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From the Outside In: Building Massive Structures in Orbit.

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ABSTRACT

Current conventional habitat construction for space involves the terrestrial fabrication of complete modules that are then shipped to orbit and assembled into a larger structure in a manner loosely analogous to a conventional construction site. This mode of construction requires considerable technical capability in orbit including the use of robotic systems, and human EVA activity. More recently additive manufacturing technologies, 3D printers, have been considered as a possible new method of constructing parts of space habitats in-situ.

Is it possible to adapt additive manufacturing, and other terrestrial manufacturing technologies to the environment of space in a way that facilitates the construction of large superstructures as one coherent whole rather than an assemblage of parts? We undertook a UK space Agency funded exploratory project to research our own novel 'Outside In' approach to this question whereby a single simple machine is shipped to orbit. Once deployed it uses a revolute additive manufacturing process to fabricate a large diameter shell by laying down material on a spinning mandrel mounted on an axial core and producing a spherical structure that completely encompasses the bulk of the machine. This shell contains the construction environment, providing containment and protection as well as a minimally pressurised workspace. It also functions as a build surface upon which new layers of material can be laid down by the machine which gradually works its way from the outside in until the final inner layer is completed and the superstructure is then ready for human occupation, or for the addition of internal features using more additive manufacturing processes.

The resulting habitat would be structurally sound and consist of many layers of different materials, each performing specific functions such as air bladders, radiation protection and impact protection with the layered structure also functioning as a bumper shield. Our construction method can be used to create large structures that employ materials shipped to orbit from Earth or from raw materials obtained from space. The methods are mechanically simple and represent a potentially cost effective way of creating built infrastructure in space. The same techniques also offer potential to produce rotating structures up to and over the kilometer scale, offering a viable method of creating spin gravity habitats.

KEYWORDS: [Habitat Construction, Additive Manufacturing]

INTRODUCTION

A key problem with any attempt to colonize space is how space borne habitats are constructed. When considering the logistics and mechanics of constructing habitats in space the challenges of working in this extremely dangerous environment have to be taken into account. There is the risk of high velocity impacts or the extremes of temperature and radiation, and the lack of atmosphere and pressure puts constraints on the ability to control heat, and to use processes that rely on atmospheric pressure. The lack of gravity and often the lack of any substantial ground mass to work against introduce problems with physical stability and control and with the containment of material waste.

By contrast on Earth we can anchor ourselves to the ground, waste materials and fluids run to the ground and can be collected, and air pressure and the presence of elements like oxygen allow us to feed and regulate chemical reactions, and keep things cool or warm.

In addition to these problems there is also, at the current stage in our exploration of space, a problem of logistics. We are unable to source raw or refined construction materials from space itself and so any modules or elements required for the construction of a space habitat must be shipped to orbit. In addition to the expense and risk, there are also limitations on the size and mass of individual items we can ship to orbit. Payload limits on launch vehicles tend to be focused on the most pressing factor – total weight and cost – but constraints on volume are also an issue if one wishes to ship a component for a space habitat that has a large internal volume.

Currently all habitable units are manufactured on the ground and shipped to orbit as a whole, where they may be joined to others to form a network of relatively small habitable units. An inflatable habitat called TransHab[1] was proposed by NASA and the concept has been developed further by Biglow Aerospace who are now testing inflatable habitats in orbit[2]. Inflatables can increase the habitation volume of the finished structure by allowing the module to be packed inside a payload fairing for launch and then expand to a larger size in orbit. This approach still has a limit in terms of the maximum inflated volume that can be packed inside a single payload fairing.

In the past, conceptual approaches to the construction of large habitats, and in particular habitats with large internal spaces, have taken traditional terrestrial construction as a starting point and imagined how it might be slowly assembled from smaller pre-fabricated units by teams of either space suited construction workers or robots.

More recently the use of additive manufacturing in space has become an active area of development[3] and offers a more versatile way to create large objects in orbit by using stock material that can be shipped in batches. This has the potential to bypass the constraints on payload mass and volume for large items. In theory an item could be fabricated as a continuous object with dimensions at the kilometer scale with raw material feedstock shipped to orbit in batches.

Manufacture of component parts in orbit and in a vacuum still presents a challenge in terms of thermal control, physical stability and waste management and the resulting parts would still need to be arranged and connected to form the finished structure. Removing some of those challenges by placing the manufacturing units inside a protected environment would also introduce new constraints.

ROTATIONAL FORMING

We propose an approach to the formation in orbit of large structures on the decimeter scale using a single machine that creates a pressurized, insulated and impact resistant structure enclosing a large volume of space efficiently. The purpose of the machine and our approach is not to create a fully equipped habitat autonomously, but to form a superstructure that can contain a pressurized environment and protect the interior from the harsh environment of space. It is, by analogy to house building, the laying of foundations, erecting walls and putting on the roof.

In its simplest incarnation the proposed machine would manufacture a spherical shell around its self. It has two degrees of freedom and consists of an axial tube or truss with a pair of rotating arms attached at the mid-point, and a pair of rotating rings attached to each end. The rings are able to rotate continuously about the axis of the main tube whilst the arms, referred to hereafter as the build arms, can rotate about an axis perpendicular to the tube in a way that allows the tips of the build arms to be brought into contact with the edges of the rotating rings, hereafter referred to as the starter rings.

At the tip of each arm is a material extrusion or deposition device that performs the same function as a 3d printer head. It can extrude or emit material and fuse it with material it comes into contact with. We will refer to this as the build head.

Figure 1 shows the machine in its starting configuration and includes a service module to provide power, reaction control and a supply of build material.

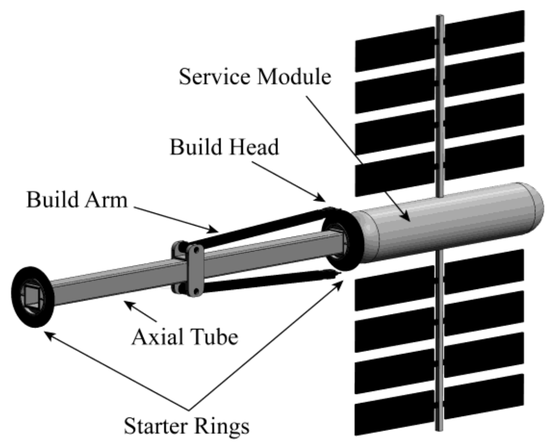

Figure 1. A simplified representation of a sphere building machine.

The build process

The machine operates by positioning the build heads at opposing edges of one starter ring. As the ring rotates they begin to deposit material on the rim, forming a thin wall. As this wall increases in height the build arm pivots away from the ring, keeping track with the surface it is forming. Due to the geometry of the machine this continuous process will gradually form a surface that curves in two dimensions, forming first a hemisphere as shown in figure 2, and eventually a complete sphere when the shell meets the second starter ring and the process terminates. The resulting spherical structure has an access point at either end through the starter rings.

At this point, with a machine that has only two degrees of freedom, the construction process would end. The resulting structure is a sphere that completely encloses the machine that built it and could theoretically be pressurized providing that the build material and process produced a robust enough shell.

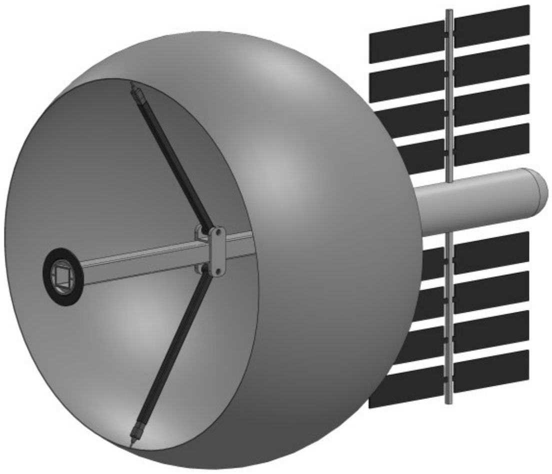

Figure 2. A spherical outer shell approximately two thirds of the way through construction.

BUILDING FROM THE OUTSIDE IN

The simplified machine described above would not produce a structure that is of much use as a habitat but it illustrates the first principle of our approach. The underlying mechanism and its operation are simple. The spherical shape it produces is an excellent pressure vessel and encloses the largest volume of space using the least material compared to any other shape. By keeping the construction machine stationary and rotating the starter ring and the subsequent shell that is being built it is possible to access the machine as it operates and supply more feedstock for the build process.

To produce a structure more suitable for habitation we need to create more than just a single thin shell. By adding a second degree of freedom to the build arms, for example a sliding member that can shorten the total length of the arm, it is possible to withdraw the build heads from the shell that they have just created and begin the process again, this time working back from the second starter ring and laying down a new spherical structure inside the existing one.

The process described above forms the first step in a process that works layer by layer from the outer shell inwards, increasing the thickness of the hull to whatever the design goals require. Constructing the outer shell first, and working inwards, provides several benefits:

- The thin outer shell can function as a build surface upon which other materials can be applied using a broader range of application processes, for example material can be sprayed onto the surface to seal it and form an air bladder.
- Once a layer has been formed that is not gas permeable the interior of the structure can be pressurized and a greater degree of thermal control can be imposed.
- With a pressurized interior, materials that require a reactant such as oxygen or an atmospheric counter pressure such as expanding foams can be used.
- By containing the whole build environment in the first stage of construction any debris or other waste from the build process is contained and will not contaminate the orbital environment.
- Each successive layer of material introduces a new barrier of protection against the numerous dangers found in space such as hypervelocity impacts and ionizing radiation.

A MULTILAYER, MULTIMATERIAL HULL STRUCTURE

The precise nature of the materials and processes that could be used is an open question and one best answered through an experimental program; consequently we are not attempting to address it in any detail at this stage. The overall properties of the resulting multilayer hull would have to fulfill some clear criteria, some of which would be met by specific materials whilst others would result from the use of composites.

The outer layer is perhaps the most problematic and important. It will be exposed to space for the duration of its existence and will need to be robust enough to withstand that environment. Because it is also the first part of the structure to be built, and because the structure will rotate when it is being built, this layer must also have sufficient mechanical strength to retain its shape, or else be supported in some way.

Within that outer shell the overall structure would consist of repeated layers of high density materials such as polymers, metals and ceramics, interspersed with much thicker layers of low density materials such as rigid expanding foams. These low density layers can potentially be seeded with materials to improve their structural integrity or provide improved protection against radiation. Additional materials would be applied to seal layers and create air bladders, and to prime layers so they bond effectively to one another and increase the mechanical integrity of the overall structure.

Impact shielding

The use of alternating thin hard layers with thick low density layers would allow the hull to perform the function of a stuffed bumper shield[4]. These are known to be effective at protecting spacecraft from hypervelocity impacts by disrupting an impacting projectile and spreading the forces across several layers, and across an increasing surface area[5].

Creating large structures with effective bumper shields is a problem where the structural components are prefabricated and shipped to orbit because the components consume payload volume despite being of relatively low mass. Creating a structure in orbit with these properties removes the problems associated with launch vehicle payload space because the build materials can be packed into the payload space with greater efficiency.

In addition, the raw material or feedstock used to create the structure may be able to tolerate significantly greater mechanical stress during launch than any prefabricated components.

Diversifying the manufacturing processes

The range of additive manufacturing techniques that can be used is diverse when you have an existing surface to work on and an atmosphere to work in. Spray coatings can be used to create non-gas permeable layers, as can spray layup techniques normally found in commercial mold making and yacht building, where chopped strands of reinforcing fibers are mixed with a catalyzed resin and sprayed onto a surface where they cure to form a fiber reinforced structure.

It should be noted that the additive manufacturing process used here may need to operate across a range of build speeds. If the structure being built rotates at a constant speed then the velocity of the surface that material is applied to will change depending on the distance from the axis of rotation. We will come back to this issue in a later section.

Sourcing raw material from space

So far we have assumed that the materials used to form the hull are refined and then shipped to orbit. It is possible to imagine a hybrid approach where unrefined materials sourced from orbital space or beyond are used in the construction process. An example would be to mix material mined from an asteroid with a binding agent to form a crude concrete which is then used to form bulk layers within the structure.

The use of material sourced from space becomes much more important when trying to create larger structures however at the stage where our societies consider it practical to create these very large structures in space it would be reasonable to assume that we have already begun to construct a space borne industry that can both gather and refine raw materials from space.

A TORUS CONSTRUCTION MACHINE

The previous sections have outlined the overall concept using a simplified machine to illustrate two core concepts: Rotational construction and the outside in build process. This next section details a machine that will produce a torus rather than a sphere and is envisioned as a complete unit shipped to orbit where it then creates a toroidal structure with a diameter of approximately 70 meters. The primary difference between this and the previous machine is that the axial core can be very short, rather than requiring its length to match the diameter of the finished sphere.

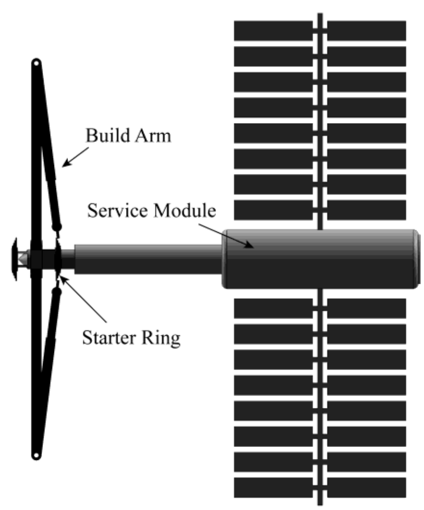

Figure 3. A torus construction machine in its starting configuration.

The machine illustrated in figure 3 consists of a short central core or axle with a symmetrical pair of build arms mounted on either side. The build arms consist of two sections joined with a rotating elbow joint in the center and with the outer section also having a sliding axis so that the overall length can be adjusted. A multi material build head would be mounted at the end of each arm.

A pair of starter rings mounted at each end of the axle can rotate around it under power and at a controlled rate. The machine is designed to fold into a compact package that can fit inside a payload fairing of existing launch vehicles but would be shipped to orbit as two modules comprising the main construction machine, and a service module to provide power and reaction control. These two modules would dock once in orbit.

Figure 4 illustrates three stages of the build process. First the build arms unfold to their start positions (A) with the build heads in contact with the same starter ring. The starter rings begin to rotate and the build arms apply material to them, rotating at their elbow joints as the outer shell begins to form (B). Eventually the arms will have rotated all the way round to the second starter ring, forming a complete toroidal shell (C) which is completed by fusing it to the second starter ring. A section view of the completed shell is also shown (D).

With the outer shell complete the build arms now retract a short distance and begin to lay down new material on the inner surface of the newly created shell. This process repeats with both arms working in unison to create successive layers of material, increasing the thickness of the hull as they go. The symmetrical arrangement of the arms and their synchronous motion means that torque induced by one arms rotation is cancelled out by the other ensuring that the only forces generated by their motion are linear, along the axis of the central axle.

The process of applying material to the spinning shell would produce a torque about the axle so part of the service modules function would be to counteract and manage these forces. The spacecraft would also be orientated so that the axle was perpendicular to the sun ensuring that solar heating and radiative cooling was consistent across the surface.

The structure is complete when a final inner layer has been formed and can sustain a fully pressurized atmosphere.

The resulting structure is spinning and can potentially be used as a spin gravity habitat, although it is equally possible to de-spin the structure after completion. The structure is also still just a shell and would require additional work in order to become a useable habitable space.

Some aspects of this finishing might be performed by the build system, with the build arms forming some internal structures, but it can also be undertaken by a human work crew, operating inside the pressurized environment.

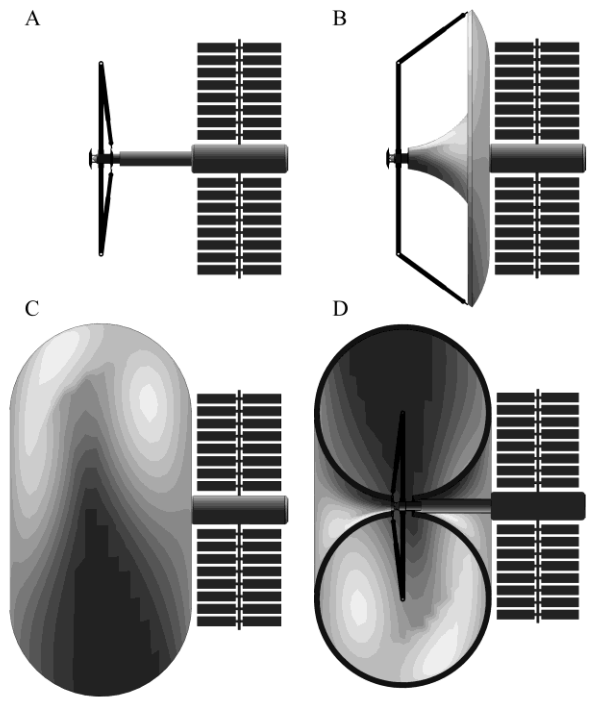

Figure 4. Three stages of constructing a torus. Starting configuration A, after one third of the outer shell is built B, and after the shell is complete C. D shows a section view of the finished shell.

A potential feature of the design is a natural lighting system illustrated in figure 5. One end of the central axle could hold a conical mirror and a transparent aperture. A free floating mirror outside the structure would reflect and focus sunlight through ninety degrees, into the aperture and onto the conical mirror; this then redirects the light to the interior of the structure. The transparent materials required to allow light into the structure can present a weak point and an additional source of mass if they are to provide protection against debris. This reflected lighting system ensures that there is no straight line path from the exterior to interior of the structure through which hypervelocity debris can pass.

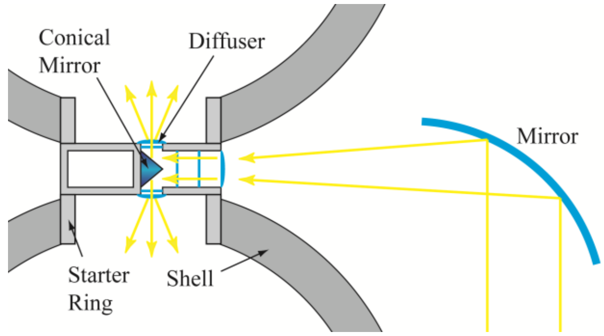

Figure 5. A passive internal illumination system.

VALIDATION

Ensuring that the finished structure is of sufficient quality and integrity to function as a habitat is essential in any circumstance, but achieving this whilst the structure is being formed in situ represents some particular challenges. The end of the main construction phase would most likely be followed by an extended period of monitoring and stress testing but a process of inspection would need to accompany the construction so that potential flaws in the structure can be identified. A continuing process of monitoring the structure thorough its life would also be required.

Continuous imaging of the build area

We suggest that construction would be accompanied by a process of continuous data gathering where the build heads are instrumented in a way that allows the material that has just been deposited to be imaged in fine detail. That data can be used to construct a model of the internal structure at every point within the finished hull. This can serve as a basis for simulated testing of the structure and to direct detailed inspections to specific points of interest or concern.

Externally assisted sensing and imaging

An additional technique might involve the use of a spacecraft located outside the shell adjacent to each build arm. The spacecraft would work in conjunction with instrumentation on the build head to gather data on the structure as it was being formed, for example the spacecraft could act as an x-ray source to image the interior of the hull, or map the thermal emissions from the structure as it is built.

Lifetime monitoring of the structure

To facilitate lifetime monitoring of the structure it may be possible to incorporate sensory networks as it is being formed. By deriving some techniques being developed for 3D printed electronics, a pattern of conductive and resistive pathways can be created and used to measure changes in the structure. It may also be practical to embed active sensors into some layers of the structure. Rather than requiring a permanent source of power, these sensors could be passive radio frequency devices that only activate and perform a data measurement cycle when exposed to an electromagnetic field.

VARIABLE CONSTRUCTION VELOCITY

As mentioned earlier, our approach may require the additive manufacturing processes to operate across a range of build speeds and this may introduce problems and technical challenges. If the rotating structure is moving at a constant speed then any build process will have to apply materials at a variable rate when the diameter of the constructed surface is changing. When the build heads first apply material to the starter rings they have the effect of increasing the rings diameter and so the velocity of the surface moving past the build head will also increase if the angular velocity remains constant.

It would be possible to vary the angular velocity of the structure, or of the build machinery, so as to ensure that the build speed remains constant, but this puts an increased demand on any reaction control system and potentially introduces additional energy costs. Part of the energy cost associated with cycling the angular velocity up and down during the build process can be met with energy recovery and storage systems but this does not solve the problem of countering the torque differences between the rotating and non-rotating parts of the system, particularly as the rotating structure begins to accumulate more mass.

A second issue here is the inertial force resulting from the spinning structure. The magnitude and range of this pseudo force will affect some build materials, causing them to drift or slide towards the outer circumference. This places some potential limits on the ratios of structure diameter and angular velocity when in the construction phase and on the materials used.

Speed ratios for different size structures

Table 1 shows a series of speed ratios and build velocities for structures according to minimum and maximum diameters, and the maximum inertial forces. We assumed a somewhat arbitrary minimum build speed of 0.1 meters per second.

Without a clear idea of the build processes and materials it is not possible at this stage to determine with any certainty the acceptable ratios between minimum and maximum build speeds, or the maximum inertial forces that materials can tolerate without slippage. It is worth noting with regard to inertial forces that where the forces are at their greatest – on the outer circumference of the structure – the geometry ensures that those forces will push material against existing surfaces rather than across them. In the example of the toroidal construction machine the inertial forces at their weakest point would act to push the material away from the surface being formed.

Table 1. Examples of the relationship between build radiuses, build velocities at constant RPM and centripetal acceleration.

Radius min (Meters)	Radius max (Meters)	Max/Min Ratio	Min build velocity (Meters/second)	Max build velocity (Meters/second)	Centripetal acceleration at max radius (g)	RPM
2.50	35.00	14.00	0.10	1.40	0.23	2.40
2.50	80.00	32.00	0.10	3.20	0.52	2.40
2.50	150.00	60.00	0.10	6.00	0.97	2.40
20.00	250.00	12.50	0.10	1.25	0.03	0.30
2.50	500.00	200.00	0.10	20.00	3.22	2.40
20.00	500.00	25.00	0.10	2.50	0.05	0.30
20.00	500.00	25.00	0.44	11.00	0.97	1.32

The first row of table 1 shows a structure with proportions similar to the toroidal structure detailed earlier and we believe it is reasonable to conclude that the maximum build velocity of 1.4 meters per second might be achievable, although we make that claim very tentatively. Based on their published specifications many terrestrial additive manufacturing machines fail to achieve these velocities, however they are generally designed to produce fine detail for small scale items so it may be reasonable to assume that in our system the coarser granularity can allow for much faster build velocities.

For larger structures the problem may be best dealt with by ensuring that the ratio between minimum and maximum diameters of the structure being built does not fall outside of acceptable limits. This might necessitate the creation of starter rings in orbit using either a different process, for example by assembly in orbit from prefabricated parts. For structures on the hectometer to kilometer scale the build machinery would be too large to be shipped to orbit as a single unit and so the assembly of the machinery in orbit would be required, and could incorporate the assembly of large diameter starter rings as a part of this stage of construction.

PRECESSIONAL INSTABILITY

The spin of the structure creates momentum bias that can help with the overall stability in a microgravity environment, however any spinning structure like the ones described here can become unstable when the axis of rotation begins to drift. In earlier sections we described how the build machine would be coupled to a service unit, art of whose function would be to maintain stability and to produce a torque to oppose the forces generated as the build system applies material to the rotating structure.

For a small machine this reaction control system may be achieved with a combination of magnetic torque rods, momentum wheels and thrusters, but for a larger machine these approaches may become impractical.

It should not be assumed that the structures created through our proposed methods would continue to spin after they have been created. Although it may be desirable for human habitable structures in space to generate a degree of spin gravity it may also be appropriate in some circumstances to create non spinning structures. Our proposed approach can still be used here; it just requires that the finished structure is de-spun.

A KILOMETER SCALE HABITAT

In the sections above we have discussed a number of problems associated with our proposed construction concept. These issues are the variable build speed associated with the varying diameters, controlling torque induced during the build process and preventing processional instability.

In this final section we propose a construction approach that deals with these three issues and introduces an additional feature of the build process that allows for the creation of tubular structures. Here we use an example of a prospective spin gravity habitat with an overall diameter of 270 meters and a length of 1250 meters.

Figure 6 illustrates the construction machine before the build process has begun, after half of the outer shell has been formed and after the outer shell is complete. It consists of a service module at the center with a pair of axial trusses at either side. On each of these axial trusses is mounted a trolley that carries four build arms of a similar design to those described earlier. The trolley is able to move along the truss. At each end of

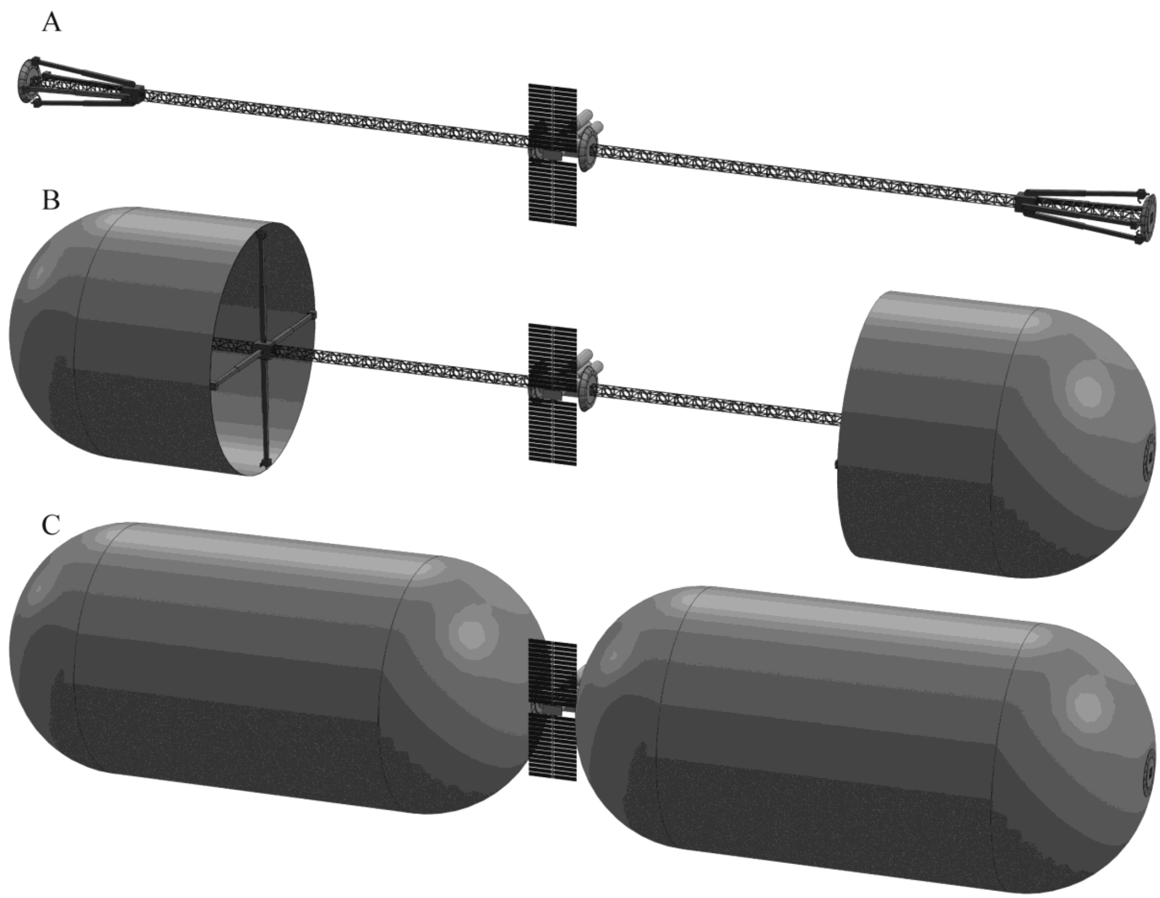

Figure 6. A kilometer scale habitat at three stages of construction.

each truss are mounted the starter rings. A detail of the build unit is shown in figure 7.

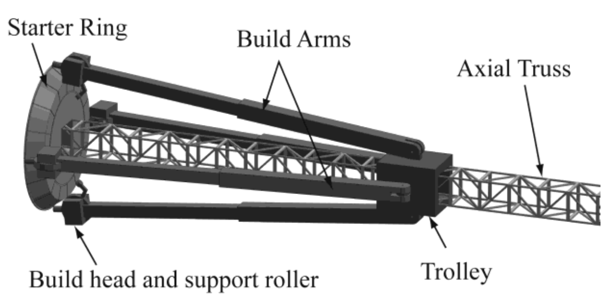

Figure 7. Detail of the build mechanism.

Each half of the machine will construct a shell in the same basic manner described in earlier sections, but the addition of the moveable trolley allows the build surface to be extended along the axis to form a tube. There is a danger with this configuration that the outer shell would become unstable when it is being formed because it is only weakly coupled to the starter ring at one end. The use of four build arms solves this problem by allowing the tube to be supported internally by rollers at these four points as it is being formed.

Symmetry for stability

The machine is symmetrical in design and is intended to operate in a symmetrical manner. The starter rings for each half would rotate in opposite directions with the build arms and their trolleys moving in opposition to each other. This symmetrical design and motion brings the following benefits.

- The torque induced by the build head depositing material on the spinning structure is cancelled out by the opposing head on the other side of the machine.
- Precessional instability is countered by the presence of two structures spinning in opposite directions.
- Reducing the build speed ratio between inner and outer diameters by adjusting the angular velocity becomes more practical because each half acts as a counter gyro and no other reaction mass is required.

- The mirrored movements of the starter rings, build arms and their trolleys cancel out, resulting in net zero torques and linear forces on the overall structure.

As with the toroidal structure this habitat would be oriented so that the axis of spin is perpendicular to the sun and, once the structure is complete, the central service area between the two rotating elements could be equipped with a solar collector to channel light into the interior of each half.

This mirrored approach can of course be applied to the smaller machines described in earlier sections.

CONCLUSION

We have presented an early stage concept detailing a set of methods for applying additive manufacturing to the construction of large scale habitable structures. The primary goal of our approach is to enclose a large volume of space in a shell that is structurally sound, capable of containing an atmosphere and of protecting the interior from hypervelocity impacts and ionizing radiation.

Our concept is not an attempt to autonomously create a structure fully equipped for habitation, but instead focusses on creating an environment more suited to human occupation, within which much of the work of finishing and equipping such a habitat can be carried out in relative comfort and safety.

As with any early stage concept there are many details and technical challenges that we have not addressed. Some of these details, such as the specifics of the materials and build machinery, are best addressed through practical experiments and physical research. Some challenging aspects of this approach are operational in nature, in particular is the problem of machine reliability. The build processes we have described require the machinery to operate continuously and where a specific layer of material is being formed it may be impractical and potentially destructive for the build process to be interrupted. Such interruptions might occur because support machinery fails, or the system of supplying feed stock to the build head jams or becomes obstructed. The mechanics of feeding stock material through the machine and dealing with potential interruptions in supply are common to any continuous production process but handling them on a machine intended to operate in orbit will inevitably amplify the engineering obstacles that must be overcome and introduce new ones that need solving.

For large structures such as the one described in the preceding section, the rigidity of the build equipment at those scales becomes an issue. Preventing the support structure from flexing and damping out oscillations in any flexural elements would be essential for such a machine to operate effectively. The effects of thermal expansion and contraction may also be a serious impediment to the construction process at these scales.

There are also a range of serious challenges relating to the operation of equipment in the environment of space that are not exclusive to our approach. Our objective with this paper was not to address those problems but to introduce and describe the general concept for the creation of large structures, the three core elements of which are:

- Continuous rotation of the structure as it is being formed.
- Building layer by layer from the outside in.
- Mirroring the construction process to produce net zero torque and linear forces on the structure.

Acknowledgments

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