The Challenge of Space Infrastructure Construction

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This paper reviews the range of technologies that will contribute to the construction of space infrastructure that will both enable and, in some cases, provide the motivation for space exploration. Five parts are addressed: Managing complexity, robotics based construction, materials acquisition, manufacturing, and self-sustaining systems.

I. Introduction

The major issue in the construction of space infrastructure is the control of its inherent complexity. Complexity, as for instance in software development or in the construction of other mechanical or electronic structures, typically makes a system more prone to failure. On the other hand ecological system complexity is thought to confer stability, so there are strategies that can be developed such as "incapsulated complexity", "loose" infrastructures and robust automation to help evolve stable and long lasting space systems.

The second crucial issue is the cost of taking materials into space. For this reason space system need to be constructed by making use, as much as possible, of local resources on planetary surfaces and possibly on asteroids. Of course the advantages of ISRU (In Situ Resource Utilization) need to be weighted against the added system complexity and increased need for automation. In addition, acquisition of raw materials in space implies the added requirements of manufacturing the needed systems, again, with an increased need and cost of complexity and automation.

One fundamental assumption we make is that the cost of human-based construction would far exceed any cost of automation, due to the complexity of life sustenance in space and inherent safety challenges. There is however also a wide range of possibilities in how space construction might be approached, from humanoid robotic constructors to self-deploying structures. The challenge, again, is to strike the correct ideal balance of cost and complexity.

Finally, we consider how it might be feasible and desirable for space structures to be able to maintain themselves by implementing self-repairing systems. Further, we suggest that a gradual implementation of self-manufacturing technologies may provide incremental benefits whether or not closure is actually reached.

II. Managing Complexity

Managing configurational entropy and staying in control of vast numbers of components and relationships in a system reduces its apparent complexity by encapsulating it. The value of the encapsulation comes from the reduction of complexity that a single modular unit needs for position, configuration, and manipulation; the complexity of the subcomponents of the module can be disregarded. The efficiency of the modular approach can therefore be quantified by how much of the complexity of the structure can be pre-loaded and encapsulated into the individual modular elements. Action or material handling can also be encapsulated.

The complexity of a system can be stored and encapsulated as potential that can be delivered and made available in locations where conventional human infrastructures do not exist, such as in space. Using metrics for measuring complexity, it is possible to prove that encapsulating the configuration and mobility into discrete, manageable modules reduces the complexity in a system and internalizes infrastructure for processes of material handling and labor.

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Complexity Metrics

Information complexity metrics (Hornby 2007) include the measure of modularity, regularity, nested hierarchy, algorithmic information content, assembly procedure size, logical depth, sophistication, number of build symbols, grammar size, connectivity, height, and branch proliferation.

Hornby's metrics are useful for measuring complexity of information in data structures and representations of physical objects. However, real-world objects also have equivalents for configuration, geometry, manufacturing, and assembly processes. Physical elements encapsulate substructures, and mechanisms for manipulating the elements also encapsulate information, representing the quantifiable parameters of all the elements needed to construct and operate that mechanism. Tentative physical equivalents to Hornby's list, constrained only to fabrications that can be produced digitally (including robotic material handling), may be as follows (Howe 2007b):

- Modularity Measure (CMM): the number of unique primitives or structural modules in it, where modules are defined as a group of substructures encapsulated in such a way that the group can be manipulated as a unit. In language, the CMM is the total number of symbols in the alphabet.
- Regularity Measure (CRM): the measure of the average number of times each module is reused.
- Hierarchy Measure (CHM): a measure of the number of nested layers of modules. Modules may in turn be nested into larger units that have their own rules for connection and manipulation. On the lower end, substructures encapsulated into a module may themselves be encapsulated groups of elements from a lower substrate.
- Fabrication Measure (CFM): (a proposed physical equivalent to the Algorithmic Information Content discussed by Hornby) the minimum number of Numerical Control (NC) fabrication steps, including robotic material handling between NC processes, needed to create the system.
- Instruction Measure (CIM): (a proposed physical equivalent to the Assembly Procedure Size discussed by Hornby) the measure of the minimum length of the file(s) required to run the NC fabricator(s) to produce the system.
- Logical Measure (CLM): Also known as "computational complexity" according to Hornby, CLM is the minimum running time of the entire manufacturing process that produces a system.
- Sophistication Measure (CSM): the number of production-related instructions present in the NC file used to generate it.
- Prepositional Measure (CPM): (a proposed physical equivalent to the Number of Build symbols discussed by Hornby) the number of non-production-related instructions in the NC file used to generate it. These are commands that reposition the NC tool between non-continuous fabrication paths.
- Grammar Measure (CGM): the measure of the minimal number of grammatical rules needed to produce the system.
- Connectivity Measure (CCM): the minimal number of connections between the modules used to assemble the system.
- Tallness Measure (CTM): (a proposed physical equivalent to the Height Measure discussed by Hornby) in a tree structure representation of a system, the CTM is the maximum number of edges that can be traversed from the root to the leaf node of the tree.
- Branch Measure (CBM): also refers to tree structures, measuring the number of nodes that have two or more children in the representation of a system.

These metrics for measuring complexity are confined strictly to digital NC processes that are repeatable and quantifiable, but human labor can also be estimated where known or repetitive motions and actions are involved. Using human labor, a vast variety of manufacturing processes, techniques, skills, and cultures have arisen. The manufacturing community somewhat resembles a scientific paradigm – efforts have been made to weed out the folk techniques and rigorously establish repeatable processes. The folk techniques will always have their place, but repeatable processes will be necessary for applications in extreme environments like space. Complexity metrics will allow us to evaluate these processes and work toward more efficient means of production.

If we can encapsulate all the minimal processes required to produce the tools we need as numerical based, repeatable technologies, we will be able to export the capability to engineer comfortable environments far away from Earth.

III. Robotics-based Construction

Where modularity encapsulates the complexity of geometry and configuration into simple, discrete components, robotics encapsulates motion and material handling into self-contained work cells. The handling of materials requires some sort of kinematic mechanism that can manipulate the components. A kinematic mechanism can be defined as a structure containing two or more physical elements that have the capacity for altering their configuration in relationship to each other based on a known or given transformation (Howe 2003). The transformations are defined and constrained by the geometry of the elements in the structure. For the purpose of design, almost all motion required for the manipulation of objects and mobility in any environment consists of combinations of translation or rotation. This is significant, because extremely complex mobility and manipulation can be encapsulated by nested sequences of linear or rotational motion, similar to how we can encapsulate complexity of vast numbers of particles by rolling them up into a single modular unit. In this way, we can design the system to have well-characterized inputs and outputs, without concerning ourselves with the complexity within.

A robotic mechanism is a structure containing one or more kinematic mechanisms, one or more actuators, one or more sensors, and a controller. The robotic mechanism functions as a device to perform a predefined work such as to reconfigure a kinematic mechanism according to external instructions. The robotic mechanism works as a feedback system: the controller receives external instructions to perform a certain work and directs the actuator to perform it. Then the sensor continually senses the current state or configuration of the kinematic mechanism and notifies the controller. Finally the controller makes a continuous judgment as to what degree the work has been performed, and instructs the actuator to continue or correct itself. When the work has been completed, the controller stops the actuator, and may broadcast whether the instructions were successfully completed or not (Howe 2003). The inputs include the external instructions and the initial configuration or state of the mechanism, and the outputs include the desired final state of the mechanism and the final signal of completion. Using robotic mechanisms with their well-characterized inputs and outputs, we can build any sort of tool for the most complex tasks. The challenge in robotic design is often how to anticipate the initial state of the environment where the robot will perform its task – either the mechanism must be made complex enough to internally characterize its environment enough to respond to it, or it must take over an ordered environment that has been pre-characterized by previous manipulation.

The simplest way to characterize the environment is by having a human in the loop – the human reads the environment and generates the appropriate set of external instructions that the controller can follow. Ironically, the human is already a robot according to our definition, where all the complex kinematics within each cell through actuation of limbs based on feedback from eyes and other sensors allow the human to evaluate and characterize its environment and respond or anticipate actions. In fact, our entire natural environment is filled with robotic mechanisms that we can observe and mimic, and an entire class of robotic structures has been established called biomimicry, based on body types, mobility, and function of insects and animals found in nature. When a human is in the loop, the robotic mechanism is said to be teleoperated. Teleoperation is a form of control that puts the robotic mechanism in a proxy environment for the human, who may safely reside in a comfortable location. Teleoperation can work well in many circumstances, especially if the operator is not too far away. However, when there is latency in the communications between the operator and the robotic mechanism due to vast distances and speed of light limitations, a certain degree of autonomy is required locally. Through automation, autonomy can be achieved within the controller, relieving and even eliminating the need for the human operator to be conscious of every little detail and performance of the system.

Robotic assembly and construction can be placed on a scale. At one extreme are systems characterized by a limited number (usually one) of assemblers that must connect together a large number of 'dumb' parts. At the other end of the scale are self-assembling systems where all the parts are either fully or partially robotic and take part in their own assembly, without the need of a specialized assembler. Assembler-type systems must address the problem of material handling – getting the parts into the right location in order for the assembler to get started in the first place – and once the assembler breaks down there is a bottleneck in production until it can be maintained and repaired again. On the other hand, self-assembling systems affect their own material handling, and there are no bottlenecks if some of them fail to function as designed. However, self-assembling systems usually have massively redundant actuators and hardware that may never end up being used in a project, creating a modularity penalty of sorts. At either extreme the system can be designed to have a human in the loop at various degrees of teleoperation, or if the various progressive states of the immediate environment can be ordered and characterized, a great deal can be performed autonomously.

The high cost of sustaining life in space or planetary surfaces, coupled with the danger inherent in handling construction materials and tools in such extreme environments, makes the use of robotic systems the obvious choice for the development and maintenance of space infrastructure. However, robotic approaches invite technology that is both extremely sophisticated and potentially varied. If one assumes that people will build and maintain structures, then procedures and tools are people-centric, and not too dissimilar from how we currently build on earth or how we have built on LEO (Low Earth Orbit, e.g. Space Station). Even on Space Station, except for maneuvering bulky objects with a large man-controlled robotic arm, all work was done "by hand" and generally consisted of bolting together the largest possible modules that would fit inside the Space Shuttle cargo bay. So the LEO approach has been to build as much as possible on the ground and to keep space assembly simple enough for a few astronauts to accomplish with "earth tools". Note that this approach to construction relies on the lifting of large amounts of mass and is thus very costly, especially in the case of infrastructure to be built on planetary surfaces

At the point where major reliance is placed on robotics, then the possible approaches to construction become extremely varied, as we no longer need to be "human centric" in terms of tools and processes. Here we attempt to describe the range of possibilities that are being considered. Some of these possibilities are valid for construction in space, some for planetary surfaces and some for both.

Figure 1: Robonaut humanoid robot (left), either autonomous or teleoperated, will be able to interface with human-centered processes and tools in IVA or EVA situations (courtesy of NASA)

Humanoid Robotics

Humanoid Robotics is at the same time the simplest step in the evolution towards robotics-based construction and the most complex. It is the simplest step in the sense that the idea is to insert robots in the same human-centered processes we have already developed – our human operator who can already be characterized as a robotic mechanism in itself, would simply be replaced by a human-designed version, especially if the humanoid is to be teleoperated remotely like an avatar. Robonaut (Ambrose, Culbert, & Rehnmark 2001; Diftler, et al. 2004) is a good example of a humanoid robot built to be able to use the same tools that humans would use (Figure 1). It was designed to be able to take on the assembly and repair tasks normally done by astronauts. It would be tele-operated, thus it would not reduce the need for human presence, but the operator could of course perform tasks in the safety of a closed environment. The design is focused on the torso for task performance. Mobility is dealt with in different ways, depending on the particular environment envisioned for the tasks. In space Robonaut might use a single grappling leg to attach itself to the exterior of a spacecraft or truss. On planetary surfaces it might be attached to appropriate mobility platforms, either wheeled or legged.

We mentioned that Humanoid Robotics would also be the "most complex" step. This is so if one wants to stretch the concept to an autonomous robot actually able to perform human tasks within a normally human context. This remains within the realm of Sci-Fi, but it is not a necessary step for needed progress in space robotics.

Figure 2: Astronaut Steve Robinson on Canadarm2 (Shuttle mission STS-114; courtesy of NASA)

Mobility platforms

Any form of construction requires transportation of materials. For transportation tasks, clearly space and surface approaches will differ. In space we usually deal with compact sites (such as Space Station) where materials are delivered via space cargo capsules (formerly the soon to be retired Shuttle cargo bay). From the delivery point transport is typically accomplished via robotic arms, fixed (Aikenhead et al. 1983) or able to move along trusses (Gibbs et al. 2005). With exception of the already deployed and very successful Canadarm robotic arm (Figure 2), most design attention has been given to mobility platforms for planetary surface construction. Here the transportation problem is crucial, as any material would be delivered to "space port" areas where habitats would not be able to withstand the environmental challenge posed by the arrival and departure of spacecraft. Mobility platforms, either tele-commanded or autonomous are envisioned to be able to provide transportation services over distances in the range of at least hundreds of meters, possibly over rough terrains. Wheeled platforms have been proposed (Howe & Gibson 2009) and legged ones.

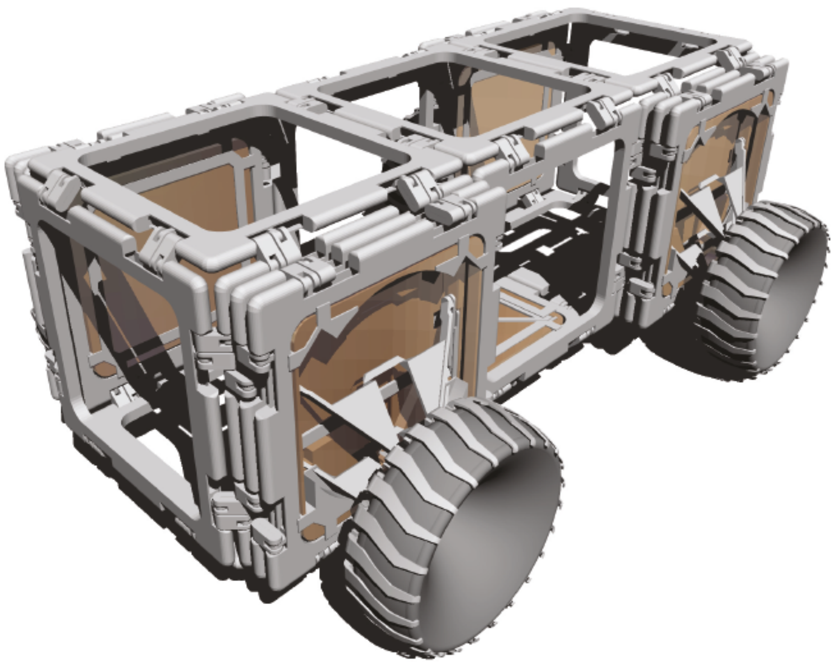

Figure 3: Wheeled mobility platform (Howe & Gibson 2009)

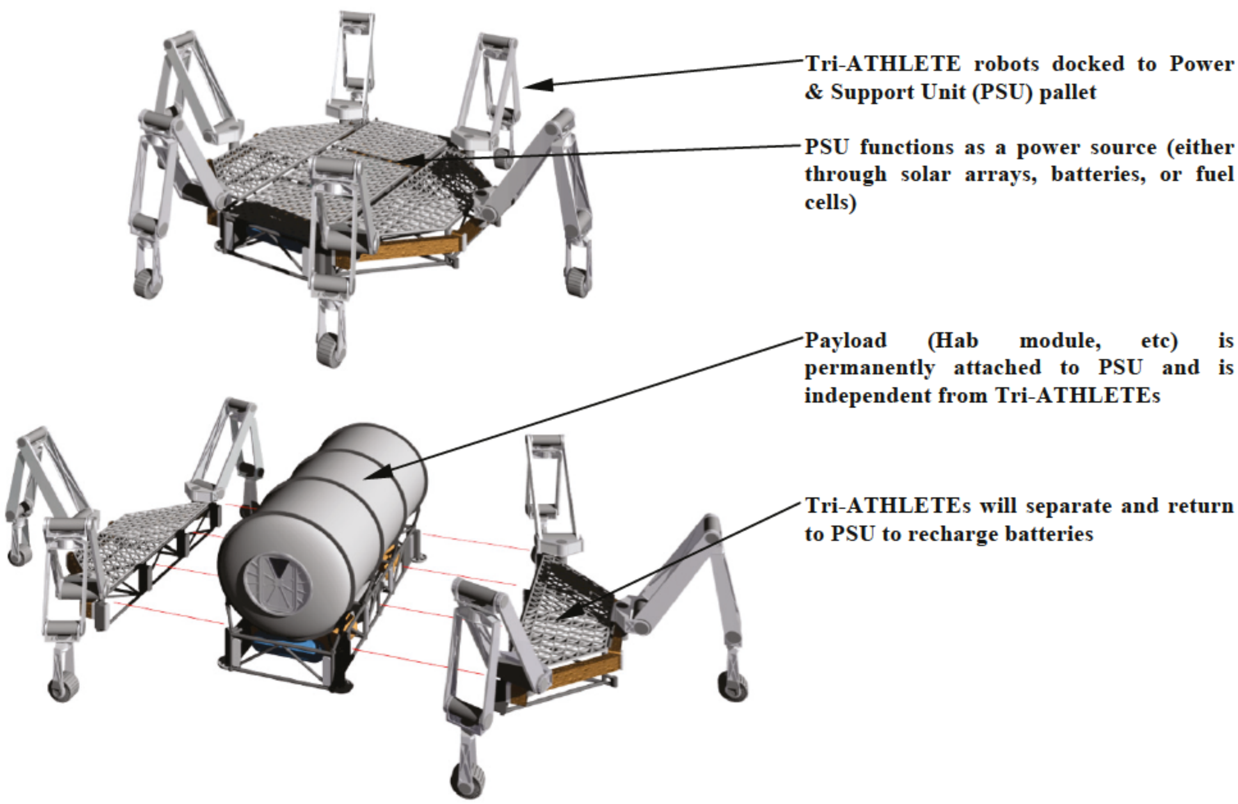

Figure 4: Two three-wheeled Tri-ATHLETE vehicles approach both sides of a payload and dock together (Howe, et al. 2010)

One interesting concept, the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE), combines both the advantages of wheeled and legged system. It consists of a six-legged platform with wheels in the place of feet (Wilcox, et al 2007). The six-wheeled vehicle is made of two Tri-ATHLETE three-wheeled vehicles that sandwich the payload to provide mobility, and is designed to carry loads as heavy as a small habitat. Wheels allow for energy efficiency and speed over smooth, possibly prepared terrains, while the leg articulation allows for negotiating obstacles and rough terrains. The legs can also be fitted with tools and thus function to some extent as end effectors.

Self-deploying structures

All options considered in humanoid robotics and mobility platforms have robots as individual entities acting on materials, to perform construction processes that can be still be human-centric or can be tailored to robotic capabilities. Robotic concepts can easily be extended to processes where the structures themselves contain the actuators and mechanisms that enable deployment in a final desired shape or functionality. These could be trusses or habitats in space or on planetary surfaces (Figure 5). Inflatable structures fall into this category (Figure 6). Self-deployment concepts range from relatively simple inflation or unfolding of structures (as often done for antennas and solar panels) to complex modular system where individual modules are "robots" capable of finding desired locations and locking themselves into place. With modular systems of this type it also possible to achieve different shapes and functionalities from the same modular elements. Examples of such robotic modular elements have been conceptualized by one of the authors (Howe 2006; Howe 2007a; Howe 2007b). Howe (2006 and 2007b) describes the Transformable Robotic Infrastructure-Generating Object Network (TRIGON) system that consists of a simple set of modular robotic units.

Figure 5: Self-deploying truss (Howe 2007a)

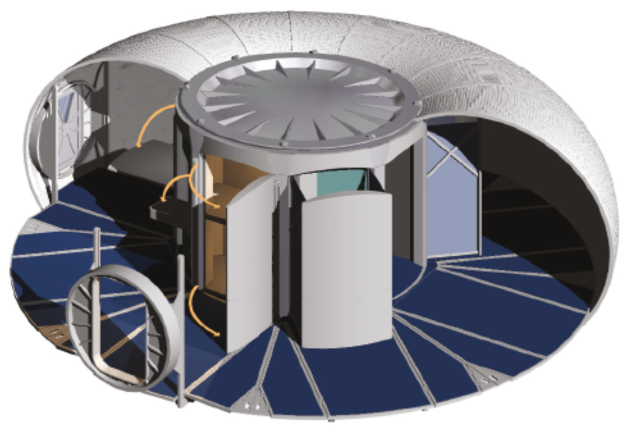

Figure 6: Inflatable habitat (Kennedy & Toups 2009)

In situ materials and structure production

The concepts illustrated in humanoid robotics, mobility platforms, and self-deploying structures allow for processes that require minimal human presence, and optimal packaging of structural materials, but mass would still need to be delivered to the desired location. The next step in facilitating space construction would consist in the ability to utilize local planetary surface materials for the manufacturing of structural elements. Even very "active" self-deploying structural elements such as the modules illustrated above (Fig. 4) contain purely passive areas where materials provide needed mass and structural rigidity. In principle then only active structural parts or actuators would need to be carried to the manufacturing location, to be fused with the structures that can be manufactured from local materials, as described above in sections III and IV. Technologies for manufacturing from in situ resources are still in their infancy and depend on the planetary surface of interest, but concepts for the production of structures from hardening liquids with techniques analogous to 3-D printing are already being developed, as described below in section V.

Clearly the deployment of surface factories for the production of structural materials would make sense in later stages of space exploitation where a commitment is made to a permanent and constantly growing infrastructure. In this case advantages could be derived not only for surface construction, but also for construction in space, as it would be less costly to lift mass from, say, the lunar surface, than from the Earth surface, even for objects in Earth's orbit. The cost savings may also be true for structures derived from materials mined in Near Earth Objects (NEOs).

IV. Materials Acquisition

Our current Earth-based manufacturing environment is set up organically, having grown in place over the centuries without any particular plan or coordinated infrastructure. We are faced with the challenge of taking all the lessons we've learned growing our infrastructures, and setting up new smart encapsulated infrastructures that acquire raw materials and produce everything we need. Since it costs less to use the materials in place rather than ship them back to earth, it is generally assumed that locally acquired materials would be applied to local space-based structures and would help boot strap a space-based economy. Entire material acquisition chains, mining operations, and material delivery infrastructures will need to be encapsulated in a simple modular way, depending entirely on numerical control technologies.

Considering encapsulation of material acquisition infrastructures, it will be useful to reflect on sources on Earth for metals and other common and uncommon materials. Common metals such as iron and aluminum are found in abundance, where other useful materials in electronics and manufacturing are considered rare materials on Earth. This is because the heavier materials, such as gold, platinum, and palladium sank to the core when the early planet was in its molten state (Brenan, McDonough 2009). The sources for these materials that we have today are due to impacts from meteorites that have added to a late veneer in the Earth's formation.

Though the moon is made of similar elements as Earth, the bombardment of asteroids has given the lunar surface similar concentrations of useful metals and other materials. Material resources have been found to be abundant on the moon, as determined from Apollo samples, and also on the asteroids through spectrographic analysis. Metals and other minerals were found in great abundance (Freitas, Gilbreath 1980, pp81-82). Freitas and Gilbreath (1980, p83) also map basalts, metals, olivine, gases, and other volatiles with their found locations on the surface of the moon (from Apollo samples) and the kinds of raw materials and resources that can be applied to lunar habitats, factories, and other in situ derived facilities. White (2005) discusses the business model for mining the moon for its platinum-based metals, and lunar factories have also been proposed. The asteroids have also been observed to have large amounts of metals and minerals that would be available to us if we wisely plan ahead for the right infrastructure (Binzel et al. 2004).

Because of the lower gravity, asteroids likely still have these materials in accessible locations on or near their surface. It has been estimated that an asteroid with the diameter of one kilometer would have a mass of about two billion tons (Lewis 1997). A metallic asteroid of this size is estimated to contain 30 million tons of nickel, 1.5 million tons of metal cobalt, and 7,500 tons of platinum. It is estimated that the platinum content alone of that single asteroid may be worth $150 billion. Asteroids and comet cores with orbits near or crossing that of Earth are called Near Earth Objects (NEOs). NEOs are easier to reach and may include volatiles such as water and other consumables, as opposed to the main asteroid belt that is farther away beyond the orbit of Mars. Thomas and Binzel (2009) have begun to map asteroids back to their source regions, based on spectroscopic data and mineral content. However, should we gain a foothold and establish an infrastructure for acquiring and processing materials in the low gravity wells of asteroids and comet cores, the resources available to us will be virtually unlimited. Lewis (1997) estimates that if the total value of all resources in the asteroid belt were divided among every individual on Earth then each person would receive over $100 billion.

V. Manufacturing

Soon after the Apollo missions had concluded and lunar regolith samples from the various landing sites had been analyzed for their mineral content, NASA encouraged interest in space-based manufacturing research through a series of specialized workshops. In 1980, a team of industry, government, and academic specialists were assembled in a groundbreaking study to identify candidate manufacturing processes that could be adapted to microgravity or low gravity environments, and the harsh conditions found in orbital or planetary surface localities (Freitas, Gilbreath 1980).

The Advanced Automation for Space Missions workshop identified several notable manufacturing processes that were thought to be particularly adaptable to space environments. Powder Metallurgy and Sintering could be used to create a large range of products composed of refractory and metal components, such as electrical contacts, structures, metal glasses, heat shields, magnets, and filters. Rolling can produce sheet stocks that could be laser-cut and bend formed in subsequent processes, and spinning can utilize basalt fibers for the creation of fabrics and composite structures (however, research would be required to replace plastics with inorganic materials primarily derived from planetary in-situ soils). Laser-beam cutting and welding would be possible with imported gas and garnet or ruby for the discharge and zig-zag tubes, or solid-state lasers. However, it was noted that Electron-beam devices for cutting and welding are probably the easiest to construct in space, since the major constituent parts can be manufactured using in-situ materials.

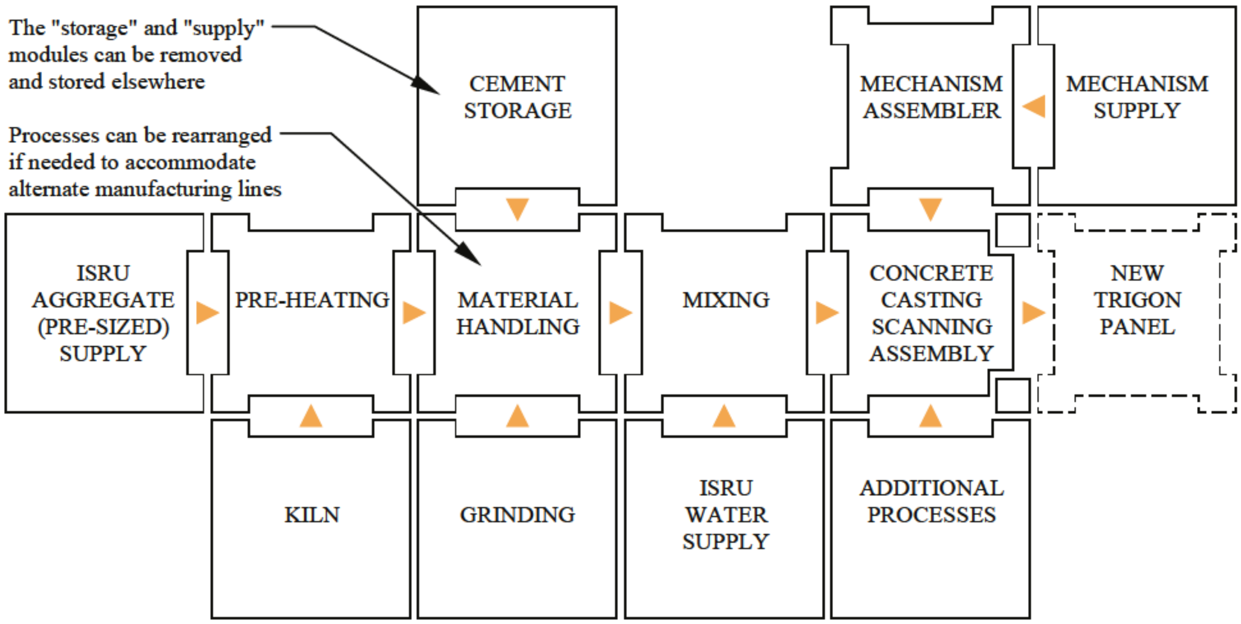

Figure 7: Lunar concrete factory with compartmentalized process blocks (Howe 2007b)

The Advanced Automation for Space Missions workshop summarized space manufacturing research up to that point, and many of the participating specialists continued to develop the research further (see for example Criswell, Abarbanel 1998). Further research has been underway regarding powder metallurgy and sintering, where recent flight experiments have demonstrated unexpected difficulties in distortion and densification control (German 2003), while at the same time suggesting possible alternative strategies. But of particular interest are the digital processes that have become commonplace in the intervening years, building upon the groundbreaking study, and from other unrelated directions. These processes are commonly referred to as Solid Freeform Fabrication (SFF), and the related Fused Deposition Modeling (FDM), Shape Deposition Modeling (SDM), Mold Deposition Modeling (MDM), and Selective Laser Sintering (SLS). The SFF processes can use a variety of materials in powder form including plastics, ceramics, and metals that are formed digitally directly from three-dimensional CAD data, but the products often require some post-processing for finishes and precision machining. Liu, et al. (2004) have fabricated complex fuel injection manifolds using SDM, with conduits and fuel passages integrated into the unit at the time of manufacture, which would be impossible using ordinary manufacturing processes. Another technique called Contour Crafting (Khoshnevis 2004) uses the layered deposition fabrication technology to form conduits for electrical, plumbing, and air conditioning into large-scale habitable structures. Taminger, Hafley, and Dicus (2002) discuss how SFF processes can be used to digitally produce large-scale space structures onsite with only a continual supply of metal feedstock. SFF processes can be used as a sustainable approach to manufacturing, repair, and maintenance of robotic ecologies and infrastructures (Malone, Lipson 2002). Entire functional mechanisms can be created using multi-material SFF processes as demonstrated by Malone and Lipson (2004), with a simple robotic device that included piezoelectric mobility and structure manufactured in a single multi-material SFF process. Malone and Lipson described some disadvantages of their manufacturing methods as using hardware that might be difficult to reproduce using fully in-situ materials and processes. However, Taminger and Hafley (2003) have shown that an Electron Beam Free-form (EBF) manufacturing technique can be used to sinter metals in a vacuum, and we have seen that e-beam devices can be constructed of entirely in-situ materials found in the Lunar environment. It appears only a matter of time before multiple-material SFF processes may use the EBF method.

Piezoelectric actuators formed into mechanical devices using SFF have great potential for space-based manufacturing. Because of their solid-state construction and the innate polarized dipoles of the constituent molecules that change dimension when a current is applied, piezoelectric mechanisms may potentially replace traditional wound motors and other complexly manufactured mechanisms.

SFF has the potential to make entire sophisticated constructions in a single process using multiple-material feedstock inputs. However, it should not be assumed that SFF would meet all needs, especially when it comes to extremely sophisticated products that would support human habitation and sustainable colonization in deep space environments. Oeftering et al. (2009) present a roadmap for surface sustainability, that begins with scavenged parts shredded or broken down into feedstock powders and raw materials, and eventually expands into extraction from native *in situ* materials. Freitas and Gilbreath (1980) suggest a "generalized paradigm" for space industrialization. The paradigm suggests process steps that can be matched with physical tools or factory modules (Humphries 2004). In a modular approach, a very basic setup would have only assembly of modules that have been pre-integrated on Earth. Using a modular robotics construction system that automatically generates structural, power, control, and spatial hierarchies in tree structures, we can begin to design function-specific blocks that have discrete inputs and outputs on top of the modularity. The equipment required to manufacture the units must also be constructed from, and actively participate in the very modular units that they manufacture. Compartmentalization is necessary to provide a series of process blocks with discrete input and outputs, and the means for one block to pass its output to the input of the next appropriate block. Modularity and compartmentalization are techniques that can be employed to manage the inevitable complexity of manufacturing processes. The final output of the final process block would be the finished modular unit, delivered into the system where it may self-relocate as needed. Ideally the very first input of the first process block would be materials found in-situ at the site (dirt, rock, regolith, etc), however process compartmentalization allows the insertion of preprocessed and preassembled components anywhere along the line, without needing to redesign the whole line (Figure 7). Process blocks and material handling (such as linear delivery, forks, sorting, etc) should be based on the modular construction system, to enable self-reshuffling of blocks to create alternate manufacturing lines for a variety of end products.

VI. Self-sustaining Systems

A final challenge for the construction and deployment of space infrastructure is the inevitable need for maintenance and repair. As for the initial construction, it is desirable to minimize human intervention. The approaches can be both structural and procedural, depending on the nature of the maintenance and repair task. Structural approaches rely on materials with properties analogous to those of biological systems, where tissues and bones are capable of self-healing. These types of materials, however, would probably be complex and would thus increase the difficulty of in-situ production.

Procedural approaches rely on a schedule of robotic inspection, or on the ability of different modules to signal the inception of problems. The structures would need to be designed for "repairability" and the modular systems described above (especially self-deploying structures) would be compatible with this need, as new modules could be brought into place and swapped in for the failed ones.

The extreme extension of a self-sustaining infrastructure is what one of the authors termed "Robosphere" (Colombano 2003) or robotic ecology. The concept here is to gradually build an infrastructure where, in analogy with biological ecologies, nothing is "wasted". A key starting point, as with systems already discussed, is modularity, where defective modules can be detected and swapped out. At the same time some of the modules could be refurbished and the need for a fresh supply of parts reduced to ever smaller and complex to manufacture devices (CPUs, for instance). In time such robotic ecologies could be built to utilize increased levels of autonomy while minimizing the input of mass and devices from Earth. This technology could be utilized for distant outposts, to prepare sites for the arrival of human explorers and ongoing habitation support.

VII. Conclusion / Discussion

We have surveyed a range of technologies that are at their inception and need to be further expanded and refined to enable a robust development for space infrastructure. The major driving costs of space infrastructure are the deployment of mass, both in space and on planetary surfaces, and the utilization, sheltering and safety of human explorers/colonizers. To minimize these costs it is essential to utilize local resources for sheltering and for the production of other structural elements. For these purposes we have identified technologies for resource utilization and local manufacturing. It would be desirable to accomplish these processes in fully automated mode to be able to limit human intervention. Construction of complex structures, in space or on planetary surfaces, would also be automated as much as possible, and here robotics would play a major role, with some appropriate mixture of three approaches: humanoid robotics, transportation/construction platforms and self-deploying structures. In orbital space the role of the transportation platforms would be assumed by large robotic arms and suitable robotic transportation space vehicles. Techniques and strategies for increasing the ability of these systems to become self-sustaining were also addressed. As we enlarge the scope of space construction we are faced with problems of stability and efficiency that would greatly benefit from the development of theories for the management of complexity.

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Nomenclature

AIAA	=	American Institute of Aeronautics and Astronautics
ATHLETE	=	All-Terrain Hex-Limbed Extra-Terrestrial Explorer
CAD	=	Computer-Aided Design
EBF	=	Electron Beam Freeform
EVA	=	Extra-Vehicular Activity (crew activity outside vehicle)
FDM	=	Fused Deposition Modeling
ISRU	=	In-situ Resource Utilization
ISS	=	International Space Station
IVA	=	Intra-Vehicular Activity (crew activity inside vehicle)
LEO	=	Low Earth Orbit
MDM	=	Mold Deposition Modeling
NEO	=	Near Earth Object
NC	=	Numerical Control (digital manufacturing)
SDM	=	Shape Deposition Modeling
SFF	=	Solid Freeform Fabrication
SLS	=	Selective Laser Sintering
TRIGON	=	Transformable Robotic Infrastructure-Generating Object Network