrication Labora-
tory development.

The Fabrication Laboratory is intended to provide a one-
stop, just in time manufacturing capability for human space-
flight. The desired capabilities for the FabLab are divided into
threshold capabilities (required) and objective target
capabilities (desired). These system capabilities (taken from
the BAA) are summarized in Table 1. The FabLab is expected to be bounded by the dimensions of
the EXPRESS rack, illustrated in Fig. 15 overleaf. The EX-
PRESS rack provides 16 cubic feet of payload volume with a
power budget of 2000 W and a mass budget of 576 lbm. Giv-
en constraints on crew time and the limitations in crew skill
sets to perform dedicated manufacturing operations, remote
communication is a critical focus of development. A verifi-
cation and validation capability for the FabLab platform is
also desired. Verification and validation of parts produced in
-space manufacturing systems remains a pre-eminent chal-
lenge, as the suite of nondestructive evaluation capabilities and
personnel expertise available on the ground may not be easily

<table>
<thead>
<tr>
<th>Threshold</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>The system should have the ability for on-demand manufacturing of multi-material components including metallics and polymers as a minimum.</td>
<td>Multi-material capability including various aerospace-grade metallic, polymer, and/or conductive inks significantly increase the merit of the proposal.</td>
</tr>
<tr>
<td>The minimum build envelope shall be 6&quot;x6&quot;x6&quot;.</td>
<td>As large of a build-volume and/or assembly capability as possible within the Express Rack volume constraints listed in Section 3.</td>
</tr>
<tr>
<td>The system should include the capability for earth-based remote commanding for all nominal tasks.</td>
<td>Remote commanding and/or autonomous capability for all tasks (nominal and off-nominal).</td>
</tr>
<tr>
<td>The system should incorporate remote, ground-based commanding for part handling and removal in order to greatly reduce dependence on astronaut time.*</td>
<td>The system should incorporate autonomous part handling and removal in order to greatly reduce dependence on astronaut time.*</td>
</tr>
<tr>
<td>The system should incorporate in-line monitoring of quality control and post-build dimensional verification.</td>
<td>The system should incorporate in-situ, real-time monitoring for quality control and defect remediation capability.</td>
</tr>
</tbody>
</table>

Astronaut time is extremely constrained. As a flight demonstration, the ISM FabLab would be remotely commanded and operated from the ground, with the ultimate goal being to introduce as much autonomy as possible. As a minimum, there should be no greater than 15 minutes of astronaut time required for any given nominal activity, with the end-goalt being to apply the same rule to maintenance and off-nominal operations as well.
transferrable to and extended space mission. In situ monitoring techniques under development for additive manufacturing of metallics (which use laser line profilemetry to measure surface roughness, IR cameras to measure temperatures, etc.) show promise in correlation of observations with material outcomes. If adapted for ISM, these techniques could provide a way to "witness" the build and certify the as-built part based on data collected during fabrication, thereby subverting a need for NDE or allowing NDE to be targeted to specific locations.

The core objective of the FabLab is an expansion of the material envelope for in-space manufacturing capabilities, which are currently being pursued through technology development under SBIRs. Technologies developed under these opportunities could also be infused into the fabrication laboratory downstream. The ability to fabricate quality aerospace grade materials (in a controlled and repeatable manner on orbit) will help accelerate the acceptance of ISM as a tool by designers and mission planners. It is generally recognized that unanticipated failures for space systems will still occur, even after nearly years of continuous operations. By virtue of the law of cumulative probability, incidences of failure will only increase with extended missions which travel farther than LEO. FabLab will provide an important capability for addressing the inherent uncertainty in system performance and provide an additional safety measure with benefit to logistics.

7 CONCLUSIONS

This paper articulates the benefits of in-space manufacturing for extended space voyages, summarizes the current activities under NASA’s in-space manufacturing project, and the path from ISS technology development payloads to systems that will eventually be deployed on exploration missions. In addition to manufacturing in the crew environment, planetary construction and external manufacturing techniques will also be required to support extended space travel. In planetary construction, robotic systems might support buildup of infrastructure prior to the arrival of crew; NASA is spurring development of these technologies through the Additive Construction for Mobile Emplacement (ACME) project, which focuses on development of a gantry style system for 3D printing of concrete (potentially infused with regolith that may be found on the planetary surface) [28]. Centennial Challenges, NASA’s prize competition program, issued a three phase challenge on 3D printing of habitats in 2015. Phase I was an architecturally design competition and Phase II focused on development of autonomous printing systems and material systems which might be used to support planetary construction. Phase II asked teams to develop extrudable mixtures of regolith based materials and polymer mixtures (the latter categorized as mission recyclables). In Phase III, currently underway, teams are asked to scale up systems to additively manufacture a 1/3 scale habitat capable of supporting a crew [29]. External in-space manufacturing is being pursued through NASA’s Science Technology Mission Directorate (STMD) Tipping Point program [30].

As these technologies progress in the coming centuries, many systems and even entire spacecraft will be manufactured in low earth orbit, deep space, or on the planetary surface. This represents an immense shift away from the traditional paradigm of spaceflight to date (where every item used in space is launched from earth) but one that is necessary to truly enable space independence and facilitate humanity’s evolution to a new solar system. Production of high quality materials uniquely enabled by space manufacturing represents an immense shift away from the traditional paradigm of spaceflight to date (where every item used in space is launched from earth) but one that is necessary to truly enable space independence and facilitate humanity’s evolution to a new solar system. Production of high quality materials uniquely enabled by space manufacturing is one of many technology gaps on our path to the stars, but it is widely recognized as a critical capability needed to support long duration missions. The activities that culminate in Fabrication laboratory development will bring us one small step closer to Earth independent exploration and provide an adaptive, rapid response capability to reduce the requirements and enhance crew safety.

Acknowledgments

Mehya Meyyappan, NASA Ames Research Center. Content relating to activities of private entities represents previously published material and/or was provided by the companies.

REFERENCES