APPLICATION OF SOLID FREEFORM FABRICATION TECHNOLOGY TO NASA EXPLORATION MISSIONS

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Exploration Mission Concepts and Constraints

NASA has begun the process of planning for mankind's next steps in the human exploration of the solar system. Missions under consideration include a return to the Moon, visits to near-Earth asteroids, and the exploration of Mars. Although each possibility presents unique opportunities and challenges, a mission to Mars is believed to present the greatest challenges and to be the most defining case from the standpoint of required capabilities.

Current planning shows that the duration for a Mars mission will be on the order of 900 days (1). This total includes approximately 6 months for both the outbound and return transits and roughly 500 days on the surface of the planet. These figures are determined by the relative positions of the Earth and Mars that are necessary for trajectories requiring minimum expenditure of propulsive energy. Minimizing propulsion requirements significantly reduces the total required propellant mass and, thus, the total mass that must be launched from Earth and injected towards Mars.

One of the features of a mission to Mars which uniquely distinguishes it from spaceflight operations in Earth orbit is the inability to abort the mission and return quickly to Earth. In the case of Space Shuttle flights or International Space Station operations the crew can be back on the surface of the Earth in just a few hours if events demand. In the case of a Mars mission, however, astrodynamics and energy requirements dictate that, once on the way to Mars, the crew is committed to a journey of the full initially planned duration. A quick return to Earth is not possible.

Another feature of a Mars mission which uniquely distinguishes it from the operation of the International Space Station is that there will be no opportunity for resupply from Earth. Optimum opportunities to launch to Mars occur only at intervals of approximately every two years and the transit time is several months at best. Whereas hardware failures on spacecraft in low-Earth orbit can be managed by replacement of components sent from Earth, missions to Mars will have to be self-sufficient from the moment they leave Earth orbit (2). The lack of abort capabilities and the need for long-duration self-sufficiency demand that the crew have highly flexible and robust capabilities to maintain and repair all system hardware to enhance the probability of mission success. However, satisfying this need for robustness must not result in enormous quantities of spare parts which impose significant penalties in terms of mass and stowage volume.

Directions in Exploration Mission Supportability

Mission supportability includes all aspects of planning for, and implementation of, those processes, capabilities and facilities that are necessary to maintain vehicle systems in an operational status. By enhancing the robustness and flexibility of the support capabilities the probability of mission success can be significantly improved while minimizing impacts to total mission mass, stowage volume requirements, and cost.

One approach is to maximize commonality of hardware at all levels. Increased commonality reduces the number of unique spares that must be carried and increases the opportunities for exchange of hardware as the need arises. Since the probability of failure of all members of a common set containing "n" members is $P(f)^n$, where P(f) is the probability of failure of each member, it can be seen that it should not be necessary to carry "n" spares since there should be a very low probability of all set members failing. On the other hand, if the members of the set are unique rather than common, it is much more likely that at least one spare must be carried for each member.

Another approach is to encourage repair at the lowest possible level. Typically, when a complex hardware assembly fails, the failure is attributable to a very limited number of small internal components rather than massive failure of the assembly at a gross level. If only the specific failed components are replaced, then the mass and volume of the required spares is significantly reduced. Traditionally, however, this approach would be truly effective only when component commonality is maximized as well. Otherwise, a massive number of small components would be required.

A third approach, which complements the others, is to provide the capability to manufacture replacement components *in situ* as required. A very significant advantage of this capability is that it reduces the need to carry specific, unique replacement components. Rather, replacements are generated as needed from feedstock material. Furthermore, *in situ* fabrication of replacement components reduces the chance that a required component will not be available and, also, reduces the chance that components are carried that will not be needed. The net effect is a major reduction in the mass and volume of spare components or assemblies and a significant improvement in mission robustness by reducing the risk of having the "wrong" set of spares. Options for *in situ* fabrication of non-electronic components include standard machining processes and solid freeform fabrication (SFF).

The Case for Solid Freeform Fabrication

It is certainly premature to select a single manufacturing methodology for *in situ* fabrication on space exploration missions; some general comments can be made, however, about the attractiveness of Solid Freeform Fabrication (additive manufacturing) relative to machining (subtractive manufacturing). One key consideration is the amount and form of feedstock materials. Assuming operations in reduced gravity, there is a need to keep the volume of materials in any melt processing to a minimum. This implies that raw materials used for subtractive manufacturing must be stored in "near net" shape (various sized billets / blocks /

sheets / rods). Although much mission hardware can be designed for remanufacture from a limited number of feedstock sizes, this will still impose a large raw material burden. Solid Freeform Fabrication systems universally have a more efficient packaging of feedstock materials.

Subtractive manufacturing by nature also produces a large amount of waste material relative to fully additive processes. This imposes additional requirements on the manufacturing facility such as containment of chips and lubricants in a reduced gravity environment. If the waste material is to be reclaimed and reused, additional material separation and melt processing steps are required. The need for tool changeouts, object fixturing, and manual or automated part positioning is also much greater in traditional machining.

Reducing the total mass and volume of an *in situ* manufacturing facility requires reducing the total number of machines; reducing the total human or robotic overhead requires reducing the total number of manufacturing / assembly steps. It is in this area that Solid Freeform Fabrication offers the most promise relative to more traditional techniques. One example would be a single FDM-type deposition system capable of building a thick-film circuit board, populating it by placing small components, and constructing the housing around it. In this case, a single machine has the capabilities of combining multiple functional materials (electrical conductors / insulators + structural materials), as well as performing assembly steps. This can potentially occur while the object is constructed in a single orientation with minimum human intervention.

Desirable Solid Freeform Fabrication Process Characteristics

Solid Freeform Fabrication processes must possess certain attributes to be attractive candidates for inclusion in the suite of space mission supportability capabilities. These desirable characteristics are described below.

Compatibility with multiple materials. A wide range of materials, both metallic and nonmetallic, are employed in spacecraft hardware. Although a single SFF process which could yield both metallic and nonmetallic components would be attractive, the continuing preponderance of metallic components indicates that, if a choice must be made, emphasis should be placed on processes which yield metallic components. However, since a variety of metallic alloys are utilized it is highly desirable that processes compatible with aluminum alloys, stainless steel, titanium alloys, and nickel alloys be employed.

Adequate properties in finished parts. It is critical that any part produced have mechanical properties that meet design requirements. In some cases, however, the properties required for a replacement part may be different than for an original part. This is because the original part may have to endure unique stress and environmental conditions during relatively brief mission phases. For example, an original part may have to endure severe thermal conditions or high static or dynamic loads during launch. If, after that mission phase, a replacement component is fabricated, it may no longer be faced with those conditions and, thus, not require the same mechanical properties. Extreme caution is mandatory in the application of this concept, however. All potential futures for a replacement part must be considered to ensure that the part will perform satisfactorily in potential off-nominal situations.

Capability to produce complex parts. Although many individual components in spacecraft hardware assemblies have quite simple configurations (e.g. washers, seals) many others are equally complex. Therefore, any SFF process that is employed must be capable of producing geometrically complex components.

Minimum number of processing steps. Attractive SFF processes will involve the fewest number of processing steps while retaining the capability of generating complex parts. This is important because increased numbers of processing steps imply greater time required to generate a part and more equipment to support the distinct steps.

Minimum crew interaction. Although crew involvement will be required for virtually all maintenance and repair operations, the primary purpose of the crew will be to explore. The introduction of processes which require additional crew time would be contrary to overall mission objectives. Thus, processes should require as little crew interaction as possible.

High production rate. Replacement part production should be accomplished in a "reasonable" period of time. Although the term "reasonable" is not readily definable, it can be said that replacement parts should be produced with sufficient speed to return an assembly to an operational condition prior to the occurrence of mission impacts and that the part production process should not become a bottleneck in maintenance and repair operations.

High yield - minimum wasted material. To gain maximum benefit from this technology, it is important that a very high percentage of the consumed feedstock material be incorporated into the final part. This requires the minimization of unconsolidated powder, overspray, or other loss of material. Also, the initial product should be near-net-shape so that material losses during final finishing are minimized.

Compatibility with reduced-gravity environments. Implementation of SFF processes in support of exploration missions will require performance in reduced-gravity environments. During transit phases, acceleration levels will be zero. While on the planetary surface, gravitational acceleration will be positive but less than the 1-g experienced on Earth. Acceleration effects could be manifested during both material deposition and, if a liquid phase is involved, solidification. These potential effects must be explored and processes developed which accommodate them.

Minimum final finishing. Initial production of near-net-shape parts results not only in higher yield, as discussed above, but also speeds the total production process, potentially requires less secondary processing equipment and consumes less power.

Minimum mass and volume of equipment. The equipment which is utilized in both initial production and secondary processing should be designed to minimize its mass and volume. This is important to maximize the overall benefit from the application of this technology.

Minimum power consumption. Spacecraft power is always at a premium. The power requirements for initial production and secondary processing should be such as to not impact operation of other spacecraft systems or to be a significant factor in power system sizing.

Minimized unrecoverable consumables. To the extent possible, unrecoverable consumables such as binders, inert gases and cutting fluids should be minimized. Unrecoverable consumables not only contribute to total system mass but also impart an additional load on filtration systems which are necessary to prevent contamination of the spacecraft environment.

Safety. Safety is a paramount characteristic. Any off-gassing or waste products must be controllable. Personnel must be protected from high temperature surfaces, sharp objects, inhalation of metal powders and fume, lasers, or other hazardous materials. All potential hazards must either be eliminated or controlled.

Limitations of the State-of-the-Art

Given the desirable process characteristics as presented above, it is instructive to review current SFF systems and the direction of their development. The research focus of Solid Freeform Fabrication technology for earthbound industrial use in many cases addresses the same needs of space-based manufacturing: materials development (especially metals), production rate, and surface finish. SFF systems that currently excel in these categories, however, may be unacceptable for use in a space-based manufacturing facility because of the unique requirements of the application. Compatibility with a reduced gravity environment, the mass/volume/consumables of the SFF equipment, and the safety issues associated with crewed spacecraft will ultimately drive the development of an *in situ* manufacturing system. In this discussion, we are considering only the direct manufacture of objects from SFF equipment. Using SFF to create patterns or tools for secondary operations (e.g. casting or injection molding) are unlikely to be practical solutions for one-of-a-kind manufacturing in a space-based facility.

In an abstract sense, Solid Freeform Fabrication systems can be categorized into *Stereolithography, Deposition,* and *Lamination* techniques. For purposes of this classification, stereolithography techniques include all methods that selectively solidify patterns within a supply bed of bulk material. This would include not only 3-D System's Stereolithography (SLA), but also systems such as Selective Laser Sintering (SLS) and Three-Dimensional Printing (3-DP). To meet the materials requirements of *in situ* manufacturing, stereolithography systems must use particles as the bulk feedstock material. This requires modification of standard SLA systems to use the photopolymer as a binder in ceramic (3) or metal (4) particulate slurries. In all of these particle-based systems, a greenbody is created on the machine in the desired geometry, and final properties are achieved through a second, higher-temperature sintering step.

The use of particles as feedstock allows for a wide range of materials to be produced using stereolithography techniques. Three-Dimensional Printing has historically focused on the creation of fully-dense structural ceramic objects (5). The Selective Laser Sintering system has recently been used to produce titanium objects through the addition of hot isostatic pressing (6). The significant amount of materials research in this area, combined with the fact that these systems have some of the highest throughput and accuracy, makes stereolithography systems attractive for *in situ* manufacturing. A primary consideration of these techniques for space applications is the placement and control of the feedstock material. The feedstock must be fully contained, yet allow energy (SLA, SLS) and/or material (SLS, 3DP) to reach the build surface. Possible methods of containment may include contact mask printing, or control of thin particulate layers by means of magnetic or electrostatic forces.

Deposition Systems (FDM, FDC, EFF, SDM, LENS, etc.) are well-suited to reduced gravity material handling. The majority of these processes achieve a liquid-to-solid transition by the rapid cooling of extruded beads from a small melt volume. Because the dimensions of these beads are below the capillary limit, gravity is not required for material flow and adhesion (7). Single deposition systems are compatible with multiple material types, including insulating and conducting polymers, metals such as steel (8), and ceramics (9). As the core of these systems is a simple x-y-z plotter, there is a good deal of commonality with robotic assembly systems, as well as the direct manufacture of electronic thick film circuits (10). There are significant limitations to these systems, however, including materials, resolution, and throughput. Another key limitation is the need in most deposition systems to support overhangs. While this may at first seem counterintuitive for a reduced-gravity application, initial studies (7) show just how important a continuous substrate is for the correct placement of beads. Shape Deposition Manufacturing (SDM) and the Sandia LENS system are attractive for producing fully dense metals, but both systems have equipment mass, complexity, and potential safety problems which must be addressed for this application.

Lamination Systems, which stack-then-cut (LOM) or cut-then-stack (CAM-LEM) solid sheets of material, also offer ease of reduced-gravity feedstock handling. Composite objects can be directly manufactured, while metal and ceramic objects are possible by using particulate sheets combined with an additional sintering step (11). These systems have some severe geometry limitations, however, and share with deposition systems the need to support overhangs. An even more significant drawback is the amount of feedstock waste. Reprocessing of this waste, while generally not economically viable for earth-based systems, would be a key requirement for adapting lamination systems to space-based manufacturing.

It is not the purpose of this discussion to quantitatively rank SFF system capabilities against NASA needs. Indeed, the subtle differences in individual techniques, as well as the pace of development makes any ranking results dubious. As we have seen in industry, there is not a clear SFF "winner" – each system has found its niche. A space-based system will not have the luxury of multiple machines, however, so a combination of design compromises and system development will be required. Some of the challenges may be answered by combinations of Solid Freeform Fabrication processes, or combinations of SFF with machining (SDM is an example). Other possibilities include using SFF equipment to create thin shells in the correct geometry for filling with composite material (12) or using as a thin-walled mold for slurries of ceramic or metal particles.

Current NASA Activities in SFF

Since 1990 hundreds of parts have been fabricated at NASA's Johnson Space Center (JSC) in Houston for form, fit and functionality demonstrations; for wind tunnel tests; and to serve as casting masters, injection mold patterns, and working models. The use of SFF has proven beneficial in reducing design-to-manufacturing time for many assembled parts such as on-orbit crew tools and robotic arms joints. In addition, larger SFF parts have been assembled together for wind tunnel and fluid flow testing, including a three-foot model of the Space Station Crew Return Vehicle, and a two-foot diameter T-38 aircraft inlet duct, respectively.

At NASA's Marshall Space Flight Center (MSFC) in Huntsville, Alabama, eight different SFF technologies are employed to aid engineers in both the design and manufacturing of parts. Research efforts at MSFC have included support in development of direct ceramic and high-precision rapid prototyping (RP) capabilities, optimization of RP investment casting patterns, and transonic wind tunnel testing with RP models.

NASA is currently evaluating different technologies for further development and use to meet the goals for the Human Exploration and Development of Space. At JSC, activities and efforts for in-space manufacturing have focused on two principal areas: developing a roadmap and plan for rapid manufacturing of space flight hardware, and performing introductory tests of the fused deposition process in a reduced-gravity environment. The roadmap includes several milestones, from the development of basic systems requirements to the generation and investigation of potential material reclamation and recycling systems.

In June, engineers from both JSC and MSFC performed introductory tests of a deposition manufacturing experiment in a non-gravitational environment. A Stratasys Fused Deposition Modeling (FDM) 1600 rapid prototyping system was structurally secured into the NASA KC-135 research aircraft which provides brief periods of a reduced-gravity environment while flying parabolic trajectories. Once reprogrammed for approximately 20-second build cycles (approximate time of reduced gravity during each parabola), the FDM was used to fabricate 14 parts in 7 different configurations, including a tensile bar, vertical column, bridge with multiple piers, hourglass, cantilever beam, dome structure, and longer-span bridge with piers.

The purposes of the reduced-gravity tests were to:

1. Analyze the inter-layer bonding of an additive layered, fabricated component
2. Evaluate the dimensional stability of the specimens as compared against the same designs fabricated under normal gravitational conditions, and
3. Determine the overall operability of an extrusion-based manufacturing process without the assistance of gravity.

Although difficulties were experienced due to atmospheric humidity (with the ABS plastic material), and part stability during the 2-g pullouts, the tests still demonstrated the ability of a deposition process to fabricate parts in a non-gravitational environment. A complete summary of the tests and results are discussed elsewhere (7).

Planned Solid Freeform Fabrication Development Strategy to Support Exploration Needs

To support future human mission needs, NASA will work towards a better understanding of SFF process capabilities and limitations. The goal will be to find ways to enhance process control, surface finish, deposition rate, and part complexity capabilities. Emphasis will also be placed on reducing processing equipment size and power requirements. Furthermore, it will be necessary to gain insight into the influence of low-g and partial-g acceleration environments on process which may be sensitive to this factor.

Finally, NASA will develop an integrated supportability strategy to take advantage of opportunities presented by commonality, low-level repair, and SFF. This will have additional programmatic and design implication such as requirements for low-level failure modes and effects analyses, aggressive Repair Level Analyses, and deliverable 3-D models of all components which are candidates for SFF.

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