Autonomous Self-Extending Machines for Accelerating Space Exploration

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ADVANCED AERONAUTICAL/SPACE CONCEPT STUDIES

PHASE I REPORT

Cornell University

Hod Lipson, Evan Malone
Mechanical & Aerospace Engineering and Computing & Information Science
Ithaca, NY 14853-7501
hod.lipson@cornell.edu

Executive Summary

"Solid freeform fabrication" (SFF) describes a set of new and rapidly evolving computer controlled manufacturing processes that construct net- or near-net-shape parts directly from geometry data, typically layer by layer, and typically without need for specialized tooling or material confinement. Trends in SFF process development are broadening the spectrum of useable functional materials, including metals, plastics and ceramics, and moving rapidly toward the integrated production of functional components, including actuators, sensors, electronics, and mechanisms.

It has recently become apparent to us that SFF processes might make possible the construction of complete, fully-functional mechatronic systems by a single, compact fabrication unit – envision a robot walking from the fabricator under its own power and control! The NIAC's recognition of the potential of the concept, and funding of our Phase I proposal, has permitted us to embark upon this new research direction. Our estimation of the impact of the concept and of its being realizable has only increased during the course of this effort.

Our investigation commenced with a survey of the literature on SFF to establish the state of the art, commercial activity, and development trends. Mission concepts were identified through consideration of NASA's current and proposed mission and exploration plans, and through discussion with members of the robotic exploration field. Conceptual realizations suitable for each mission were explored, including some estimated costs and benefits, and supporting infrastructure. A technology development roadmap organized around two avenues was conceived. The first avenue is hardware development complimentary to the trends in commercial and academic R&D – namely a focus on compaction, integration, and automation of processes to permit fabrication of maximally functional products from restricted sets of materials. The second avenue is the development of new design paradigms which will permit the realization of desired functionality within the new design space associated with SFF and restricted material sets.

A technology evaluation platform has been constructed, based on an articulated industrial robot arm, and a variety of simple material deposition tools. This effort has permitted us to identify some of the practical challenges associated with realizing the concept, including real-time coordinated control of tools and manipulation, compatibility of materials and processes, process and path planning, and system automation and robustness. The parallel efforts in conceptual study and technology evaluation have resulted in a development roadmap that combines broad, long-term perspective with an emphasis on remaining realizable. We intend to continue in these parallel efforts, and consider both essential for the goal of achieving a proven and deployed architecture in less than four decades.

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Introduction to Architecture Concept

The Challenge

CAN WE LAUNCH A ROBOT BEFORE WE DESIGN IT? The recent robotic exploration of Mars has revealed a serious bottleneck: Mission cycle time is too long. The time taken to design, fabricate and test exploration systems is on the order of several years. Combined with the wait for an optimal launch date and an extended one-way trip, a single robotic exploration cycle takes years. Add to that the fact that not every cycle is successful, and the effectiveness becomes even lower. All this leads to a runaway of risk and cost, in turn leading to more stringent design and tests, and so forth. Moreover, as seen in the Mars exploration case, cycles are carried out in series and results from a previous cycle are required before the next cycle can proceed. As we plan to explore more distant planets the situation will become even worse: A one-way trip can last a decade, remote control is slow and difficult, and likelihood of failure increases. Is there a way to shorten this process, and break out of this vicious circle? Most current approaches for accelerating the exploration cycle focus on new travel and propulsion technologies, but leave the robot design-fabricate-test-launch cycle fixed. Here, an alternative approach is proposed based on reversing the cycle: We will launch a robot before we design it!

A Remote, Autonomous Fabrication System

The concept advocated here permits a new approach to exploration, shifting the focus from designing and launching the maximally capable and robust exploration robot to launching a fabrication system that can construct and recycle task-specific robots and other fully functional systems in the field. The fabricated systems need not be super-capable, nor ultimately robust, because repairs can be performed, design changes can be applied retroactively in the field, and new systems can be fabricated as necessary for new or unforeseen tasks. This approach, suggestive of the science fiction series *StarTrek*'s "Replicator", suggests sending a versatile, 100% automatic fabrication system to a remote planet along with a supply of components, raw materials, and/or a set of *in situ* resource utilization (ISRU) systems capable of generating some or all of the raw materials needed. The fabrication machine should be capable of producing a wide variety of functional systems in such a degree of completeness that they are not only operational, but operating. A completed robot should be literally able walk away from the fabrication system. While the fabrication system is in transit, design work progresses on Earth and alternative designs are considered as more information arrives and new concepts are developed. Designs could be tested on a duplicate fabrication system on Earth. When the system arrives at the destination, selected robot designs, for instance, are transmitted and produced on site. Typically, the first robot would be a general-purpose machine, capable of testing preliminary aspects of the new environment and verifying the function of the fabrication system itself. With the feedback obtained from this cycle, new machines with more specific capabilities can be designed, transmitted and fabricated. Complete new systems designed to achieve specific tasks not foreseen at launch time can be fabricated by recycling obsolete systems and using stock material and components. Most importantly, the exploration cycle can be reduced from years to the time required to fabricate a system and deploy it. With repair, recycling, and use of *in situ* resources, the functional lifetime of a successfully deployed mission could be almost unlimited. Subsequent launches from Earth, if any, would become “care packages” of new technology, rare materials, and difficult to fabricate components – in all likelihood less critical and more cheaply and easily transported than fully-functional landers and rovers.

Ultimately, with proper design, such fabrication systems would be able to extend their own capabilities (hence the “self” in the title). One can imagine a set of robots producing extension parts, such as new grippers, to be installed on one of the robots themselves to extend its functionality. Although full self-replication is not the direct goal of this endeavor, one can see how autonomous fabrication coupled with modular design can lead to self-repair, then self-extension, then ultimately toward self-replication, given sufficient resources.

Critique

The skeptical, many of whom are likely to be found in the field of planetary exploration robotics, might rightly point out that this idea proposes to send what sounds to be a very complicated fabrication system with no intrinsic value for exploration in lieu of fully tested, fully assembled functional exploratory robots. Assuming that flight experience for Earth-constructed robots continues to accrue in the future, and that their performance and robustness continue to increase, how can sending a less mature fabrication technology in lieu of a more mature robotic technology ever be justified? In our opinion, it cannot. A fabrication system will not be a substitute for conventional robotics for critical initial exploration. However, a fabrication system does hold tremendous promise as a component of a robotic outpost, for instance, where it can repair, alter, or replace robots and other systems to prolong and extend the capabilities of a mission. A careful consideration of risk and marginal cost might justify a salvage deployment, wherein a fabrication system, suitably extended for mobility, would be deployed to the site of former missions, where it could salvage and restore dead systems. These and other (hopefully) sensible missions will be discussed in more detail in the Missions section.

Inspiration

The primary value of a self-extending autonomous fabrication system to NASA’s missions of science in and exploration of space is to increase the amount of useful activity achievable from a given deployed mass by repairing and extending other deployed systems, and fabricating new systems from Earth-originating, recycled, or ISRU materials. It might be argued that a self-replicating system provides the ultimate return from a given deployed mass, assuming that it is not dependant upon resupply, and can perform work other than replication, and an interest in the self-replication of artificial systems inspired the concept being proposed. Self-replication as a process is studied as a feature of living systems, of course, but more recently has become a topic of interest to nanotechnology and molecular-manufacturing researchers for whom self-replication (of nanoscale fabrication machines) is a means of developing macroscopic production capabilities – see [Hall, 1999] for instance. In the very long term, nanotechnology may leave no aspect of our technology untouched, but it is remarkably difficult to find examples of useful working nanosystems (as opposed to MEMS), let alone significant progress toward self-replication. Perhaps it will be a race for second place (life has already won first) between macro and nanoscale technologies to achieve a self-replicating system.

At the macroscopic scale, some significant effort has already been spent exploring the possible roles of self-replication to space exploration. The 1982 publication, Advanced

Automation for Space Missions, edited by Robert Freitas and William Gilbreath, summarizes the work of a 10-week NASA / American Society for Engineering Education sponsored study on the potential for computers, automation, and artificial intelligence to enhance the scope and performance of space missions. To focus the study, participants selected four mission concepts that they considered to have "high relevance to future NASA program goals,"[Freitas, p.8] and which would provide excellent applications for machine intelligence. The missions considered included the establishment of an automated space manufacturing facility which would use extraterrestrial resources, and a self-replicating lunar factory. Although there was "no assumption that these specific missions would ever be carried out,"[Freitas, p.8] there is some indication that space-based manufacturing and self-replicating systems were topics of active research in NASA circles in the early 1980's [ref pubs by von Tiesenhausen and Darbro, Freitas, O'Neill; see p215 of Advanced Auto.], and may well have seemed less far-fetched then than now. The study includes a very impressive, even humbling collection of information and ideas on automation, manufacturing, *in situ* resource extraction and processing, commercial utilization of space, engineered self-replicating systems, even research and development plans, and is likely to remain an essential reference and starting point for future work on space based manufacturing and self-replicating factories. Given the effort and detail contained in the study, it is difficult to believe that the participants viewed these missions as unlikely to be carried out. Yet they remain, as yet, unrealized. Space exploration is a lower societal priority now, and budgets have decreased accordingly. In this light, one key problem in the two conceptual designs described for self-replicating factories is simply the very large scale: the smaller of the two consists of a 100 ton seed facility, amounting to a "miniaturization" of an entire civilization's engineering industry, requiring roughly 1 MW of power generated by about 11000 m^2 of photovoltaics (the larger design calls for several GW of power!). Considering that this mass could have been delivered by four Saturn V launch vehicles [Freitas, p215], and that the International Space Station already has 892 m^2 of solar arrays deployed[1], these values are not that outlandish, but they dwarf current exploration mission scales – each Mars Exploration Rover spacecraft has a mass of 1063 kg, including all stages[2]. Furthermore, these concepts were developed to highlight applications of machine intelligence, and assume far greater autonomous capability than research in AI and Moore's Law have contrived to provide. While self-replication from raw materials is a distant goal, and the autonomy and intelligence issues remain unsolved, new fabrication processes and *in situ* resource utilization (ISRU) technologies have emerged which can dramatically reduce the scale and complexity of an autonomous, deployable fabrication system. Our concept is inspired by these new developments.

Fabrication Process Metrics

It is an essential early step in the development of new technological concepts to define quantitative measures by which to judge the merits of the new against each other and against existing competing technologies. Of primary interest to us is a means for comparing the functional utility of the full set of output products capable of being produced by different fabrication processes, given a specific set of input materials. Over the course of this research

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[1] http://spaceflight.nasa.gov/station/isstodate.html

[2] http://mars.jpl.nasa.gov/mer/mission/spacecraft.html

effort, several frequently used but vague comparisons in this domain have gradually congealed into a single concept, which we have called “functionality gain.” Intuitively, the fabrication processes with the highest functionality gain are able to make the most useful products out of raw materials with the least preparation. For remote fabrication systems of a given mass and power consumption allotment, the ideal process would have a functionality gain sufficient to permit the conversion of raw extraterrestrial resources directly into operational robots, instruments, structures and more. To permit comparisons of output products on the basis of functional utility, some measure of “functional equivalence” must also be applied. The reason for this is that different fabrication processes might be able to arrive at products with identical functionality, given any set of criteria for this, but which are otherwise quite distinct in materials, morphologies, physical principles. Conventional replacement parts are more or less identical to original parts, but as an example, a MEMS resonator device might replace a tuned LC oscillator in a radio-frequency communications system – for most purposes, the two are indistinguishable, despite the different fabrication methods and physical operating principles involved. To state that the fabrication system in our concept can build an operational robot with certain functionality does not imply that the robot would be recognizable to someone at JPL, for instance. With actual output products in hand, it is simple to establish the functionality through testing, but being stuck at the conceptual level we have need of a rational basis for allocating our research efforts, and for communicating ideas and results to others.

Quantifying the concepts of functionality gain and functional equivalence are therefore top priorities for the next stage of our research, and the feasibility of a remote fabrication system in the foreseeable future depends upon the incorporation of fabrication processes with very high functionality gain.

Solid Freeform Fabrication

Introduction

The key to and inspiration for this concept is a set of manufacturing processes known as Solid Freeform Fabrication (SFF) and sometimes known as Rapid Prototyping (RP). Intuitively at least, these processes have a far higher functionality gain than traditional fabrication processes like machining, casting, or welding.

SFF processes differ from traditional fabrication processes primarily by being additive, rather than subtractive – material is added to the workpiece in small droplets, streams, or layers, rather than being cut away from a bar or billet. The process flow for solid freeform fabrication begins with part geometry designed in a solid-modeling computer aided design (CAD) software package.

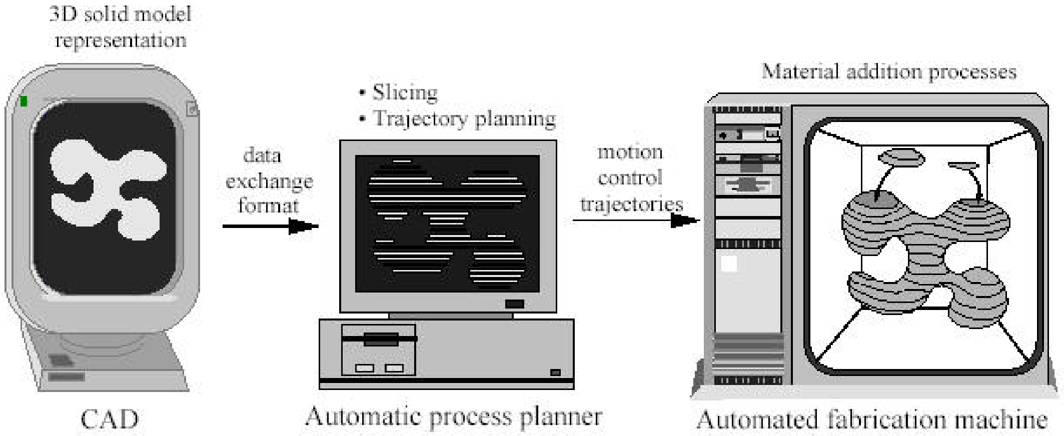

Figure 1: SFF Process Flow (Prinz et. al., 1997, p.5)

The geometry data is typically exported as a stereolithography (STL) format file (most CAD packages include this feature), wherein surfaces are represented by a triangular mesh. Most commercial SFF systems provide software which can automatically verify that STL geometry data is valid (represents a finite solid part), and then "slice" the part into 2.5 dimensional layers and generate tool paths at a resolution appropriate for the capabilities of the system. Paths typically consist of interpolated curvilinear part boundaries, and lower-resolution, piecewise-linear raster scans, which are used to fill part interiors. Computer control of the location and rate of material deposition permits the fabrication of parts with almost arbitrary geometry, and many of these processes produce almost no waste material by depositing only what is needed. Many SFF processes also possess the capability of producing working mechanisms and articulations in one step – no assembly required.

Figure 2: Functional Ball Joint made via FDM

Depending upon the particular process, it may be necessary for overhanging or detached portions of parts to be supported during fabrication. In some cases this is achieved by explicit construction of easily detached support structures, using the primary material or a specialized support material. In other cases, excess construction material (powder, for instance) provides support. Support structures typically need to be removed before the part can be considered complete. Careful design can reduce or eliminate the need for support structures in many cases, however.

Currently, three use categories dominate the commercial applications of SFF systems. The first, and probably still the dominant use, is for production of tangible three-dimensional, dimensionally accurate models. Such models are used for the communication of design information e.g. to customers, before more costly prototyping and detail design begin, for fit and finish testing of parts e.g. to check mating and alignment, or serviceability, and more recently, for the quick production of prostheses and reference models for reconstructive surgery and other medical applications [Crawford R., et. al., 1999, p40].

Figure 3: Skull Model made via SLA[3]

The second use category is the production of injection molding tooling, and is growing rapidly and driving much of the innovation in SFF materials and processes. Traditional methods for producing injection molding tooling require the labor intensive machining of complex cores and fixtures (the negative of the parts to be molded), and careful design and expertise is required to achieve good quality parts and long tool life. A typical mass-production quality tool can cost $10K or more. As a result, there is strong incentive to find cheaper and faster methods for producing tooling. SFF processes have filled this demand in two ways. The first is by providing a means of producing tooling directly which is sufficiently durable for production testing, and capable of lasting for short production runs of up to a few thousand parts. The second is an indirect process, in which a casting wax part form is made via SFF, including the gates and runners (channels which direct plastic into the mold). The wax form is then coated with plaster or ceramic, and a metal investment casting process is used to produce the tooling, which then usually requires some machining to be ready for use.

The third use category is the smallest, and has only become possible with the advent of commercial SFF systems capable of producing parts from more durable materials. Anyone

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[3] University of Zurich, Multimedia Lab

who has produced an engineering part model using an SFF process has probably wanted to go ahead and install and use the part, at least for testing in a prototype. In the past, the build materials were too fragile for this to be sensible, but now that commercial systems can produce parts directly in a few engineering thermoplastics (and most recently in high-performance metals and alloys), it has become a reality. In many cases, the parts may need to be machined to achieve satisfactory tolerances, but in some cases the parts can be used directly after fabrication. SFF system manufacturer's websites are now beginning to include customer anecdotes of emergency repairs and dramatic downtime cost savings resulting from being able to manufacture reasonably durable critical replacement parts from designs in hours[4]. Despite this exciting development, certain drawbacks still limit the application of commercial SFF processes in the production of functional parts to small niches, namely slow build rates (typically a few hours per cubic inch of part), limited choice of materials, poor surface finish / low resolution, high capital costs, and poor energy efficiency.

History

A fascinating description of the technological precursors to solid freeform fabrication is given by Prinz[5]. Some noteworthy milestones are worth mentioning here.

Blanther (1892) describes a layered method for the production of geographical topographical models: sheets of wax are cut to the shape of topographical contour lines, then stacked and smoothed to form a model of the 3-dimensional topography. A 1902 patent application describes a technique for the production of 3-D likenesses by exposure of photosensitive gelatin to light through photonegatives taken from different perspectives. By the late 1960's the concepts of stimulating the polymerization of photosensitive resins by lasers or masked UV sources was being explored, and by the early 1970's, the sintering of powders using various directed beam energy sources had been described. In 1988, 3D Systems shipped its first Stereo-Lithography (SLA) machine, and proceeded to define the commercial market for rapid prototyping[6].

Survey of Commercial SFF

Chapter 2 of JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan, Volume I[7] is an excellent summary of commercial SFF processes, but since its writing (1997), several new processes have entered the marketplace.

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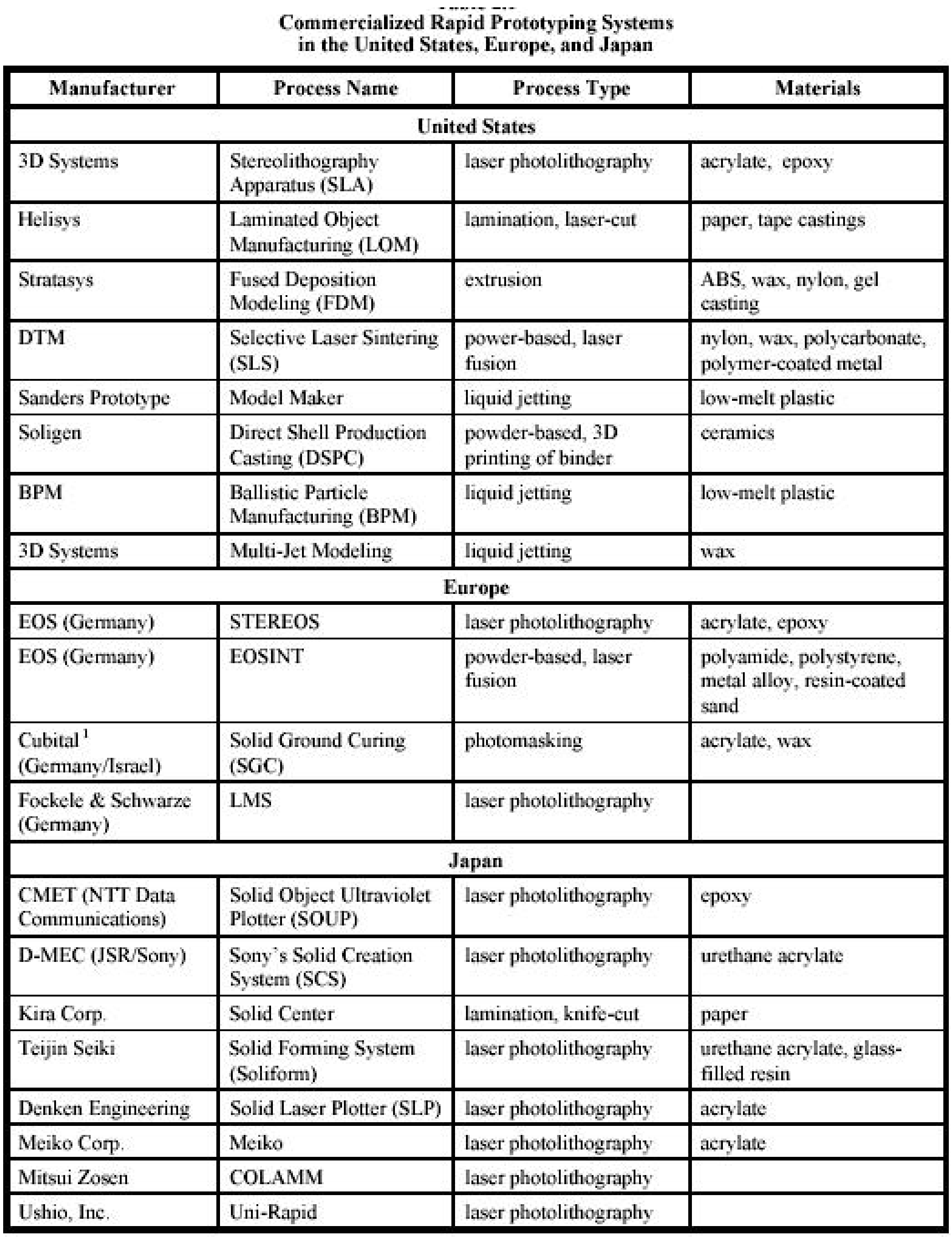
[4] http://www.stratasys.com/pulley.html

[5] Prinz, F. et. al., 1997, Chap.3

[6] Prinz, F. et. al., 1997, p25

[7] Prinz, F. et. al., 1997



Commercialized Rapid Prototyping Systems
in the United States, Europe, and Japan

Manufacturer	Process Name	Process Type	Materials
United States			
3D Systems	Stereolithography Apparatus (SLA)	laser photolithography	acrylate, epoxy
Helisys	Laminated Object Manufacturing (LOM)	lamination, laser-cut	paper, tape castings
Stratasys	Fused Deposition Modeling (FDM)	extrusion	ABS, wax, nylon, gel casting
DTM	Selective Laser Sintering (SLS)	power-based, laser fusion	nylon, wax, polycarbonate, polymer-coated metal
Sanders Prototype	Model Maker	liquid jetting	low-melt plastic
Soligen	Direct Shell Production Casting (DSPC)	powder-based, 3D printing of binder	ceramics
BPM	Ballistic Particle Manufacturing (BPM)	liquid jetting	low-melt plastic
3D Systems	Multi-Jet Modeling	liquid jetting	wax
Europe			
EOS (Germany)	STEREOS	laser photolithography	acrylate, epoxy
EOS (Germany)	EOSINT	powder-based, laser fusion	polyamide, polystyrene, metal alloy, resin-coated sand
Cubital[1] (Germany/Israel)	Solid Ground Curing (SGC)	photomasking	acrylate, wax
Fockele & Schwarze (Germany)	LMS	laser photolithography	
Japan			
CMET (NTT Data Communications)	Solid Object Ultraviolet Plotter (SOUP)	laser photolithography	epoxy
D-MEC (JSR/Sony)	Sony's Solid Creation System (SCS)	laser photolithography	urethane acrylate
Kira Corp.	Solid Center	lamination, knife-cut	paper
Teijin Seiki	Solid Forming System (Soliform)	laser photolithography	urethane acrylate, glass-filled resin
Denken Engineering	Solid Laser Plotter (SLP)	laser photolithography	acrylate
Meiko Corp.	Meiko	laser photolithography	acrylate
Mitsui Zosen	COLAMM	laser photolithography	
Ushio, Inc.	Uni-Rapid	laser photolithography	

Figure 4: Commercial SFF Processes as of 1997[8]

Among the most exciting new technologies are Laser Engineered Net Shaping (LENS), developed at Sandia National Labs, and available from Optomec Incorporated[9], and LasForm, offered by AeroMet Corporation[10]. In these processes, a high-power (> 500W) Neodymium

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[8] Prinz,F. et. al., 1997, p.8

[9] http://www.optomec.com

[10] http://www.aerometcorp.com

Yttrium-Aluminum Garnet (NdYAG) laser is used to melt metal powders which are sprayed into the focal point of the laser beam. These processes can produce fully dense, near-net shape metal parts without the kiln firing required for SLS metal parts, and with the ability to control composition (through content of powder spray) in 3 dimensions. Because of the very rapid cooling of the molten material, metallurgical properties are excellent. Feature size (~ 0.030") is one of the few current limitations of this process, but one which seems likely to improve with technological maturity. Several military contracts have been awarded for the use of LasForm in the repair and production of aircraft parts[11], and there is some indication that this may permit cost reduction and fabrication time reduction compared to other fabrication processes, despite still requiring finish machining (Arcella, F.G., 2000).

Figure 5: Titanium Parts made by LasForm DMD Process[12]

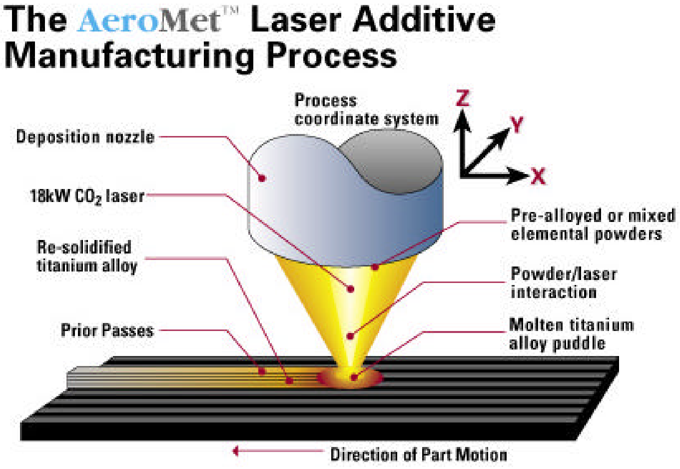

Figure 6: AeroMet LasForm Process[13]

Optomec has also commercialized a process which can be used for the solid freeform fabrication of small parts in metals, ceramics and combinations, capable of producing feature sizes as small as 25µm. The M^3D process[14] is a refined thermal-spray deposition process, in

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[11] http://www.aerometcorp.com/News.htm

[12] [Arcella, F.G., 2000]

[13] http://www.aerometcorp.com/additive_process.htm

[14] **http://www.optomec.com/m3d/index.htm**

which a powder feedstock is atomized (presumably by a plasma) and sprayed in a fine stream by a compressed gas. Superheated droplets are deposited onto the workpiece or substrate, where they remelt neighbors to form a bond. The resultant material may need to be further densified with a laser or in a furnace.

Survey of SFF R&D

There is a great deal of commercial and academic R&D seeking to overcome the aforementioned weaknesses of current processes, and commercial applications are moving rapidly from production of engineering models for fit, finish, and design communication, through tooling production for injection molding and near net-shape metal forms which can be machined into useable parts, toward multi-material, multifunctional components and mass-customized products. In general, the aggregate capabilities of all SFF processes seem to be progressing toward "functional universality," meaning that for any functional system made by conventional fabrication processes, it is becoming possible to see how a system of equivalent functionality can be made via SFF. Relative to the fabrication processes involved in the factory concepts of the Advanced Automation for Space Missions studies, namely traditional machining, casting, welding, etc, SFF processes intuitively seem to possess far greater functionality gain, and permit comparable or superior fabrication work to be achieved by a far smaller, simpler, more efficient deployed system.

At the University of Connecticut, an SFF process called SALD has been developed which can fabricate and weld ceramic and cemented carbide parts [Marcus *et al*, 1998]. SALD is based on the idea of using a laser to trigger localized chemical vapor deposition (laser CVD). SALD has also been used to produce functional silicon carbide/carbon thermocouples on alumina substrates [Sun *et al*, 1998]. At Rutgers University, piezo-ceramic actuators that include conductors and other materials have been fabricated via a fused-deposition-modeling (FDM) process, followed by densification in a furnace [Safari et al, 2000]. A standard Stratasys FDM machine was employed, but a custom made feedstock was used to generate the green (unfired) ceramic part, which was then densified and "poled"(electric polarization applied near the Curie temperature, and frozen in) in a furnace. The feedstock is a wire made of lead-zirconate-titanate (PZT) powder bound together with a thermoplastic. Processes are being investigated at Sciperio Inc.[15] which can write electronic components directly to the surface other structures, even high-temperature intolerant materials, such as plastics [Barrow , 1997]. These processes are based on the deposition of precursor materials in the form of sol-gels, which are then stimulated to reaction by a laser beam to form the desired material with electronic properties. The precise localized heating of the laser beam prevents damage to a more delicate substrate. A laser CVD process has been used at Louisiana Tech to produce functional microsolenoids, inductor coils, and springs out of silicon carbide [Williams *et al*, 2000]. SFF optics based on sintered glasses are also being investigated [Barrow, 1997].

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[15] http://www.sciperio.com

Early work exploring the production of functional mechatronics by SFF has been performed by one of the authors [Lipson and Pollack, 2000]. The Golem robots demonstrate the capability of an SFF process (FDM in this case) to fabricate complex, articulated mechanical assemblies in a single process, and having been designed via a simulated evolutionary process, arguably represent the first ever physical incarnation of artificial life. Nevertheless, Golem robots require significant human input and exogenous components (power, control, actuators) to be actively functional. The ability to build components that are exogenous to the SFF process, such as sensors or electronics, into a part has been demonstrated [Li *et al*, 2000; Weiss and Prinz, 1998], but the actual autonomous fabrication of sensors, actuators, power sources and circuitry along with structure in an SFF process is only beginning to be investigated.

Space applications of SFF are beginning to generate some publications. An investigation of the pros and cons of using conventional laser direct metal deposition (like LENS or LasForm) of on-demand spare parts in space [Krantz et. al.]. A Stratasys FDM machine has been flown on a NASA KC-135 “Vomit Comet” airplane in order to investigate the behavior of fused deposition modeling in reduced gravity [Crocket et. al., 2000]. Focused Solar Sintering [McKay et. al. 1996] has been suggested as novel and very energy efficient SFF process. The authors suggest that solar photons, focused by a mirror or other concentrator could be employed in lieu of lasers in sintering or direct metal deposition type processes. Near the Earth, the sun provides about 3 kW/m^2 of collecting area, and studies by Nakamura (Nakamura et. al. 1994), suggest that an optical waveguide (fiber optic cable) could be used to transport and direct or distribute the collected solar energy for use in a variety of ISRU processes with high efficiency (80%) over moderate distances (10m). Cognizant of the low efficiency of lasers, and the potential problems of handling powdered feedstocks in reduced gravity and vacuum, researchers at NASA JSC and LaRC have begun to construct an electron beam SFF system (Watson et. al.). One drawback to employing an electron beam is that the sudden deceleration of electrons upon hitting atomic nuclei in the feedstock or surroundings causes the release of (Bremsstrahlung) X-rays, which are hazardous to humans, and can degrade some materials (polymers, for instance). The design proposed copes with the X-ray problem by using low acceleration voltage, hence lower electron kinetic energy, but compensates for the lower energy by increasing the electron current. Some of the possible space applications for this system and SFF in general are explored in (Taminger, Hafley, Dicus, 2002)

Hopefully the above information has convinced the reader that a rapid expansion of the capabilities and applications of SFF is underway, supported by commercial, academic, and governmental R&D. Prior to receipt of this NIAC Phase I grant, we possessed only limited experience with SFF technology, and that as users of commercial systems. The literature survey and experiments conducted have led us to the conviction athat SFF is already far more capable and progressing far more rapidly than we expected.

Architecture Concept in Detail

Introduction

Beginning from the initial idea of fabricating functional systems *in situ* in order to accelerate the design and deployment cycle for robotic exploration, and the identification of SFF as a key enabling technology family, we have proceeded to explore our initial deployment scenario, namely planetary surface exploration. Most of that informal vision has been described in the introduction to the concept, but from it we have derived most of the qualitative requirements and conceptual models in this architecture.

Using planetary surface exploration as the archetype mission, we were able to identify some of the key requirements for a remote fabrication system suitable for promoting NASA's exploration efforts beyond the next decade. The most fundamental requirement from our perspective is that to propose our system as part of an exploration mission, it must be of greater net benefit to the overall mission goals than any foregone alternative. From this we have been able to derive some slightly more concrete requirements which we should be able to propagate into detailed engineering requirements with additional research.

As a simple example, take the archetype mission to be the upcoming Athena/MER mission, in which two identical rovers will be sent via separate launches to Mars.

Nominal Mission Duration	90 sols	
Rover mass allocated/cumulative	185 kg (408 lbs)	185 kg (408 lbs)
Lander mass allocated/cumulative	348 kg (767 lbs)	533 kg (1,175 lbs)
MER Solar Power mission start / end	140W * 4 h/sol	50W * 4 h/sol
Cruise Stage Dimensions (diameter, height)	2.65 m	1.6 m

MER / Athena Mission Facts (Source

In the context of this archetype mission, what might a fabrication system be deployed in lieu of? The obvious answer in this case would be one of the rovers (arguments have already been made about why both rovers is an unlikely choice). Well, the safely landed mass of the lander and rover is 533 kg. We can take this as an order of magnitude mass for a fabrication system. The next question is, "Can a fabrication system of 533 kg mass offer more benefit to our archetype mission than a duplicate rover?" The duplicate rover adds redundancy to the mission, as well as the chance to collect data at two separate locations simultaneously – double the scientific return in the best case. This implies two more requirements: first, increase mission reliability by 100%, or perhaps in proportion to the fraction of mission mass comprised by the fabrication system; second increase scientific return by 100% or again in proportion to mass. These are very challenging requirements and perhaps overly pessimistic about importance of launch costs 10 – 40 years in the future, but they provide a dose of realism, and are quantitative – both difficult to come by in studies of futuristic concepts. These requirements provide a focus for creative and critical review of the concept: Can of a fabrication system double the scientific return by enabling a doubling of the mission duration through maintenance and repair, or by fabricating additional instruments, or even specialized scientific robots as data is obtained? To what extent do maintenance and repair increase the reliability of a mission, as opposed to the fabrication of new systems? The reliability and robustness of the fabrication system itself are obviously critical from this perspective. Recycling and ISRU might extract more value from a given mission mass, but can these capabilities be included within the mass limit without reducing the capability and reliability of the overall mission?

Decomposition

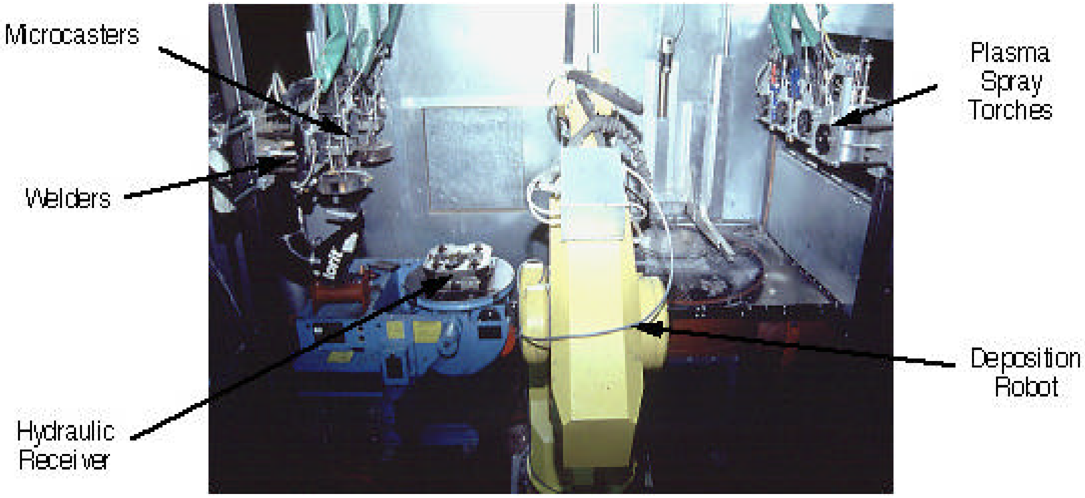
Such questions have guided our decomposition of the remote fabrication architecture into sets of building block technologies.

Decomposition of Fabrication Architecture

1. Primary Hardware
    a. Manipulation
    b. Deposition Tools
    c. Feedstock management
    d. Enclosure / environment
    e. Sensing / control
2. Primary Software
    a. Low Level Control
        i. Tools
        ii. Feedstock management
        iii. Manipulation
        iv. Build environment
    b. Overall process feedback control
3. Consumables
    a. Power

Primary Hardware

a. Manipulation – Solid freeform fabrication systems require the relative motion of the workpiece and the point of material addition. Most commercial systems use Cartesian robots (basically comprised of stacked linear motion stages) to move either the deposition tool or the workpiece, because they simplify control and can be made very rigid, which permits fast and accurate fabrication. As an alternative to this, one might consider using an articulated robot arm to manipulate the workpiece or tool as has been experimented with at Carnegie Mellon University's Shape Deposition Laboratory, and in our own technology evaluation platform. In general, articulated arms are more difficult to control, less rigid, and less accurate than Cartesian robots, but may offer more dexterity and perhaps can serve more purposes in the context of a fabrication system. This is really an unfair comparison, in that most commercial Cartesian robots have two or three controlled axes– completely adequate for current commercial SFF processes – while most articulated robots have five or more controlled joints. The comparison does serve to illuminate some aspects of the manipulation tradeoff space that are of concern in a fabrication system. Dexterity is desirable because it permits deposition along more general paths, which can enable engineering of anisotropic materials and optimal alignment of material properties to part geometry and functionality. Wiring or reinforcement fibers can then follow more arbitrary paths through a part, for instance. A more general manipulator can be employed in a broader array of assembly, disassembly and repair operations, resulting in a more compact and perhaps simpler system. Combinations of designs make a lot of sense - arms can hold tools, or perhaps position workpieces for a build operation performed by a more rigid positioning system. Multiple manipulators can increase the generality of fabrication, but also the robustness of the system – simple redundancy enables the system to keep functioning despite a failure, but more importantly, a failed manipulator might be repaired by the remaining capability. Multiple manipulators also make self-extension and perhaps self-replication more feasible - one manipulator might add capabilities to another by disassembling and restructuring it, or by adding components directly to it. In general, one would expect that the manipulation system would be optimized for the deployment scenario – and not necessarily conform to the designs of today's commercially available manipulators – 10 to 40 years of development may bring a revolution in manipulation technology.



Source: CMU[16]

b. Deposition Tools / Processes - As the section describing solid freeform fabrication indicated, there are many different ways of adding material to a workpiece. The cost of space transportation, the demand for reliability, and the promise of self-replication all suggest searching for a "basis set" of processes those processes with the highest possible functionality gain which taken together can fabricate a set of systems capable of a desired range of functionality. What constitutes a basis set of processes depends upon the functionality desired of its end products – so here again we base our concept on an archetypal mission. To support a robotic planetary surface exploration mission, we would like to be able to fabricate entire exploration robots, making use of the most readily obtained materials (minimizing the use of materials and components sent from Earth). Being built locally, such robots would not need to survive launch and landing conditions, and could be specialized for the environment in which they are deployed – hence they could be simpler and less robust than conventional planetary robotics. Nevertheless, they would need to be more or less functionally equivalent to a scientific rover – including science instruments, actuators, structures, joints, communications and control electronics, power storage and generation. No single process conceived of today can do all of this, but as has been described, many of these functions have been demonstrated by products of SFF processes. We are convinced that eventually a suitably developed combination of current and future processes will constitute a basis set for this and other target functionalities. Until that time, the production of systems of the required functionality will require the incorporation of components and subsystems supplied from Earth. Of the current commercial and research SFF processes, three seem to stand out in terms of their potential for high functionality gain and suitability for space applications. SFF using solar photons collected by a mirror and delivered by an optical waveguide to melt a feedstock is applicable to a wide variety of materials, and extremely efficient in the inner solar system, but may be resolution (focusing optics) limited. Electron beam SFF emits x-rays, and may require some modification to work with non-conducting materials, but has a high power efficiency, high resolution, and is relatively simple to build and is robust. Laser Direct Metal Deposition (DMD) offers broad material applicability - though highly reflective metals can pose a problem, and has high resolution, but is more complex to build, less robust, and power-inefficient. Laser materials processing is fairly mature, and studies and industrial application have demonstrated the ability of lasers to weld, polish, harden, clad and more (Nagarathnam1 and Taminger). Some of these capabilities extend to electron beams, and focused solar energy is probably the least flexible in this respect.

c. Feedstock management –It is essential that feedstock delivery systems be extremely reliable, easily repaired and constructed, and robust – for this reason our inclination is to avoid processes that involve extrusion from reservoirs of molten materials or liquid state feedstocks, such as FDM, SLA, or any kind of

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[16] http://www-2.cs.cmu.edu/~sdm/

liquid polymerization. Nozzles are prone to clogging, and are difficult to repair, and fluids are difficult to control with precision. Solid state feedstocks which are heated at the point of application seem the best choice – the most environmentally stable. Current metal deposition SFF processes (LENS, DMD) typically use powdered feedstocks. This might be a relatively easy form to produce via recycling or ISRU, but compressed gas is typically required to feed the powder, clogging is problem. In addition, powders are probably not suitable for use in vacuum or zero-g because of vacuum welding of the feedstock supply, and the uncontrollable spreading of residual powder (Krantz, 2001). Wire or tape form feedstock is preferable in many cases and can be fed from a spool by a motor. Solid feedstock forms may be well-complemented by triggered chemical vapor deposition (as in the SALD process) where the deposition of chemical reaction products is necessary. Technological advancements may improve the utility and ease of use of any or all of solid, liquid, or gas phase feedstocks, and in any case, the appropriate choice will depend on the deployment environment.

d. Enclosure / environment – Some processes may require vacuum (electron beam) or gas shielding to ensure desirable material properties (e.g. DMD); others might require a gaseous chemical precursor environment (SALD). These could be incorporated into the feedstock management system as a gas jet or small bell jar, or the fabrication system might be fully enclosed by a sealed chamber. The latter restricts manipulator motion and generality of construction somewhat. Additional concerns are the contamination of tool optics or electrodes by vapors – careful enclosure or tool design will be required to maximize useful lifetime and the ease of repair/replacement of less durable components.

e. Sensing / control – It has come to be realized that achieving consistently high product quality from SFF systems requires feedback on the full process, including material feed, quality, power levels, melt –pool or stream sizes and cooling rates, etc. Some commercial systems now offer process sensors to monitor melt-pool temperature and size in order to provide feedback on many of these variables (LasMet, Optomec), but it is not clear whether a set of single process sensors will suffice to monitor integrated production in multiple processes and materials – especially when process quality includes evaluating the functional performance of the produced system. Perhaps it is possible to identify a basis set of process sensors to accompany a basis set of processes. In addition to process control sensing, a fabrication system will require a complete suite of computers and sensors as required by autonomous operation or teleoperation. Keeping such components as simple as possible enhances their robustness and the likelihood that they can eventually be produced *in situ.* Distributing control across redundant computational hardware will also ensure graceful degradation and improve robustness. In the near term, sensing and control do not comprise a major portion of the technical challenge of this architecture, but with increasingly remote deployment, process control autonomy, and eventually design automation will become essential, and will include substantially greater computational resources.

Primary Software

a. Low Level Control - Local low level automation is necessary because the timescales with many of the fabrication operations are fast relative to communications latency to likely exploration targets, and process quality control demands automation. Frequent minor process deviations will also require human intervention or local intelligence to permit continuous long term operation.

    i. Tools – The control system for each tool needs to be tuned for best performance and longest life. There will be merit to including process monitoring to predict upcoming failures, and performance degradation. There is a tradeoff, here and everywhere, between the control enhancement of additional sensing and prediction and the additional failure modes associated with this additional complexity.

    ii. Feedstock management – Material feeds are a likely source of system failure or malfunction (manipulating powders or wire), so the control system needs to have substantial diagnostic and error recovery capability.

    iii. Manipulation – If articulated arm manipulators are moving the fabrication tools or workpieces, the resolution of the build operation will be limited by the manipulator path tracking accuracy, which is very sensitive to the quality of the feedback control system. If multiple manipulators are included in the realization, then robustness may be enhanced by distributed control, with each manipulator acting as a separate system. In the event of failure of one manipulator, the fabricator might retain most of its capabilities, and functional manipulators might be able to effect a repair or reconstruction of the faulty one. In any event, coordinated real-time control of tools and manipulators is essential to achieve high-quality fabrication.

    iv. Build environment – If a controlled atmosphere is required for a given process, it will be necessary to control gas pressures, flow rates, and perhaps temperature or other variables to ensure process output quality.

b. Overall process feedback control– most current commercial SFF processes, if they use any feedback control at all, use it only for low-level control of subsystems, for instance deposition motion, and feedstock feed rate – they do not include an overall process feedback loop to ensure that all subsystems are operating in optimal coordination. For technician-attended build operations in a controlled environment, this is not a great concern, but for an autonomous field deployed system, this becomes essential, so that environmental, power supply, feedstock quality, or manipulator performance fluctuations do not adversely impact the quality of products. This issue is beginning to be investigated by members of the SFF research community (Kranz et al, 2001). Closed loop process control of this sort requires the creation of fairly detailed and accurate dynamical model of the process – this is not a trivial task, and such models must be constructed or adapted for each material / tool combination. A fabrication system incorporating several tools and working with less than ideal recycled or ISRU materials in poorly understood and poorly controlled environments will need very robust and sophisticated process feedback control in order to produce operational functional systems.

Consumables

a. Power – Current commercial SFF systems are not optimized for power efficiency. Wall plug efficiency is not even listed for most of them, but estimates are possible from the known efficiency of key components. Nd-YAG Lasers – 10% and electron beams – 80% efficient with electrical input power, which is likely to come from PV (12-15% efficient), RTG, or sun/shade thermal generation. Focused solar with optical waveguide is 80% efficient for guides of ~10m – but this is direct from solar flux. Power is the same concern for all future missions – solar near sun, nuclear otherwise. Tools are primary power sink, so tool efficiency is critical.

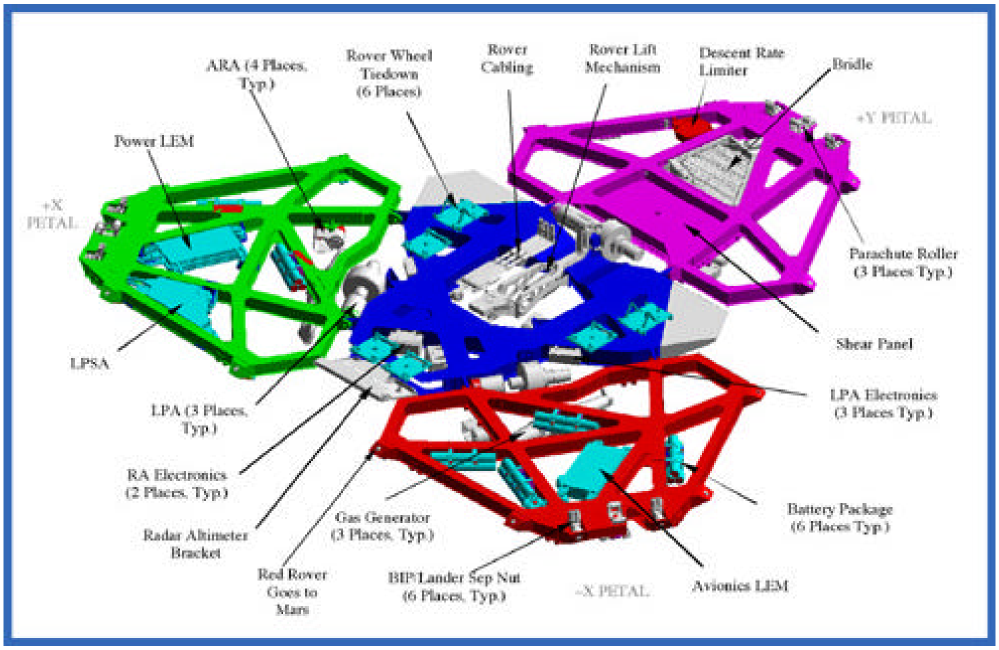
b. Feedstocks

c. Parts / components

Enabling Hardware

a. ISRU feedstock generation – Truly revolutionary possibilities occur when a remote fabrication system is combined with the ability to produce critical feedstocks from raw materials *in situ.* Mission duration and mission capability are then limited by what cannot be made, repaired, or recycled locally. To move beyond generating feedstocks from atmospheric gases, it must be possible to locate, extract, gather, and transport the desired raw materials to the site of the ISRU feedstock generation system. This is an enormous challenge, and worthy of several NIAC studies on its own, but this capability would be enormously valuable to any sort of *in situ* production, including support of human missions and robotic missions.

b. Reuse, Recycling – To make the most of a given amount of deployed mass, it is desirable to use material for multiple purposes. The ability to recycle complex components and refined raw materials may be a very powerful way to extend the scope and duration of a mission especially if all landed mass can be converted into functional systems which then actively serve the mission goals. This is only true as long as the recycling capability itself is not too complex, massive and resource intensive. As an example, a rover deployed to Mars needs to be equipped with some protection for descent through the atmosphere, and some means of achieving a safe landing. The robots of the upcoming MER Mission comprise only a small fraction of the mass that arrives at Mars. The lander is primarily a protective and deployment structure (see below) – once the rover is safely deployed, it becomes waste, despite being constructed of high performance materials and components, and comprising several functional subsystems. A lander might be disassembled for spare parts, or converted into feedstocks. One argument for the inclusion of articulated arm manipulators in our architecture is the possibility of using them for disassembly operations, and thus obtaining some of the benefits of recycling without need for specialized recycling equipment. For a long-term robotic outpost mission, the ability to recycle defunct or obsolete robots and systems into new designs based on improved knowledge of the environment, or new task definitions, may permit many different missions to be extracted from the same initial delivered mass, and in far less time and cost than required to send additional missions.



Source: JPL[17]

Enabling Software

a. Planning / Modeling / Simulation / Design Automation – As the focus of exploration moves beyond the inner solar system, communication latency and bandwidth limitations will demand increasing degrees of autonomy from all deployed systems. The products of a fabrication system are not needed in "real-time" – it is difficult to conceive of how a couple of hours either way would matter, so complete automation may be a lower priority for a fabrication system than for rovers, for instance. It may be in the nature of fabrication operations that they cannot be entirely scripted, however. Errors or deviations from the predicted behavior of deposited materials or process operation could result in faulty fabrication. Frequent enough deviations can only be handled by local feedback control, regardless of the proximity of humans. In this case, the remote system will need to be able to perform many of the more complex functions of action planning itself.

b. Product performance monitoring / feedback– In general, it will be necessary to monitor the overall performance of the fabrication system via testing or observing the performance of the fabricated system, and comparing this to a model or simulation of the expected performance. This may be necessary on top of low level process control because the goal is to fabricate an integrated functional system, for which performance as a whole is not guaranteed by the performance of subsystems alone, but also depends upon correct systems integration. This may

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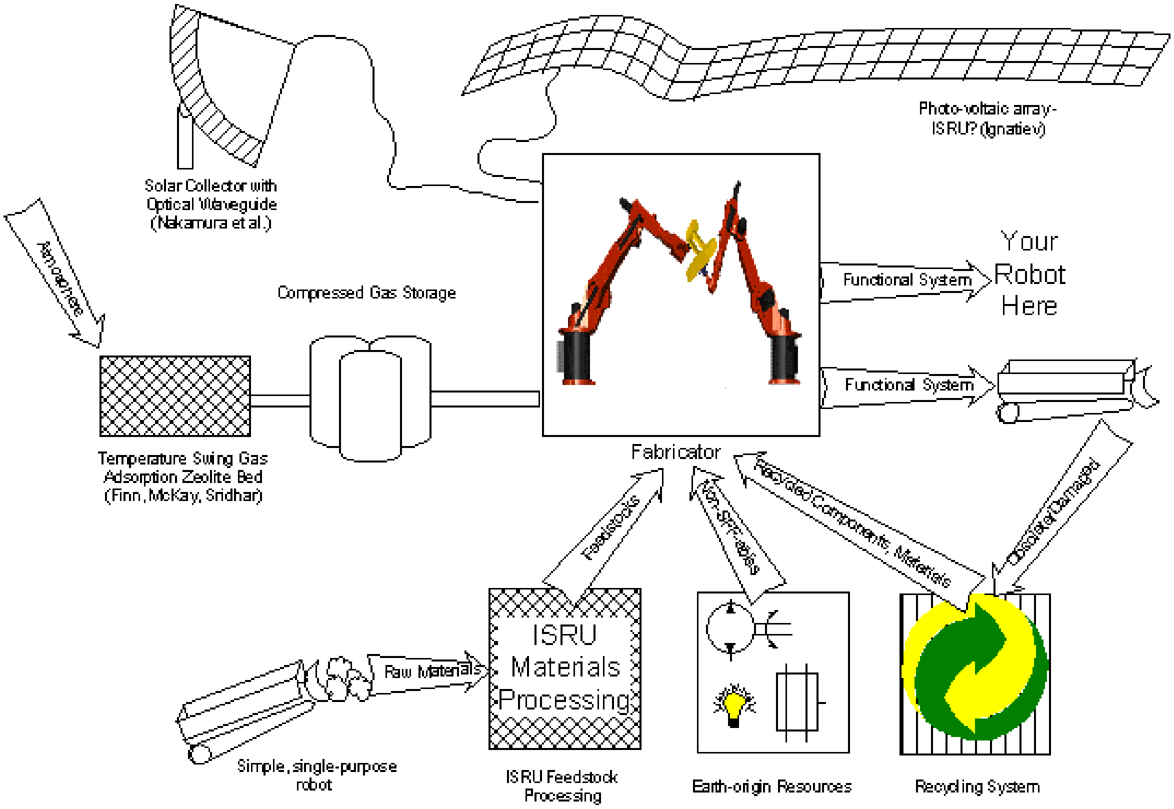
[17] http://mars.jpl.nasa.gov/mer/mission/spacecraft.html

or may not be autonomous, depending on the communication latency with Earth, or other cost/effectiveness measures. If autonomous, this is a very challenging machine intelligence problem.

c. Community interaction – There is some growing consensus that to progress beyond the current paradigm of exploration- namely one costly, brief mission at a time - will require establishing prolonged or permanent robotic outposts or even self-sustaining "robotic ecologies" [http://robosphere.arc.nasa.gov/#]. We would argue that a fabrication system is an essential and enabling member of such a community of robots, and as a member of such a community it would need to be capable of participating in the control system of the community, be it distributed or centralized. A fabrication system would be likely to be a major consumer of resources (power, materials), and also a major source of services (repair, new components, enhancements, other construction), and careful allocation of both according to the mission goals or community needs would greatly promote the success of such a mission.

Schematic

Below is a schematic of a mature fabrication system deployed with supporting ISRU and recycling technologies, and Earth-originating supplies. The configuration might be suitable as part of a Martian robotic outpost.



Mission Categories

Spares / repairs for near-Earth manned missions / large structures

This class of mission includes the nearest term deployments, possibly in this decade. These would likely be limited to simpler systems designed for spare parts production and repair activities near Earth, for instance on the ISS, or more likely on other large space structures such as Solar Power Satellites.

A spare parts production facility offers some relief from the need to launch and store a full inventory of spare parts, and the greater the capability, reliability and speed of the fabrication system, the more substantial the savings. NASA's HEDS Strategic Development Plan states that it is a mid-term (2006-2011) goal to "Test and validate technologies and systems that can reduce the overall mass of the human support system by a factor of three compared to 1990's levels." A compact fabrication system capable of producing and repairing parts, and more importantly of entire mechatronic systems, may achieve much of the desired support mass requirement, especially when coupled with advanced, efficient recycling technology.

It should be possible to begin to generate some quantitative requirements for this application by examining the actual spares inventory on the ISS to establish the volume, mass, and parts categories, and also to investigate the types of mechatronic systems which are prone to failure, but difficult to keep in stock. In any case, it is clear that because of the risk of fabrication system malfunction and its dependence upon power supply, an inventory of the most critical spares would probably still be needed.

A bit further off, but perhaps only a few years more, is the idea proposed by K. Taminger of NASA LaRC[18]. A mobile repair system based on SFF technology, which can move along the exterior of a spacecraft or large space structure (ISS, Solar power satellite, large telescope) might use its tools in one mode to search for structural failures and damage, and in another mode to perform repairs by welding or material deposition. Such a system offers significant cost and risk reduction if it can reduce the need for human EVA in repair and inspection tasks.

These missions are amenable to the near term deployment of a fabrication system because their proximity to Earth or manned space structures permits them to be teleoperated, reducing the level of machine intelligence required. Their location near Earth, in the inner solar system, also makes the use of solar concentrator-based SFF plausible. In addition, the technology for production of structural components in plastics, metals and ceramics is well demonstrated, and is being commercialized, and adaptations suitable for space deployment are being actively researched[19].

Mission	Near-Earth Spares on Demand Near-Earth Space Structure Repair
Timeframe	10 – 15 years

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[18] Taminger powder metals

[19] 2002 SFF, Watson

System Components	- Electron beam or solar concentrator energy deposition tools - Feedstock positioning - Tool / workpiece positioning - Mobility (for mobile diagnosis and repair) - Enclosure (for human protection or controlled atmosphere – not req'd when remote from humans) - Control, Communication electronics - Teleoperation sensors (video, process monitoring / telemetry)
Feedstocks	- Solid metal (wire / foil / tape) - Solid thermoplastic (wire, tape) - Ceramic powder in binder (wire, tape)
Products	- Structural component spare parts - Tools for human needs - Welding repairs
Selected Prerequisites	Validation of Solar Concentrator SFF Flight Qualified E-beam SFF system Fully net-shape parts (no post processing)

Robotic outposts for science and preparation for / support of human missions

The ability to fabricate entire, fully functional mechatronic systems permits major shifts in mission capabilities after deployment, while spare parts, even if fabricated *in situ* and on demand, only prolong the duration of a mission within its defined capabilities. As has been argued, it does not make sense to deploy only a fabrication system for critical early exploration of a planetary surface – conventional robotic systems will continue to improve in capabilities and robustness, and will offer a lower risk of failure for mass limited missions. There may be an exception to this eventually, in which a fabrication system could be sent to the site of a prior mission which is no longer operational to attempt to repair and recycle the previously deployed equipment. This might prove a more cost effective means of achieving a given deployment than sending an entire mission.

- acquire data and validate technologies,
- construct and validate infrastructure for later human expeditions, and
- make possible unique science activities before the arrival of human explorers

before 2011, as part of an ambitious and optimistic space frontier exploration. In such a mission, risk and cost can be decreased by the deployment of a fabrication system, since repair and recycling can prolong the useful life of other systems, and fabrication of new systems can ensure that an unforeseen need can be met without requiring additional launches from Earth. Interestingly, in this case the fabrication system itself limits the lifetime of the mission. It might be sensible in this case to allocate more resources, design effort, and mission mass and energy to ensuring the robustness and redundancy of the fabrication system over that of the other systems – presumably there is some optimal distribution which will maximize the benefit to the mission. It is for this reason that the default configuration of the fabrication system in our concept includes multiple dexterous manipulators with distributed control, permitting simple redundancy but also the possibility of self repair.

Similar arguments and concerns apply to the mix of feedstocks and parts sent with the system. Dependence on parts and feedstocks supplied from Earth limit the capabilities and lifetime of a fabricator mission. Addition of disassembly, recycling, and ISRU technologies to a mission will greatly reduce the dependence upon shipped materials, and therefore increase the scope and duration of the mission, but at the cost of mass and complexity. These technologies are only just beginning to be explored, making it difficult to perform rigorous trade studies to find the optimal mix for a given mission. We hope to collaborate with experts in these technologies to quantify the synergies and explore the trade space of what seem to be a suite of related and mutually beneficial technologies.

At the tail end of the time frame of robotic scientific outposts are missions which establish a robotic outpost in preparation for or support of a human mission. Such missions are intriguing because they are at the confluence of human and robotic exploration efforts, and the sometimes separate technological threads will begin to merge. The ESA Aurora program includes a robotic outpost on Mars in the 2020-2025 timeframe[21]. A robotic

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[20] http://www.hq.nasa.gov/osf/heds/hedsplan.html

[21] http://www.esa.int/export/esaCP/Pr_64_2002_p_EN.html

outpost is an extension of the idea a "robotic work crew"[22] to the establishment of a heterogeneous community of multiple work crews specialized for different tasks. Whether on the moon, Mars, or elsewhere, preparation for the arrival of humans will involve many of the same tasks. These include: deployment, assembly, and construction of large structures and systems including power generation systems, ISRU systems, shelters and habitats for robots or humans; site clearing; resource identification, gathering and processing; generation and storage of consumable and durable products, including propellants, consumable life-support gases, foodstuffs, tools, etc. Many of the same concerns associated with a scientific outpost apply here as well, with the exception that ISRU systems will almost certainly be deployed, along with a great deal more. The value of fabrication system beyond mere repair is evident in this setting: Immense mission mass savings through *in situ* fabrication of passive and functionally active products and systems which may include power generation systems; conversion, extension or recycling of series of robot work crews into new types dictated by phases of activity, e.g. site-clearing robots converted into construction robots. The transported mass of such a mission is likely to be much larger than one of purely scientific purpose, and the value of fabrication, recycling, and ISRU systems to not only reduce the initially deployed mass, but to multiply its effect once deployed, and to redirect it – autonomously, or on command, will justify allocating a substantial portion of that mass to these systems. A heritage of development for more tightly constrained missions will permit the inclusion of redundant, robust, full-featured, high performance fabricators on such a mission.

Mission	Robotic Scientific Outpost Manned Planetary Mission Preparations Manned Planetary Mission Support
Timeframe	15 – 25 years
System Components	• Electron beam or solar concentrator energy deposition tools • Multiple articulated manipulators • Control, Communication electronics • Teleoperation sensors (video, process monitoring / telemetry)
Feedstocks	• Solid metal (wire / foil / tape) • Solid thermoplastic (wire, tape) • Ceramic powder in binder (wire,

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[22] http://prl.jpl.nasa.gov/projects/rwc/rwc_index.html

	tape)
Products	• Structural component spare parts • Tools for human needs • Welding repairs
Selected Prerequisites	Validation of Solar Concentrator SFF Flight Qualified E-beam SFF system Fully net-shape parts (no post processing)

Self-sustaining / self-replicating robotic colony

At some point in the future of our exploration of space, a critical event will occur. It may approach so gradually that it will pass unobserved, but it will have dramatic implications, nonetheless. This event will be the elimination of the need of extraterrestrial human habitations for material contact with the Earth – the biosphere of the Earth releasing a seed; symbiosis of humanity with its own technology. Our technology may arrive at this milestone before us, however.

Self-sustaining robotic ecologies was the topic of a recent workshop at NASA Ames[23], and NASA's HEDS Enterprise proposes sometime beyond 2012 – to:

> • Complete the development of safe, self-sufficient, and self-sustaining systems that can enable humans to live and work in space and on other planets independent of Earth-provided logistics for extended periods.
>
> • Pursue ambitious collaborative robotic/engineering missions that expand activities at existing and additional key sites (i.e., "outposts") beyond low-Earth orbit.[Str. Plan]

Significant research is underway on how to control and organize heterogeneous teams of robots, how to construct them, and what their tasks might be, but there is very little discussion of how to actually make them self-sustaining. The conventional approach is to make everything more robust and longer lived, and perhaps to send swarms of small machines, or duplicate larger machines. When reconfiguration or repair are discussed (Dubowsky), they typically involve very complex systems, and it is not clear that the benefits of these concepts are worth the additional complexity (typically numerous specialized connectors, sensors, actuators). A fabrication system coupled with ISRU and recycling technology offers the alternate approach of repairing, reconfiguring and constructing

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[23] NASA Robosphere 2002

functional systems on demand, and greatly prolonging the useful lifetime of mission mass, systems, spares, feedstocks delivered from Earth.

Unfortunately, information leaks out of matter over time, even out of a stockpile of spare parts. Truly self-sustaining ecologies will require the construction of new robots, new power generation systems, new ISRU systems – even new fabrication systems! The line between self-sustaining systems and self-replicating systems is indistinct. Self-replicating machines have already been demonstrated[24], but only in circumstances where the environment has been structured specifically to promote this activity. Self-replication in "the wild" – an unstructured, hostile environment is much more difficult, but the simple demonstrations suggest the useful concept of a layered architecture for self-replication, in which each layer provides a structured environment to promote the replication of the layer above it. In general, for a system to be self-replicating, the entire suite of functional systems must be fabricated by the aggregate capability of those systems. This is sometimes referred to as a "recursive constraint." The self-replicating lunar factory of the Advanced Automation for Space Missions study struggled with this recursive constraint because of the low functionality gain processes considered. This required larger and more complex systems to produce any given product, but then these larger and more complex systems would need to be fabricated, and the system must grow to quite large size. In the intervening time, the functionality gain of fabrication processes has increased substantially, and an SFF-based system will be able to accomplish what required an entire production sector before. Even with decades of development, the best compact fabrication system will not be able to produce precisely the mechatronic system desired – it will not be truly universal. It may be much easier to approach a kind of "functional universality", in which the fabricated system can perform the desired function, though perhaps not operating on the principles expected or appearing as expected. The recursive constraint still exists, however, and a radical shift in perspective is necessary to cope with it. Everything must be as simple as possible to produce and just sufficient to perform its function, which typically means low tech, stupid, and ugly – human aesthetics get in the way. System performance is not optimal, but if self-replication is possible then probably additional systems can be produced to permit the desired level of productivity. A fabrication system designed as part of a self-replicating robotic ecology would need to be able to make most itself as well as all of the other systems, and must therefore be based on the simplest set of processes that can produce themselves.

Roadmap

It is our assumption that the current trends in research and commercialization of SFF technologies will continue for some time. The result should be an even broader range of processes, and functional product types than are available today, including some that have perhaps not yet been conceived. Many more materials will be available for use in these processes, and multiple material systems will become more common. There is probably sufficient commercial incentive for the elimination of most post-processing by increasing system resolution and perhaps incorporating surface finishing processes, such that true net-shape parts will be possible in durable materials. For this reason, we do not believe that it is necessary to our concept to expend research funds on developing or discovering particular

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[24] Chirijkian, Penrose

SFF processes, at the moment. However, commercial motives are not likely to result in the identification and integration of basis sets of processes into one compact unit, or to make great strides in energy efficiency, or to achieve the fabrication of entire functional mechatronic systems, or to work with extraterrestrial stimulant materials, ISRU product materials, and recycling systems.

For application to space exploration missions, however, a compact, efficient and integrated process is what is required. Unfortunately, even successful integration of all extant and nascent processes into one compact system would probably not be sufficient to justify deployment for NASA interests. Current processes are too sensitive to the form and quality of input materials, too little is understood of the requirements for solid freeform fabrication of integrated functional systems**,** and most of all there is a lack of a systematic method, or even experience, in the design of systems to be automatically fabricated, repaired, recycled, assembled, disassembled, and extended by these processes, using a limited range of materials, especially *in situ* derived materials. These new design paradigms need to be developed, and this is a significant challenge.

The complication of the design process associated with the introduction of these new paradigms will demand the use of advanced design automation methods. Evolutionary algorithms have demonstrated significant successes in searching complex design spaces and discovering novel solutions, and recent work in applications of evolutionary algorithms are building a foundation for the automatic design of complex functional systems (Hornby *et al*, 2000; Seo *et al*, 2002).

With the availability of mature design paradigms and design automation, missions making use of an advanced manufacturing capability might be designed by first specifying functionality desired of the mission hardware – mobility, sample collection, etc.- including perhaps a decision tree of functionality desired over time given discoveries made during the mission. An automated design process would then attempt to generate system designs to meet the functionality required under the constraints of mission mass, *in situ* and Earth-originating resources, and available ISRU, recycling, and fabrication technologies. Analysis of the results of the design process should be able to indicate the binding constraints, and which types of functionality are infeasible. This information would guide new technology development, and restatement of mission parameters, and mission objectives until convergence is obtained (Fig. 1). The beauty of a mission which includes these technologies is that the mission design process can continue after deployment, as new information is available, and for the duration of the mission. For a given supply of Earth-originating resources, far greater lifetime utility should be possible through reuse in successive generations of *in situ* manufactured equipment. Additionally, mission duration and capability would be limited by materials and products not available or fabricable on site, so pre-deployment design and development efforts can concentrate on those.

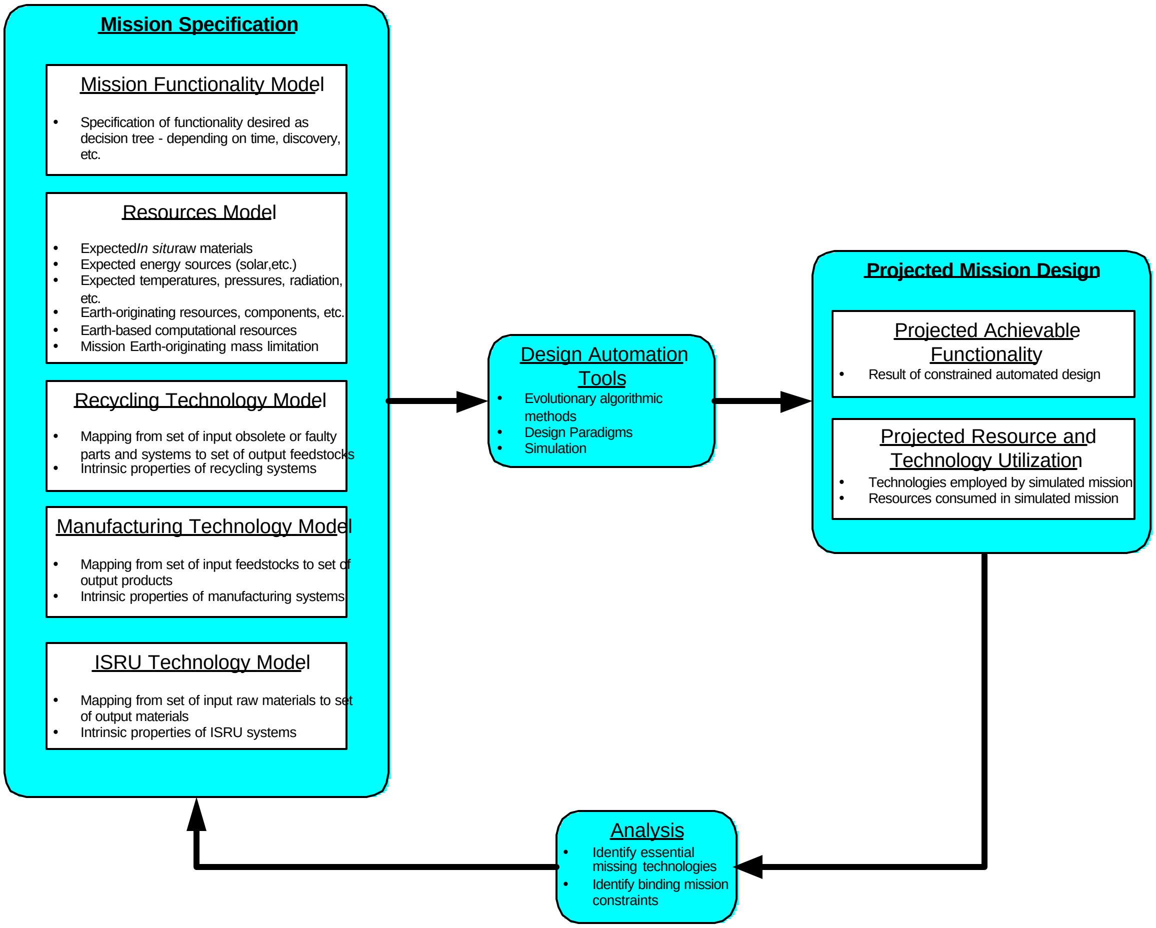


Figure 1: Mission Design Loop

Emerging from these observations and projections is an organization of the architecture development roadmap around two arteries – the integration, generalization, and automation of SFF, ISRU, and recycling processes for fabrication, maintenance and extension of nearly arbitrary functional systems, and the development of the design paradigms and design automation tools to make effective use of the technologies.

It is our hope that we can interest others in this concept, and form collaborations with researchers in the fields SFF process development, and ISRU and recycling technology in order to begin experimenting with the most promising new processes, and the types and forms of materials most likely to be produced by ISRU and recycling. Such collaborations can also serve to identify how our concept might enable the repair, extension, and eventual production of these associated systems, and we may be able to suggest some new avenues of research by presenting our concept as a potential consumer of SFF processes, and of particular types of recycled and ISRU products.

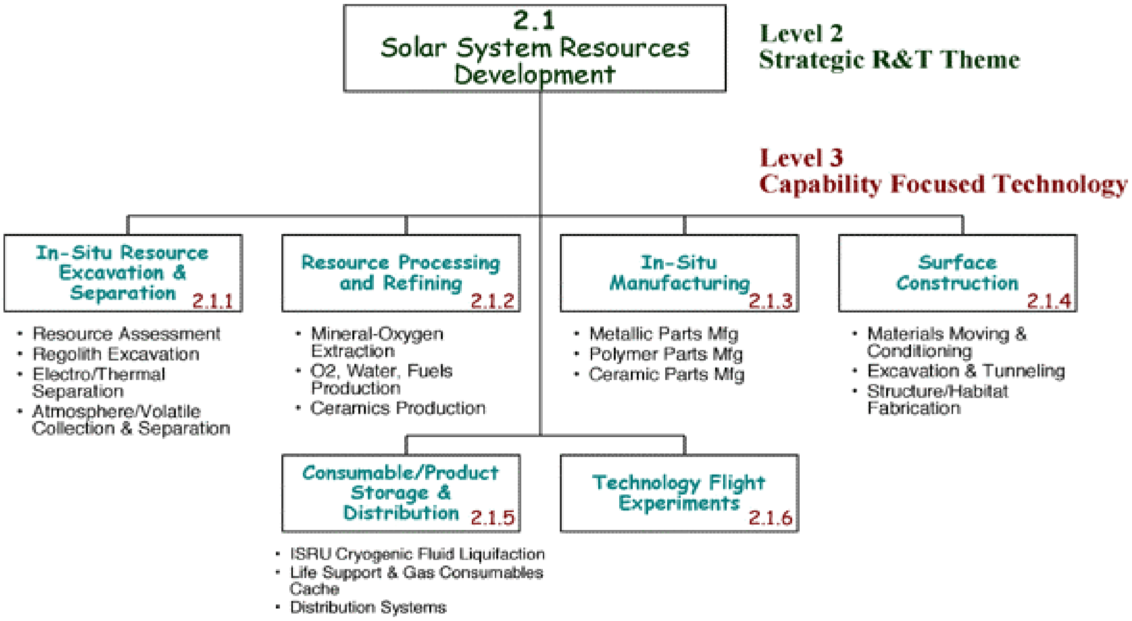
NASA’s HEDS Enterprise Advanced Systems Office has recently identified several of the key aspects of our concept within its Technology for Human/Robotic Exploration and Development of Space (THREADS) roadmaps.

Objectives:

- Develop and validate the technology to utilize local resources, such as Regolith/Minerals, Ices and Atmosphere--in order to produce, process and deliver consumables; fabricate key physical structural systems/elements from local materials; enable local fabrication of selected "finished products" and/or "end items"
- Test key technologies and demonstrate innovative new systems concepts in space
- Establish a foundation for profitable commercial development of solar system resources in the mid-to far-term

Goals:

- Drive down the cost of human/robotic exploration missions and campaigns
- Support improved health/safety for human explorers beyond Earth orbit
- Work collaboratively with the space science community to test concepts and technologies



(source http://threads.nasa.gov/program_2.1.html)

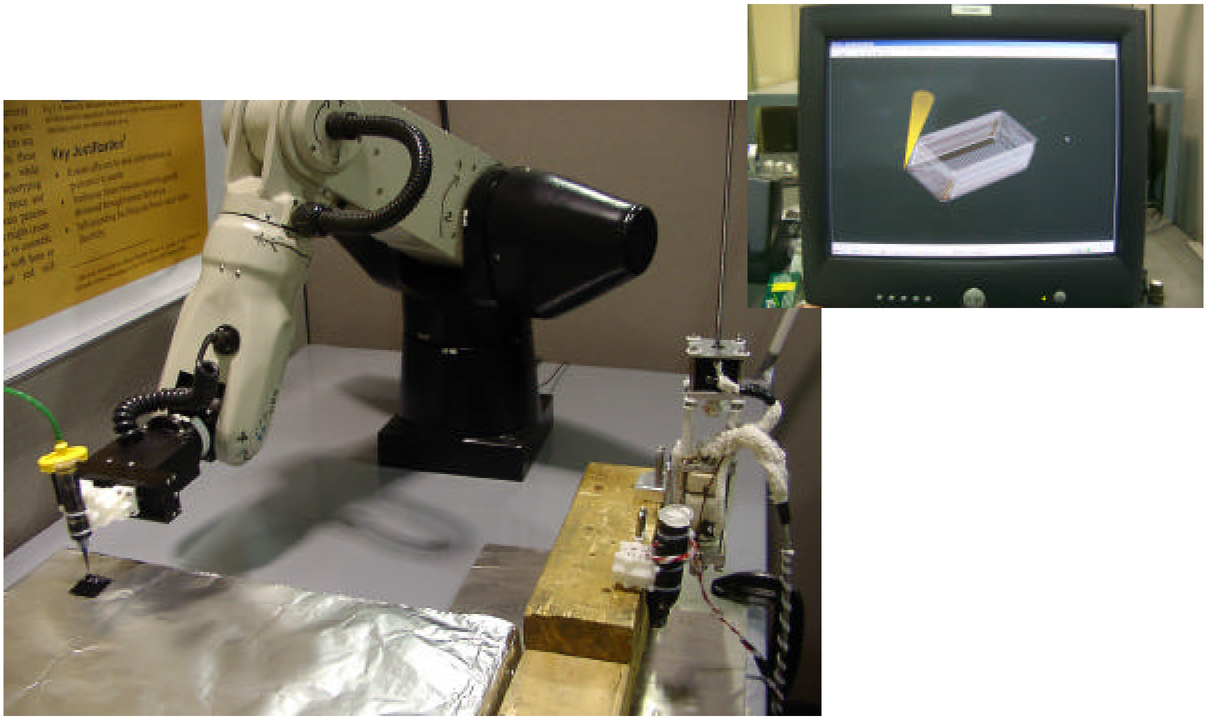
It is worth noting that production of functional systems is not mentioned explicitly. The THREADS roadmaps are described as providing “a comprehensive overarching framework for consideration of both ongoing and planned research, technology development and demonstrations that may support the goals of ambitious future human exploration of space beyond low Earth orbit and the complementary commercial development of space.” [http://threads.nasa.gov/objectives_goals.html] This is the perspective of NASA’s HEDS Enterprise, Advanced Systems Office, hence the focus on human exploration.

The first flight-approved fabrication system will probably be used in support of manned missions in the relatively near future, and research and development pursuant to this is underway at NASA LaRC and JSC, as has been mentioned (see SFF section, and [2002 SFF Proceeding, Watson, Taminger et. al.]). Although likely to be designed and employed only for the production of structural parts and monolithic tools, having such a system flight approved, and actually flown is a major milestone in the development of our concept. We expect it to significantly lower the threshold for consideration of more complex systems with greater capabilities, as well as providing excellent engineering data to guide the design of subsequent flight-worthy fabrication systems.

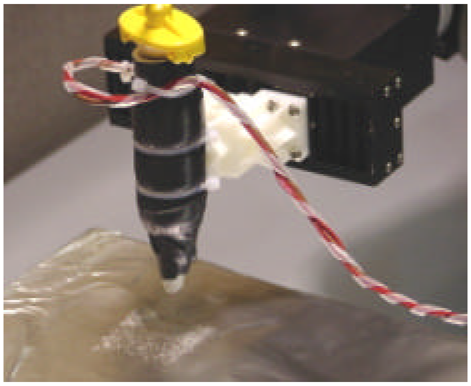
Technology Evaluation Platform

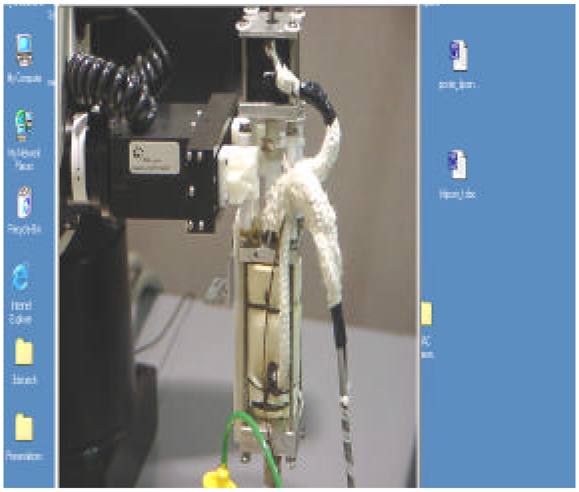
As has been mentioned, in order to identify some of the practical challenges associated with realization of the concept we are espousing, we have constructed a technology evaluation platform that captures many of the essential features of the concept, and which permits experimentation to test the acknowledged assumptions and reveal the hidden assumptions which underlay the concept.

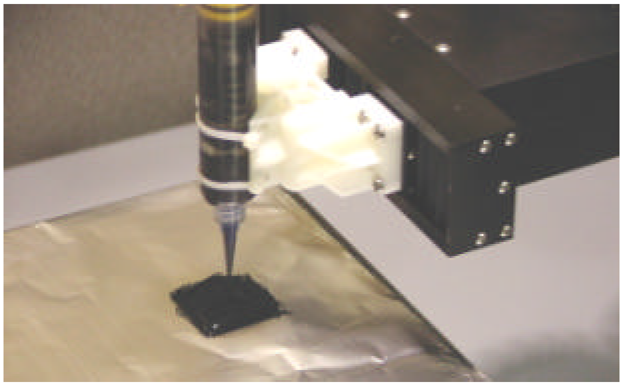
The features that we have focused upon are articulated manipulation, the use of multiple tools, and multiple materials, and the production of functional systems. The robot, tools, and materials with which we are working were deliberately chosen to be simple to work with, and cost-effective so that we could progress as far as possible into the system issues without spending too much time on the engineering of processes that are well behind the state of the art.



An A465 6-axis industrial robot arm from Thermo CRS Inc. (http://www.robotsdotcom.com/images/a465.pdf) forms the basis of our platform. The robot is equipped with a two finger servo gripper, for which we have constructed self-aligning fingers and matching deposition tool handles to enable simple tool changing. The robot is equipped with its own controller, model C500C, which can run motion programs as a stand alone system, includes all servo amplifiers, and which performs the low-level PID control loop and the inverse-kinematics calculation required to actuate the robot. Our path planning and control software interfaces to this controller via hardware serial communication connection, and a software dynamically linked library (DLL) named ActiveRobot, provided by Thermo CRS.







We have two types of tools, and both are of the extrusion type. One tool is an in-house designed and constructed thermoplastic extruder, which employs an HSI Inc. linear stepper motor to drive pieces of ½” diameter thermoplastic bar stock into a temperature controlled heater block and nozzle combination. The low level control of the stepper motor is performed by a Pontech STP100 stepper control board, which receives its commands from our path planning and control software via an RS-485 serial link. The heater block was extracted from a 3M hot-glue gun, and fitted with an in-house nozzle and a thermocouple, and the temperature is regulated by a standard process temperature controller. The flow rate, turn-on time, and turn-off time of this tool is very unpredictable, and the material capacity is quite limited – these limitations are primarily responsible for the poor quality of parts that we have been able to produce with this tool. As a result a second tool is under construction which should offer vastly superior performance. Most of its structural components will be produced using a Stratasys FDM SFF system, and the design of the tool is based upon the Stratasys thermoplastic extrusion method.

The second type of tool based on an EFD Inc. model 800 pneumatic fluids dispensing system, which has been modified to be activated by a digital output from the C500C robot controller. We use this system to dispense several materials from different syringes, although it is built to control only one syringe at a time – we are forced to manually connect the desired syringe to the system for use. The syringes are standardized, 10cc polyethelene barrels with Luer lock fittings to allow attachment of a variety of needles and tips – all of which were obtained from EFD Inc. We have modified one of the syringe barrels by surrounding it with a silicone rubber resistive heater, a thermocouple, and thermal insulation, permitting temperature control.

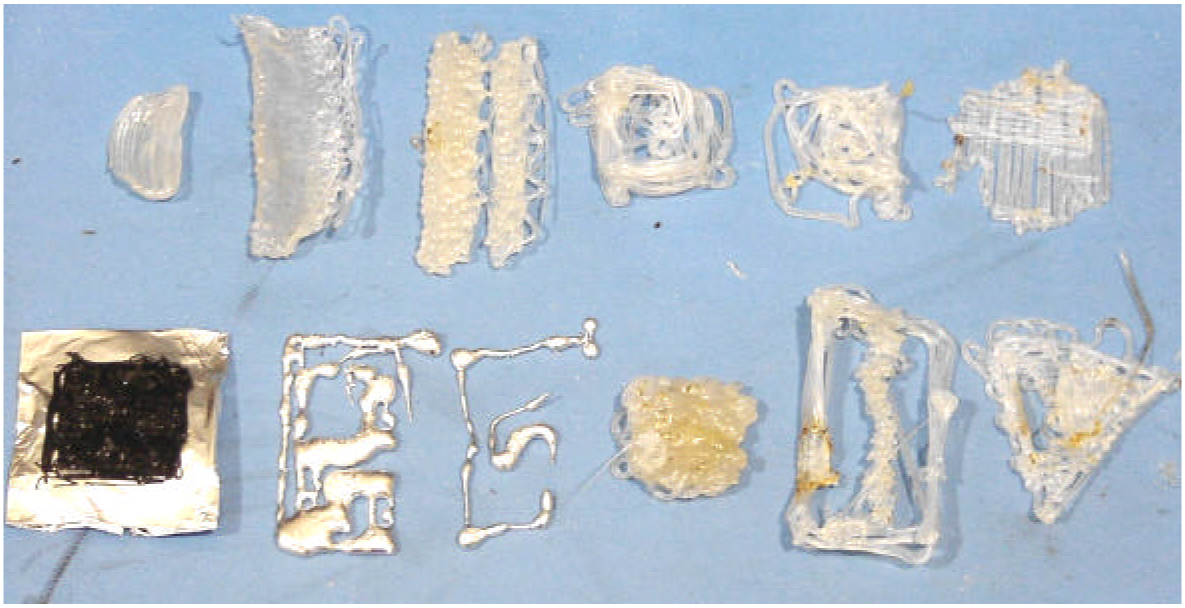
We have written a software application to integrate and automate the system control activities, and to perform the automatic generation of toolpaths from an input geometry (STL format) file. This application is called SCM (Santa Claus Machine), is written in C++ using Microsoft Visual C++, and is compiled to run under Windows 2000 on a Dell Optiplex Pentum4-based PC. A graphical user interface, written using Microsoft's MFC, allows the user to import an STL file of the desired part, view, scale, and orient it in the build envelope, to assign a material type to a part, to generate and view toolpaths, and to execute the build operation. Manual control of some tool and robot arm functions is also included via menu commands. The software is object oriented to permit abstraction of some of the details of robot and tool control, which hopefully will permit reuse of the basic structure of the program for future platforms, tools, and planning and control experiments.

We have performed experiments with several different materials, and have focused on a small set which we deem suitable for a next and more ambitious set of experiments. A range of thermoplastic materials have been evaluated for use with our first extrusion tool. Most thermoplastics seem to be hydrophilic, or contain other sometimes toxic volatiles (Delrin acetal releases formaldehyde) which cause the liquid thermoplastic to foam and the extrusion quality to be very poor. So that our feedstock does not need to be dried and carefully handled, we have chosen to work with polypropylene, which is neither hydrophilic, nor contains volatiles. Processing temperature (~250C) is reasonable for our equipment, and the properties of extruded material are quite good – flaw-free, and good strand to strand adhesion.

We have found a low melting point (117 F) alloy (44Bi 22Pb 8Sn 5Cd 19In) that is extrudable using our modified heated EFD dispensing syringe. It has been somewhat tricky to find the right combination of nozzle diameter, material temperature, and dispensing pressure and pullback vacuum to use, and dispensed streams have been irregular.

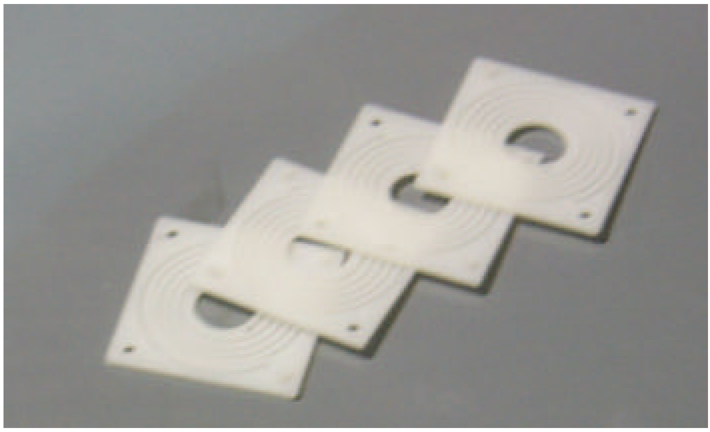
Other materials have proven easier to work with – namely carbon conducting grease, and silicone RTV elastomer. It is relatively easy to produce dilutions of either of these with sufficiently uniform viscosity to permit the desired dispensing properties.

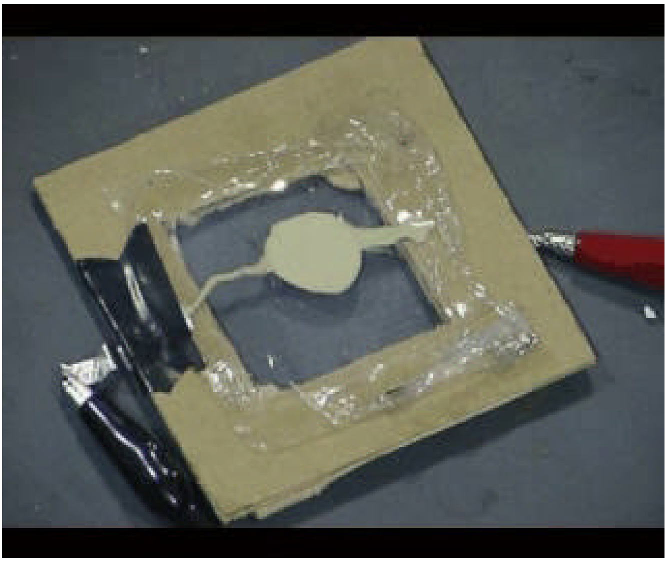
We have fabricated a few simple shapes with our system. The quality has not been acceptable, in part because of the poor performance and predictability of our thermoplastic



extruder. A few weeks of work will be required to refine the control of the robot and tools to provide sufficient output quality to warrant proceeding with our next set of experiments. These next experiments will involve attempts to construct some simple functional electromechanical devices, specifically:

- a **contact switch** incorporating electrical conduction and mechanical articulation
- a **functional electroactive polymer actuator** consisting of a thin silicone film, carbon grease electrodes, and polypropylene mechanical interface
- a **functional solenoid** consisting of a polypropylene frame, Bismuth-alloy coils, and an Iron-powder filled silicone RTV plunger
- a **Zinc-air battery** (described in detail below)
- a **simple mobile robot** incorporating one of the actuators, a battery, wiring, and simple, single-jointed chassis





Silicone based electroactive polymers are being investigated for actuators, but the requirement of high voltages for actuation makes them less desirable since we currently lack the ability to fabricate the appropriate high-voltage electronics, and would be forced to install a DC/DC converted. We are investigating the possibility of fabricating ionic electroactive polymers, which do not require high voltage. For information on EAPs, see (see http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm), and [Pelrine, Electrostriction of Polymer Dielectrics… Sensors and Actuators A]

Progress in Solid Freeform Fabrication of a Zinc-Air Battery

Chemical Reactions

The zinc-air battery utilizes zinc as its anode and oxygen in the air as its cathode. An electrolyte, potassium hydroxide (KOH), is also present within the system. Oxygen from the air reduces the zinc to zinc oxide. This produces free electrons, which, when a circuit is completed, move from cathode to anode, producing current.

The chemical reactions that produce the energy in a zinc-air battery are as follows:

$$AtAnode: Zn + 2OH \rightarrow ZnO + H_2O + 2e^-$$

$$AtCathode: O_2 + 2H_2O + 4e^- \rightarrow 4OH$$

$$OverallEquation: 2Zn + O_2 \rightarrow 2ZnO$$

The reaction produces a 1.4V potential.

Commercial Zinc-Air Batteries

Zinc-air batteries are commercially available. Button cells are the most common. Some typical applications are watches and hearing aids. The power characteristics of zinc-air batteries are predominately a function of the air electrode area and the catalyst formula employed. To optimize the power capability of the system, a high area, flat configuration is preferred so as to maximize cathode area. The zinc-air battery provides the highest capacity to volume ratio of the various miniature battery systems. It has a relatively flat discharge curve and is less rate sensitive than mercuric oxide or silver oxide batteries.

The most common problem associated with zinc-air batteries involves the air in the cells. The air is introduced into the cell through small holes in the cathode can. Too much air can “dry out” the battery. The relative humidity of the air is an important characteristic also. Too much humidity can “flood” the battery. In an attempt to control these characteristics, air management systems have been developed which control the flow of air into and out of the cell.

Some figures showing some common configurations of zinc-air batteries in commercial use are shown below.

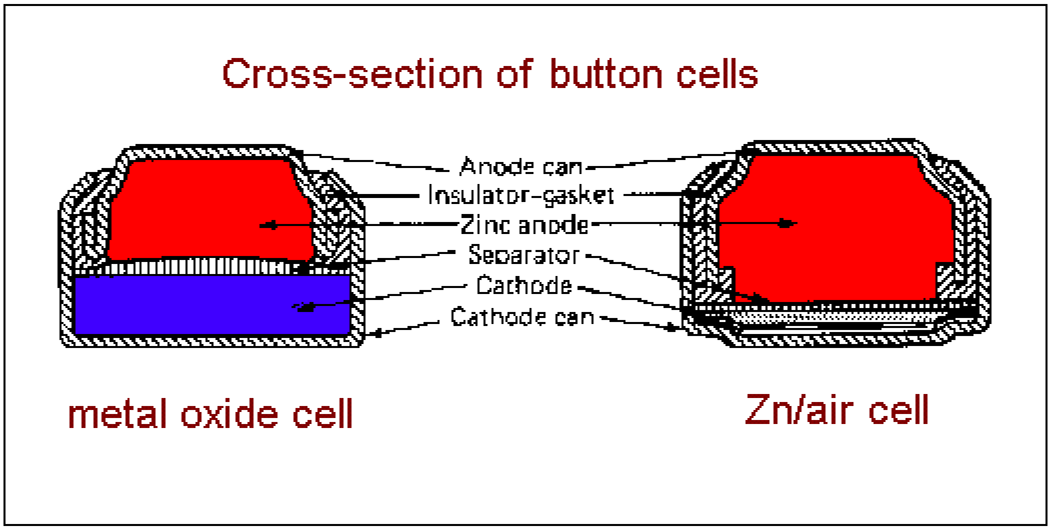


Figure 7 – Comparison of Zn/Air cell to a Metal Oxide cell

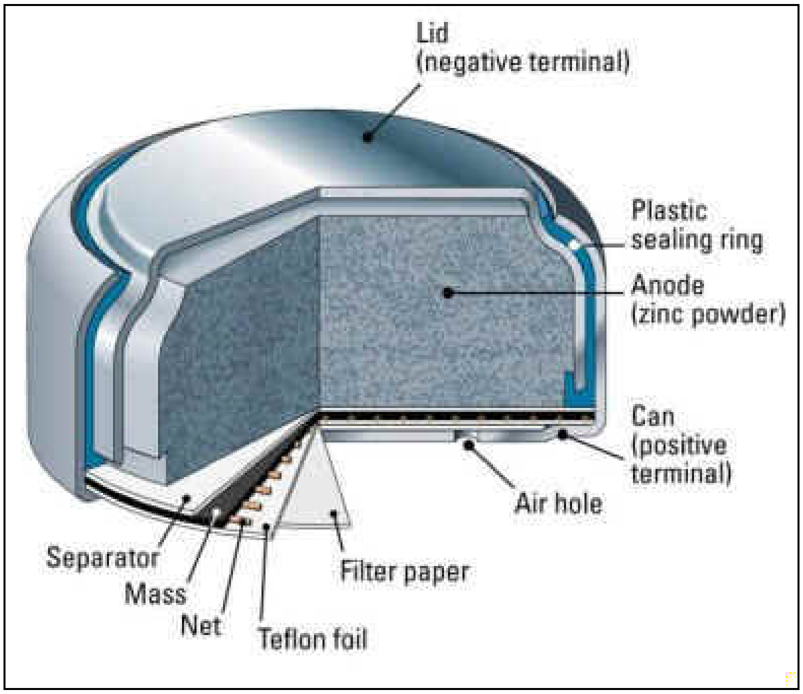


Figure 8 – Zn/Air cell Composition

Our Battery

The battery that will be created with our system will be a zinc-air cell. In keeping with the philosophy of our technology evaluation effort, we selected this chemistry for its simplicity and reasonably good performance, rather than because it is a good candidate for space applications or production from *in situ* resources. Initial models of the battery system have been created by hand and tested. The first model was created purely to test our understanding of the chemistry and operating principles. No attempt was made to create the model in a form that would be reproducible on our machine. The first model was created using aluminum foil to form the anode can. Zinc dust was put into the can and soaked with KOH (electrolyte). Paper towel was used as a porous, insulating separator. The paper towel was also soaked with the electrolyte. The potential across this model setup was then measured. The maximum resulting voltage recorded was 1.4 volts. A photo of the system is shown below.

Figure 9 - Photo of Initial Test Model

This model was a success in that it proved that a battery could be produced given the properties of the materials used (i.e. amount of zinc, strength of electrolyte solution). The next task was to develop a model that could be produced by our fabrication system.

For this purpose, a second design was conceived which utilizes materials that can be deposited by the system. Several versions of this design have been made by hand to evaluate different alternatives for the separator material, which is the most problematic to deposit. In this model the anode can was created from polypropylene rod. A cavity was drilled into the stock. Then a smaller diameter hole was drilled through the remaining material. This hole was filled with a low-melt alloy to create an electrical contact. Then the cavity was filled with zinc and the zinc was wetted with electrolyte. The separator used was acrylic powder with cyanoacrylate glue to harden the powder.

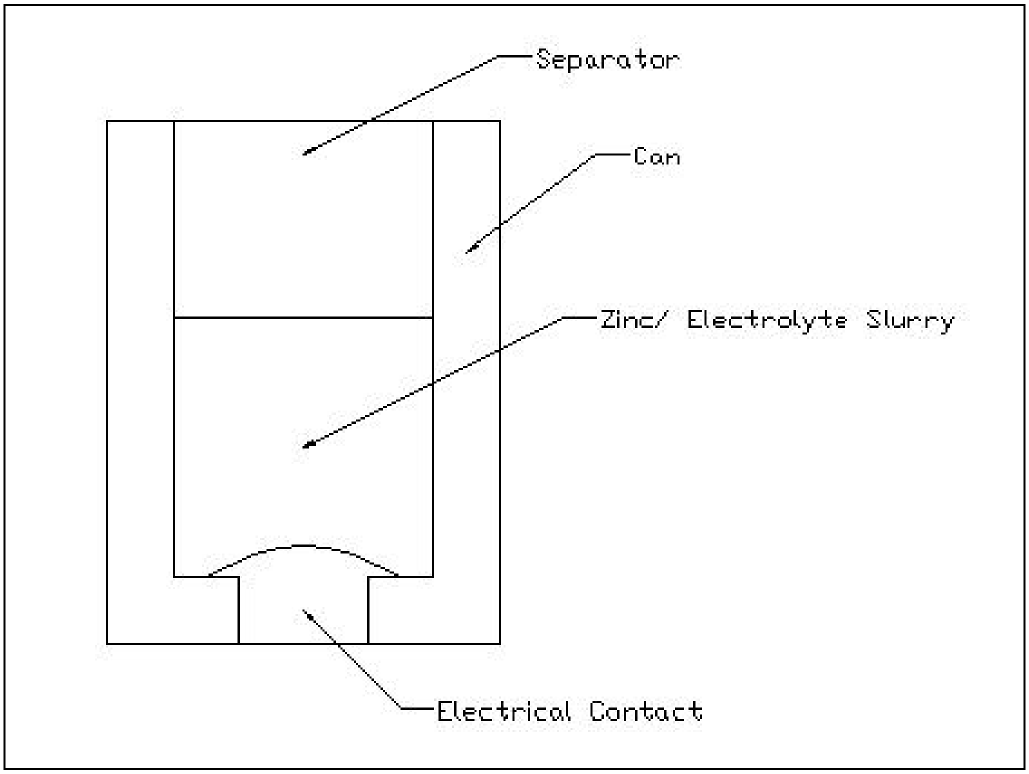


Figure 10 - Cross-Section of Second Model

Again, these models produced about 1.4 volts, open circuit. Their current / voltage characteristics have not yet been obtained. The photo below shows several examples of this second model along with the first model.

Figure 11 - Photo of First and Second Test Models

We expect to be able to fabricate examples of the second design in the near future with our current platform. The system has already produced extruded strands of polypropylene. The system has also extruded the low-melt alloy. The system utilizes a syringe-like device for both of these materials. There is no reason to believe that the remaining materials needed to create the battery could not be deposited in a similar manner, although, admittedly, more testing remains to be performed and the process optimized.

Therefore, further research will be performed in the area of deposition of the materials needed to create a battery on this system. It is believed, from the results of these models and the previous tests of the system (i.e. deposition of polypropylene strands and low-melt alloy), that a battery is indeed "printable." The materials needed to produce a battery in a deposition manner should be able to be deposited with a syringe-like apparatus. Some designs have already been made, which may be able to be modified for each specific material. More research, design and testing will be performed with the ultimate goal of producing a battery with the system.

Next Steps

1. Conceptual Study:
    a. Establish quantitative measure for fabrication system comparisons (e.g. "functionality gain", or "functional unive
        i. Establish quantitative measures of functional equivalence for parts, components, systems (e.g. same inputs and outputs, same interfaces, same functional lifetime, but otherwise black-box)
        ii. Establish quantitative measure of feedstock complexity
        iii. Establish quantitative measure of product functionality
    b. Explore tradeoff / sensitivity parameter space for fabrication systems (mass, volume, product quality, cost, reliability, complexity, energy requirements / efficiency, material requirements / efficiency)
    c. Develop reliability models applicable to different system realizations (reliability is critical issue given high threshold for deployment)
    d. Investigate current and proposed ISRU material processing capabilities in depth and implications for *in situ* fabrication systems
    e. Investigate recycling technologies appropriate for *in situ* fabrication
    f. Define requirements for automation, intelligence, and control
    g. Explore / model self-sustaining system concept in detail
        i. Fabrication system
        ii. ISRU systems
        iii. fabricated systems
    h. Explore concept in other contexts (asteroid, deep space, outer planets)
    i. Identify quantitative requirements for fabrication system to be desirable in each mission context (define target criteria for deployable systems) vs. conventional approaches.
        i. Cost

        ii. Mass
        iii. Mission lifetime / productivity benefits
        iv. Mission design / deploy cycle length reduction

2. Technology Evaluation:
    a. Continue investigation of product functionality axis
        i. Continue using easiest materials (plastic, low-melt alloy, silicone, carbon grease). Perhaps these might be a 1st proposed minimal material set?
        ii. Set up gantry robot to simplify control – focus on maximally functional products.
        iii. Standardize extrusion tools (stepper extruder, heater) to simplify interface.
    b. Continue investigation of automation axis
        i. Automated, intelligent process planning
            1. Path planning
            2. Fabrication sequence (material / process compatibility)
            3. Assembly / Disassembly / Repair
        ii. Closed-loop control of full system and process
        iii. Self-diagnosis, repair
    c. Begin investigating minimal process sets
        i. Construct / obtain testbeds for key process technologies (solar concentrator, e-beam, maybe laser if funds permit) – chance for collaboration with K.Taminger et. al. at LaRC for e-beam, McKay, Ennex Co. et al for Solar;)
        ii. Begin exploring functionality gain of each - push limits of materials, functionalities of products
    d. Begin investigating recycling and ISRU-process generated materials, simulant raw materials
        i. Explore functional fecundity of current / prospective ISRU-system generated materials (collaboration with ISRU research by Sridhar (Arizona), people at JSC, etc.
        ii. Experiments in fabrication with lunar, Martian, other simulant soils.

A commercial perspective

Although not required by NIAC, recent history shows that long-term national-level technological expeditions are much more likely to succeed when they are backed up with a possible commercial vision as well, even if this vision is long term. What would be a viable commercial justification for autonomous, 100% self-contained fabrication systems? Certainly not mass-production. But one could imagine a future home desktop printer that allows consumers to purchase a product online, download the blueprint, and instantly generate the physical product at their desktop. A consumer would be granted a license to print one instance, and once printed, that product would self-test, register and activate itself. Today's rapid prototyping machines are not unlike the first mainframes of the '50s: They cost $100,000 a piece, require a technical operator and complete roughly one job a day. On a similar timescale and with some vision, in 40 years we might see home fabricators for $199, with a replaceable material cartridge from *hp* for only $99.

Conclusions

One way to break the vicious circle of exploration costs is to depart from the earth-centered view of fabrication, towards machines that can generate robots on site. Those robots would not need to be as robust, could be much more task specific, and their blueprints can be beamed up from earth as a mission develops. Most importantly, the entire design-fabricate-deploy cycle could be operated remotely, potentially reducing mission cycle times and costs significantly, and opening the door to future endeavors of self-repair and self-replication.

Many of the scientific ingredients needed to realize this vision are now maturing; we see a large variety of moldable polymers with various functionalities, extrusion technologies which have been developed for the rapid-prototyping industries, actuation technologies, scrap reclaim machines, precision robotics, geometric modeling and motion planning. All these technologies combined provide the substrate upon which the concept of fully autonomous fabrication of complete systems can now be investigated as a viable alternative. Our estimation of the impact of the concept and of its being realizable has only increased during the course of our Phase I effort, and we foresee a new path for completing missions more frequently, less expensively, and with greater flexibility.

Acknowledgements

This report has been co-authored by Evan Malone and Hod Lipson. Todd Issacson performed the research relating to printable batteries, and wrote the respective section. Daniel Cohen assisted in the design and construction of the prototype system.

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