Castles in the Sky

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Introduction

Orbital Construction Pioneers, Inc. (OCP), a Texas Corporation built on the foundation of Christ with investors from multiple States, is developing an orbital fabrication process for exceptionally large space structures that uses non-traditional methods and materials. The patent pending process uses unusual raw materials and methods to fabricate components in orbit that can be used to construct large space structures. The system takes a radical innovative approach that differs greatly from other organizations' approaches. This results in final structures that are flexible in design, and are adjustable to fit almost any mission, including storage, long term habitats, and as vessels when equipped with propulsion.

Just as ancient civilizations used in-situ resources, we are proposing to use resources recovered from the moon and other space bodies mixed with polymers to construct components for all types of structures. The manufacturing of the components will occur in orbit eliminating the size, shape and vibration constraints imposed by current lift vehicles.

By combining new and old technologies together, cost-effective construction of large to exceptionally large structures in space becomes possible.

Human Sized Structures

As mankind expands into the solar system, certain needs must be met such as energy, food, water, breathable air, and shelter. The primary issue will be the health of the people and their ability to maintain their physical capabilities, so that they can efficiently complete complex and physically demanding tasks in a harsh environment.

Research has shown adverse effects happen to the human body in microgravity. Loss of muscle mass, bone density and changes to the lymphatic system are all effects from spaceflight.[1] The longer the duration, the more pronounced the effects. The research has also shown that these changes may never be fully undone after returning to a gravity environment. NASA has tried to mitigate these issues with a regimen of exercise, sleep, and food with some success, however none of these measures have fully prevented damage to astronaut's bodies.[2]

It follows that to have people remain healthy and in good physical shape, they must live in a gravity, or gravity simulated, environment. How much gravity is unknown as the research has been extremely limited. We can postulate that if long term habitation is to occur on the Moon, then one-sixth Earth's gravity needs to be sufficient.

Currently man can only simulate sustained gravity with acceleration through rotation.

Studies have shown that about 98% of the population can withstand 1-2 rpm without nausea or disorientation. As you increase the rpms, less and less of the population can tolerate the faster speed. Above 3 rpm will require training and adaptation for humans to function normally.[3]

All the facts and assumptions come down to this: we need a simulated gravity field that has a strength of no less than the Moon, but is more effective as we approach Mars gravity (38% of Earth normal). It must be generated through rotation, and the rotation cannot be greater than 1 rpm (for the maximum accommodation). This requires a structure that is three hundred meters in diameter for Moon gravity or 680 meters for Mars equivalent.

Mission requirements

Having humans in good physical condition is paramount for the completion of any mission which requires physical labor, such as a mission to Mars. A standard manned Mars mission plan has the crew in micro-gravity for approximately 9 months [4] during the transit. The crew will then travel to the surface and perform manual labor, in spacesuits, setting up a base and scientific gear. The time in micro-gravity will result in loss of muscle and skeletal mass along with changes to their respiratory and circulatory systems. Over time the crew will acclimate to Mars gravity, but initially it will result in slower progress, possible mistakes, and injuries. However, if the ship were a large structure which provided a Mars gravity environment, the crew would be acclimated immediately and at full productivity at touch down.

Other types of missions would benefit from large structures, such as on orbit manufacturing, communications, astronomy, and many other civilian activities.

The development of Stellamer-P, and Stellamer-R based additive manufacturing, will also have potential defense and military applications. The technology could lead to facilities and ships fulfilling roles, analogous to aircraft carriers, in support of independent, autonomous mission operations / fulfillment. This technology would enable the military to meet core objectives and maintain a position of semper supra.

The adaptation of Stellamer will not only help the military support space operations and enhance Space Domain Awareness (SDA); these concepts are also applicable to commercial space operations. Additional military developments will translate to further civilian applications. The full impact of the Stellamer technology is currently unknown.

Traditional way of building large structures

The International Space Station (ISS) is arguably the largest structure created by humans in space. It took more than 40 flights from Earth and over 10 years with an estimated cost of greater than $150 billion to complete. [5][6][7] For sustainability of habitation in space we must find ways to build larger structures quicker and at a far lower cost.

The cost of lifting stuff (mass) to space is directly proportional to the depth of the gravity well (the strength of the gravity). It takes more energy, and a stronger vehicle, to lift 1 kg of mass from Earth to orbit than it takes from Mars to orbit. In Earthly terms, envision it as a mountain. The higher the mountain (stronger gravity) the more energy it takes to reach the top.

Current construction methodology requires all materials for construction to be lifted from Earth resulting in huge transport costs. The costs could be lowered if we could find the required materials in a lower gravity well, such as the Moon. In the Earthly analogy, if we built a structure on top of a mountain, we could lower our costs if we could find the materials (cement, wood, stone, etc.) we need ½ or even ¾ to the top as compared to transporting it from the mountain base. The amount of cost savings would be proportional to the amount of usable materials that can be sourced from the area close to the mountain summit.

When constructing a space structure / habitat, the assumption is that most of the assembly's mass is in the structure such as a habitat shell, beams, decks, walls, shields, etc. These items which are currently made from aluminum, titanium, and carbon fiber for weight reduction, could be constructed from reenforced concrete or similar materials.

Research has shown that regolith (Moon dirt) mixed with water makes excellent concrete. Using in-situ resources lowers the transportation costs but the problem with this approach is that water, when lifted to space, is an expensive and otherwise useful commodity that would be wasted in construction. It would be better utilized as fluids for the astronauts or broken down into oxygen and hydrogen making breathable air and rocket fuel. There are also issues with concrete when dealing with non-compressive forces (tensile, tortional, and shear stress). Our approach uses a waterless process that produces a superior material that can handle the different stresses associated with structures not located on celestial bodies.

Mass/size constraints

Traditional construction techniques used in building structures in space, e.g., the International Space Station (ISS), involves the fabrication of modules on the ground and then lifting them, one at a time, into orbit. Once in orbit they can be attached to each other forming the final structure. The size, shape and mass of each module is constrained by the lift vehicle.

Each Earth manufactured module must fit under the vehicle shroud, or in the case of Skylab, be a modified vehicle stage, and have a mass within the lift capability of the vehicle. This results in modules that are round short tubes which may or may not be the optimum shape for the mission. Once in orbit they can be attached together to form a larger structure, which can take multiple shapes such as a long tube, a tree or even a ring.

The construction of the ISS used this method. It took 42 flights, 37 U.S. and 5 Russian, of which 16 were pressurized modules. This resulted in a structure that is 109 meters long with the length of longest pressurized module at approximately eleven meters. Applying this technique to a 300 m diameter ring station, which is the best configuration for creation of artificial gravity, it would take over eighty-five flights, just for the pressurized area of the ring.

OCP System

OCP is developing an orbital infrastructure, which reduces the reliance on material from Earth, for the construction of large orbital structures. The development includes both a material consisting of a polymer binder combined with lunar regolith and additive manufacturing processes for the on-orbit manufacturing of structural components. Our goal for the infrastructure is to manufacture hexagonal, circular, pentagonal, and square panels that are up to 100 meters across, along with beams that have customer specified lengths for use in the construction of persistent human occupied structures (250 m diameter minimum) and sensor / detector / defeat platforms that can a have a span greater than 250 m.

Our approach is not limited by launch vehicle constraints, the raw materials are lifted to space as bulk items. The payload size and shape constraints of a launch vehicle are negated as the items will be in the form of liquids, gases and powders which will fill any shape container. The only constraint will be the mass the launcher can carry. The manufactured components are now constrained by the manufacturing facility, which can be expanded over time, and not by a lift vehicle.

The use of polymers as binders allows for the material to fit the missions. Different polymers have different strengths, radiation resistance / blocking and flexibility capabilities, the mission and / or placement of the component will determine what polymer properties are needed. The use of polymers also provides the ability to “glue” the panels together for large structures and for easy repair / refurbishment.

The additive manufacturing printers will be completely different from their terrestrial counterparts. A printer that is 150 to 200 m across and free floating in orbit will be very sensitive to Newton’s third law of motion: Action and Reaction. Each movement of a “print head” or “table” will have to be countered with an equal but opposite force. The design must focus the forces of printing in one direction, allowing for a single opposite direction force to bring the system into equilibrium. The OCP printer design meets these requirements and has a patent pending.

Material

The OCP program has its foundation in the ancient past. As outlined in a paper [8] from the Geopolymer Institute, the Tiahuanaco monuments (Tiwanaku / Pumapunku) in Bolivia and possibly the Egyptian pyramids were built using a polymer / rock dust system similar to what we are proposing. However, instead of using molds and water, as the ancients did, we will use additive manufacturing and a waterless process.

Our main goal, for all brands of Stellamer, is to use at least 70% of in-situ products by mass. In most versions of Stellamer, the mass can be any dry mass including regolith, dirt, or any other material from a celestial body.

Two broad categories of Stellamer are being developed: Stellamer-P and Stellamer-R. Stellamer-R is designed for use in a gravity environment and has superior compression strength, while Stellamer-P is for use in a micro-gravity environment with excellent tensile strength and able to withstand impacts of micrometeors.

Stellamer-P

Stellamer-P is designed for structures in space that may be subject to micro-meteoroids, thermal and mechanical stresses. It has a higher tensile strength than Stellamer-R and can be used for pressure vessels. The construction of a pressure vessel would use a tri-layer approach. A ballistic gel like adhesive would be sandwiched between an outer layer that is semi-flexible and a rigid inner layer. If the outer layer is penetrated, the middle layer will seep into the breach and harden when exposed to sunlight, providing a minor self-heal capability.

Stellamer-P will be used in manufacturing processes in microgravity. Liquids in microgravity form balls due to surface tension. Since Stellamer-P is a high viscous liquid, it will be subject to surface tension which could adversely affect the printed shape. To prevent this a UV activator is added that, when exposed to UV, forms a thick surface skin, negating surface tension.

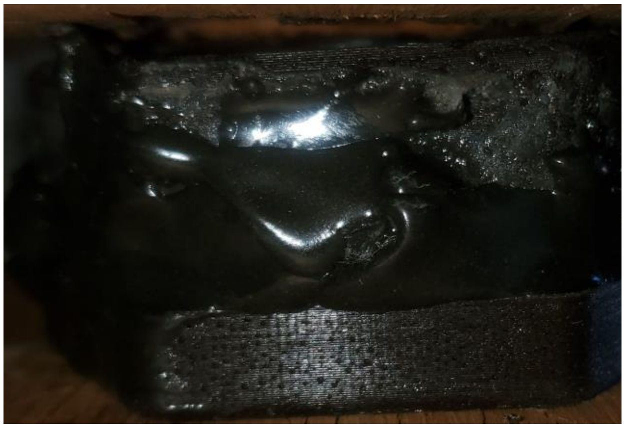
Goals

The initial goals for Stellamer-P are:

- Waterless process that can be used in additive manufacturing.
- Compose 70% of in-situ products, by weight. Basalt is substituted for regolith in initial tests.
- Withstand slow speed impact (< 16 kph)
- Stop impacts from small space debris
- Have a tensile strength > 200 kPa.
- Demonstrate the capability to maintain printed shape in microgravity before full cure.

Testing

All test samples are molded into hexagonal shapes with a side length of 79.73 mm and a thickness of 12.78 mm. The layers in a three-layer construction have the designation of “A”, “B”, and “C”, starting with the outermost layer “A”, (the layer that is exposed to the space environment) and proceeding to the innermost layer “C”, which is used for the construction of pressure vessels.



Stellamer-P tri-layer prepared for testing.

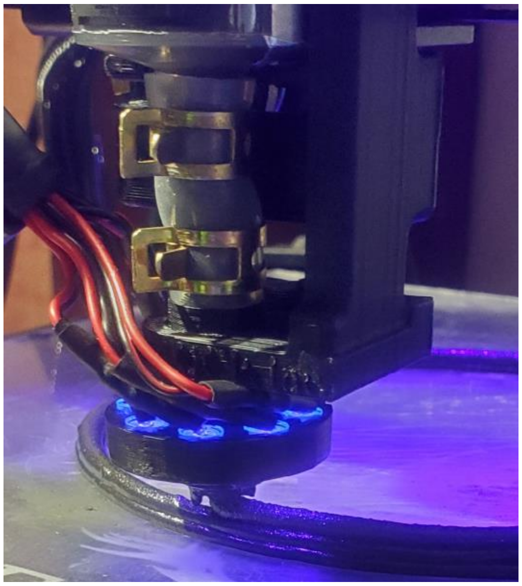
All tests were conducted at room temperature.

To simulate a micrometeor impact on layers A and C, we used a .22 rifle at 38 yards. The first test used Winchester 555 varmint rounds; a 36-grain jacketed hollow point with a muzzle velocity of 390 m/s (1280 fps). The second test used Blazer 22 a 40-grain bullet with a muzzle velocity of 376 m/s (1235 fps). To pass this test, the sample may allow the bullet to pass, but the sample must remain intact, with little to no cracking and material loss.

Tensile strength was measured using a manual tensioner with a digital force meter. The test articles had a surface area of approximately 10 cm^2.

Successful shot test

Layers A and C are subject to a slow speed impact test. A 1 kg steel ball is dropped from a height of 1.5 m. The sample is supported at the edges and must remain intact after the impact with little or no cracking.



Printability Test

The three-layer sandwich is evaluated using the micrometeor and impact tests. The micrometeor and impact tests are done in the same manner, however the bullet must not pass through, and the C layer must be intact and undamaged.

The printing test uses a modified 3D printer extruding Stellamer-P. To pass the test the printer must be able to make multiple passes, creating a wall that can support itself and maintain its shape against gravity.

Results

- All final test articles were made with 70% basalt by weight.
- Space debris test – The three-layer test sample was able to stop both types of bullets without damage to the C layer.
- Slow impact test – Layers A and C withstood impact from 1.5 m with no damage or marks.
- Tension testing – Values are averages:
    - Layer A - 531 kPa
    - Layer B – 350 kPa
    - Layer C – 865 kPa
- Printer testing – Successfully printed multiple layers. UV curing agent prevented running and slumping of material.

Successful three-layer space-debris test. The silver item in the hole is the bullet.

All goals were met or exceeded resulting in successful proof-of-concept.

Future Development

Continued proof-of-concept development of Stellamer includes:

- Extreme temperature testing. Samples will be soaked for 48 hours in a cold chamber exposed to Dry Ice, reducing the temperature of the sample to approximately -78.5° C. The hot test samples will experience a 48 hour soak in an oven at 120° C. Samples will be subjected to slow impact, space debris and tension testing at temperature.
- Samples will also undergo temperature cycling where they will be subject to 3 cold / hot cycles before testing.
- All proof-of-concept development has been done with basalt as a substitute for regolith. Future testing will use regolith simulant for closer approximation to the real world.
- The final area for proof-of-concept printing is the additive printer. The current test printer only tests the printability of Stellamer and not the function of the real printer design. Future development will take an incremental approach at incorporating microgravity printer design elements

into a functioning printer. The goal is to print Stellamer test articles using the microgravity printer design.

Economic Effect

On orbit geopolymer construction will have a large positive impact on the space economy. To illustrate, the BNRC Deep Space Data Network (DDSDN) platform will be used as an example. Multiple printed components will be connected to form the platforms. Each component can have a mass of over nine thousand tonnes necessitating a construction framework or scaffolding complete with robotic arms, and other material handling devices, essentially a shipyard. As the demand for items (ships, containers, habitats, etc.) increases, the number of printers and size of the shipyard will also increase.

As proposed by BNRC, a DDSDN platform will have a structural mass of approximately 90 million tonnes. Using the geopolymer printer method, 70% of the material will be regolith, or approximately 63 million tonnes. BNRC is proposing twelve initial platforms to be built with more added as humanity expands into the solar system. A system would have to be in place to mine and transport 756 million tonnes of regolith from the Moon just for the BNRC project.

Before the regolith can be transported and used it must go through beneficiation, reducing it into a usable granular size and, as capabilities increase, the removal of useful elements such oxygen (O), silicon (Si), iron (Fe), magnesium (Mg), calcium (Ca), aluminum (Al), manganese (Mn) and titanium (Ti), with oxygen, iron, and silicon being the most abundant.[9] Some of these elements can be removed during processing for use in other products without affecting the final printed product. The oxygen content alone, estimated at 45% (by weight), is worth additional processing / extraction.

NASA MSFC has proposed ways to use many of the materials that can be extracted from regolith to include electronics, furnishings, rocket fuel, etc. Many of the items that will be used to outfit a habitat or ship could be manufactured from material found on the Moon. This will result in a large mining, processing, and manufacturing facility on the surface and in lunar orbit. The facility will also need to support the personnel that operate the base(s) and orbital shipyard(s).

Supplying these facilities from Earth will quickly overwhelm the launch infrastructure, forcing the Moon infrastructure to become as self-sufficient as possible. As humanity expands into the Solar System, so will the need for structures of all types. The Moon facilities will grow and be replicated on other Celestial bodies to satisfy the demand.

The military will also contribute to the space-based economy. The development of Stellamer technology, as stated above, will have potential defense and military applications. The economy will benefit from the construction of military structures and the logistics that will develop in support of the military mission.

As commercial and military systems are brought online, a space economy will be established providing goods and services to be used outside of Earth. Eventually, as humanity spreads throughout the Solar System, Earth becomes one of many suppliers and consumers in the Solar System economy.

Closing statement

It has become apparent that if humanity is to become a spacefaring race, then how we build space structures has to change. We must learn how to utilize in-situ resources with newly developed construction techniques. The OCP approach meets both requirements and provides the ability to construct extremely large structures. However, it is only one piece of an exceptionally large and complex puzzle. Just as building a large structure on Earth requires many different processes, companies, and resources, so will construction in space. Eventually a space-based economy will develop that is not Earth-centric but where Earth is a part of it.

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