AIAA SPACE Forum
12 - 14 Sep 2017, Orlando, FL
AIAA SPACE and Astronautics Forum and Exposition

AIAA 2017-5227

Archinaut: In-Space Manufacturing and Assembly for Next-Generation Space Habitats

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The National Aeronautics and Space Administration (NASA) and Made In Space, Inc. (MIS) have teamed up to develop Archinaut, a novel platform for in-space additive manufacturing and assembly. Building upon a heritage of technical and logistical knowledge accumulated from operating the MIS Additive Manufacturing Facility (AMF) on the International Space Station (ISS), Archinaut is a free-flying system combining additive manufacturing and robotic precision assembly capabilities. Adopting the Archinaut platform enables and drives a radical shift in space architecture design and construction. Archinaut can construct and assemble all functional elements of a space habitat by leveraging the benefits of additive manufacturing to offer flexible, end-use tailored functionality. Liberating space habitat design from the need to assemble and precisely package all components for launch from Earth to orbit, the platform represents a foundational shift in in-space manufacturing, assembly, and logistics. This paper reviews in-space manufacturing and assembly milestones, the foundation of technical work supporting Archinaut, a description of Archinaut's capabilities, and a vision for an Archinaut-enabled next-generation space habitat.

Nomenclature

3DP	3D Printing in Zero-G Experiment
AMF	Additive Manufacturing Facility
ASAL	Automated Structures Assembly Lab
BEAM	Bigelow Expandable Activity Module
CONOPS	Concept of Operations
DARPA	Defense Advanced Projects Research Agency
DSG	Deep Space Gateway
ECLS	Environmental Control and Life Support
EEL	Engineering Evaluation Laboratory
EVAs	Extravehicular Activities
EXPRESS	Expedite the Processing of Experiments for Space Station
HST	Hubble Space Telescope
ISA	In-Space Assembly
ISM	In-Space Manufacturing
ISRU	In-Situ Resource Utilization
ISS	International Space Station
MIS	Made In Space, Inc.
NASA	National Aeronautics and Space Administration
P(LOC)	Probability of Loss of Crew
PEEK	PolyEtherEtherKetone

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SAMEE	Scanning & Additive Manufacturing End Effector
SBIR	Small-Business Innovation Research
STMD	Space Technology Mission Directorate
TRL	Technology Readiness Level
TVAC	Thermal Vacuum
VULCAN	Vulcan Advanced Hybrid Manufacturing System

I. Introduction

The development of robust, reliable, in-space manufacturing and assembly capabilities is essential to the progression of human exploration and development of space. The logical next step in sustaining a human presence in space is complementing current in-space manufacturing and assembly capabilities with integration of advanced additive manufacturing and autonomous robotic assembly technologies. A next step in developing a robust, enduring, and sustainable human presence in low-earth orbit and beyond, integrating these capabilities liberates space mission architectures from stagnant mass, volume, and cost trends dictated by current space system manufacturing and assembly technologies.

Current space architecture design is bound by the paradigm whereby all mass necessary for human space habitation is upmassed piecemeal via inefficient, expensive chemical propulsive processes. The cost-per-kilogram of placing individual segments of a space station into orbit hovers precariously around $10,000/kg. Although launch providers are reducing this cost via reusable rocketry and production optimization, a decrease of an order of magnitude or more still evades the market.[1] No matter the time frame for anticipated reductions to launch cost per kilogram, the manufacturing and assembly process is a prime candidate for enabling payload mass-optimization using additive manufacturing to eliminate the need for launch-rated structures and complex deployment mechanisms.

II. The Development of In-Space Manufacturing

Archinaut is the result of years of efforts bringing additive manufacturing to space and other extreme environments. A combination of reliable and robust manufacturing and assembly hardware matched with the logistics and operational experience, these novel capabilities are foundational to the next-generation space habitat. Drawing upon this experience equips its operators with the tools necessary to manage the technical and programmatic challenges of this next step in in-space manufacturing and assembly.

A. 3D-Printing in Zero Gravity Experiment & the Additive Manufacturing Facility

In 2014, the MIS 3D Printing in Zero-G Experiment (3DP) became the first ever space-based additive manufacturing device. In partnership with NASA, MIS deployed and operated 3DP as a technology demonstration mission onboard the International Space Station (ISS). By demonstrating microgravity-capable additive manufacturing, 3DP met the objective of reducing risk for a larger, more capable additive manufacturing device - AMF. MIS operates AMF on-board the ISS as the only commercially-owned and operated fabrication system in space. Launched on Orb-6 in March 2016, AMF is capable of printing in ULTEM, PEEK, and polyethylene and improves on the capabilities of 3DP. The AMF is designed to safely and reliably produce thermoplastic polymer parts with minimal crew involvement. Once plugged into the Expedite the Processing of Experiments for Space Station(EXPRESS) Rack Locker (see Figure 1), the crew is only needed to periodically remove finished parts and exchange consumables. MIS services NASA utilization needs and commercial customers under the auspices of the ISS National Lab. AMF is a unique, upgradable microgravity laboratory and assists with on-going development of space-based manufacturing and materials characterization. AMF is responsible for raising the TRL of space-based polymeric additive manufacturing to 9.

Figure 1. AMF installed and operational in the EXPRESS Rack locker on the ISS.

B. Vulcan Advanced Hybrid Manufacturing System

The Vulcan Advanced Hybrid Manufacturing System (VULCAN) is an innovative hybrid extruder system incorporating post-processing of additively manufactured polymer and metal parts. Supported by a Phase I Small Business Innovation Research grant (SBIR) from NASA, it builds upon the advances in additive manufacturing demonstrated by 3DP and AMF. VULCAN capabilities inform and shape Archinaut development and makes innovations in the following areas: development of microgravity capable hybrid additive and subtractive manufacturing, microgravity process control, use of high-performance polymer and metal feedstock materials, and scalable and upgradeable system components.

Based on lessons learned from the development of space-rated devices such as AMF, the VULCAN build volume is completely sealed and environmentally controlled during operation. This innovation ensures a desirable ambient environment and prevents fumes or other particulates generated during manufacture from being released into the air surrounding the device.

C. Scanning & Additive Manufacturing End-Effector

The Scanning and Additive Manufacturing End Effector (SAMEE) is a Defense Advanced Research Projects Agency (DARPA) research and development contract supporting development of robotic end-effector enabling surface characterization and additive manufacturing. MIS developed SAMEE as part of the DARPA Robotic Servicing Vehicle program.

III. The Development of In-Space Assembly

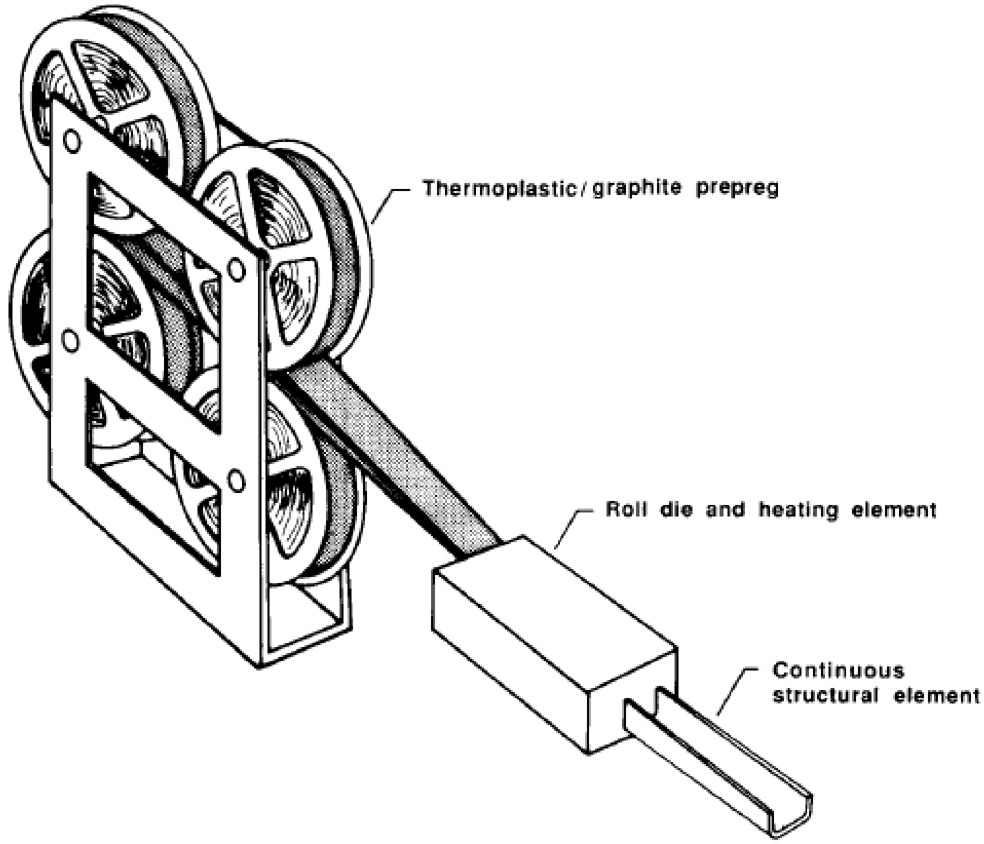

Figure 2. Pultrusion system producing thermoplastic composite structural element.[2]

A. Past Efforts

Pushing at the boundaries of the state-of-the-art, Archinaut's in-space manufacturing and assembly capabilities are the culmination of a vision decades in the making.

In 1980, Wilson et al, based out of NASA Langley Research Center, studied the potential for in-space manufacturing using a pultrusion process. On the ground, this process entails operators manufacturing and spooling a composite material, or prepreg. On-orbit, the spool is fitted to an apparatus that draws the stock material into structural elements (see Figure 2). In theory, this process can produce functional electrical elements and an array of composite elements of variable dimensions and tensioning. A spider crane robot is proposed to assist in on-orbit assembly. The space shuttle plays a critical role in housing and dispensing the pultruded material. Notably, this study recognizes the role that packing efficiency plays in implementing mass and volume optimizations that enable space structures tailored for the space environment. Efforts to utilize this technology are on-going, but none have resulted in a demonstration in a relevant space-like environment.[2]

Rhodes et al, a follow-on study also out of NASA Langley Research Center, identifies a framework for autonomous truss assembly for space structures. The Automated Structures Assembly Laboratory (ASAL) controls development of this system. Leading to the fabrication and testing of an apparatus for containing a 102-strut truss system, this study sought to understand the concept of operations (CONOPS) for such a system as much as it did the necessary technical components. Creating a backbone of assembly and coordination tasks, the study estimates strut assembly timescales, analyzes errors in the assembly process, and concludes that, despite a multitude of errors, this technique is a viable method.

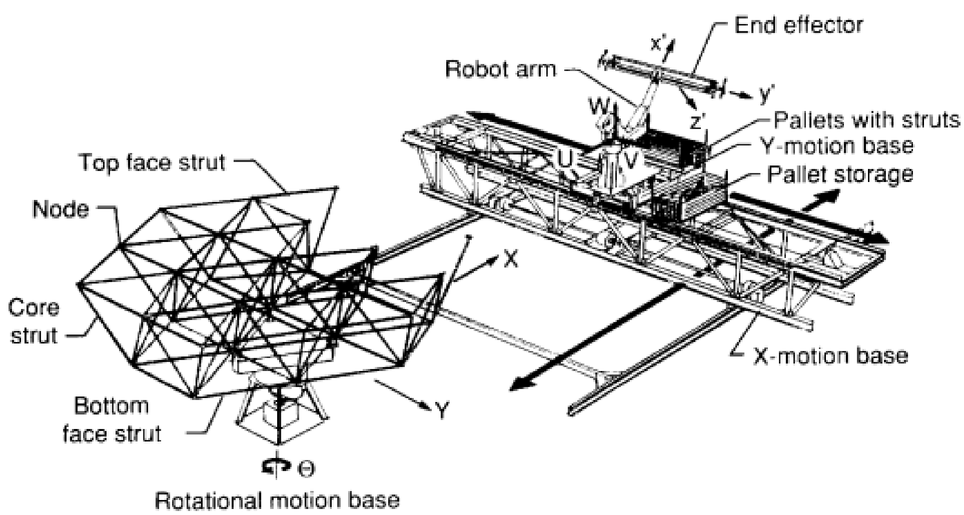

Figure 3. The experimental ISA setup at ASAL.[3]

See Figure 3 for a diagram of the experimental setup at ASAL. Although a microgravity environment is not a factor in this study, its conclusion is nonetheless in line with Archinaut's in-space assembly accomplishments.[3]

Doggett further refines the 1995 conclusions with a focus on work done at ASAL since its inception. As of writing, the ASAL includes multiple motion bases, end-effectors, cameras, and an industrial robot. Machine vision is used for part alignment and the study describes in-depth its experimental setup. The study identifies a number of critical features for successful operation of the robotic assembly apparatus, including but not limited to: task verification parameters, force and torque feedback, part features, the need for specialized end-effectors, path planning and safety, and ample robotic operating room for maximizing system dexterity. Figure 4 displays the ASAL industrial robot manipulating the truss structure.[4]

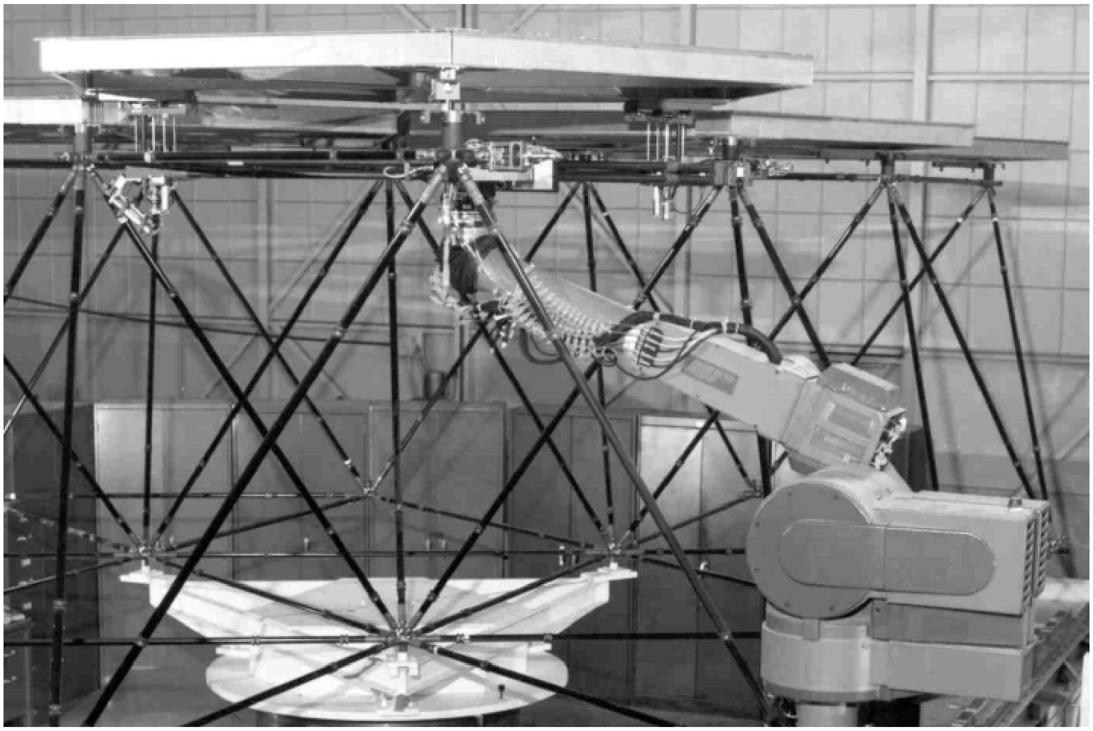

Figure 4. The industrial robot running through ISA tasks at ASAL.[4]

B. Space Architecture & Archinaut

The field of space architecture is growing at a rapid pace. Archinaut provides the capabilities that allow designers to exceed the status quo. Grounding Archinaut in this burgeoning paradigm frames and clarifies its role in defining the next-generation of space habitats. There are three classes of space architecture. Class I describes habitats that are tested and integrated on earth and are limited by the volume and mass constraints of launch vehicles. The on-orbit configuration cannot change. Class I habitats encompass all launched missions since the beginning of human spaceflight. Class II habitats are prefabricated on earth, but assembled in-space. Some subsystems are tested and integrated on-orbit, but most must undergo extensive testing on earth. Critically, this class is less constrained by the mass and volume limits of launch vehicle fairings. Robotic assembly is required to deliver the vision of Class II space habitats. Class III space habitats utilize in-situ resource utilization (ISRU) and every aspect of these habitats are assembled and integrated on-orbit. While subsystems may be tested on earth prior to launch, no part of these habitats is launched pre-fabricated. Class III habitats are not limited by launch vehicle fairings. Their volume and mass depend only on resources available and accessible in nearby locations. This class depends wholly on robotic systems for assembly and integration.[5]

As a seminal and contemporary piece of space architecture, the ISS falls within Class I. Next-generation space habitats constructed by Archinaut fall into Class II with a path forward to Class III. While Archinaut immediately allows for Class II space habitats, this suite of technologies is required for Class III. Diverse in-space manufacturing and assembly capabilities are the bounty of the vision that Archinaut realizes. Crucially, while at the present Archinaut operates using feedstock supplied from earth, inevitably this capability will evolve to accept in-situ derived materials. With the shift towards IRSU Archinaut will close the loop on sustainable human space development and a next-generation of space habitats.

IV. Archinaut Capabilities

In November 2015, MIS was selected to develop Archinaut, the Versatile In-Space Robotic Precision Manufacturing and Assembly System, as part of NASA's Tipping Point program through the Space Technology

Mission Directorate (STMD).

Archinaut is a free-flying space manufacturing and assembly capability that enables advanced spacecraft and structures to be produced in the space environment. MIS leads an industry team including Northrop Grumman and Oceaneering Space Systems. Northrop Grumman provides expertise in electronic interfaces and external thermal control analysis. Oceaneering Space Systems is designing and building the manipulator arm for the program.

A phased approach is being taken by the Archinaut Technology Development Project to mature the technology through ground experiments and potential in-space technology demonstrations.. Phase I is focused on reducing overall risk for key Archinaut subsystems while raising the overall TRL to 6. Ground tests validating constituent Archinaut technologies provide the path to raising the TRL while also offering valuable operational and test experience. The full vision of Archinaut sees manufacturing and assembly of otherwise unlaunchable structures once on orbit, permitting new mission capabilities such as large antennas, base stations, and, of course, next-generation space habitats.

A. ISA

State-of-the-art on-orbit assembly is presently defined by the numerous extravehicular activities (EVAs) performed by astronauts while constructing the ISS. While they are staggering technical and logistical feats, these EVAs are cost and mass prohibitive and are at odds with the development of the next generation of space habitats. Further, EVAs pose tremendous risk to human life. A risk prone environment no matter the perspective, space will continue to demand an unwavering commitment of the humans who venture beyond the forgiving cradle of earth.

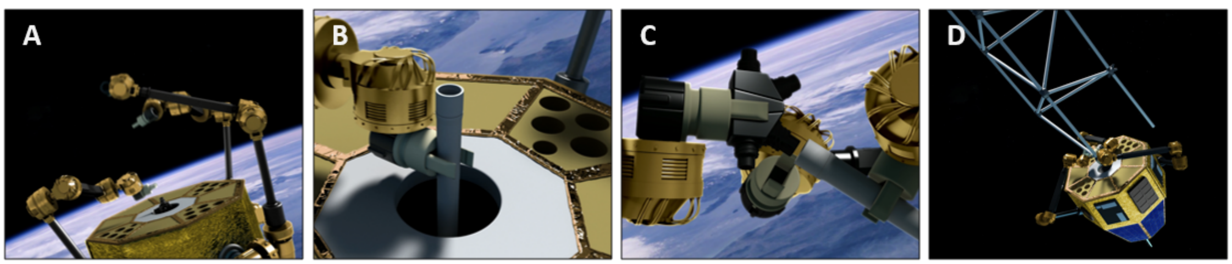

Figure 5. (A) Archinaut manufactures nodes and (B) struts, (C) Archinaut's robotic manipulators work together to mate structural elements, and (D) Archinaut autonomously assembles structural elements into a truss.

Archinaut advances the state-of-the-art and equips mission architects with the tools necessary to cut out avoidable and unnecessary risk to human life via development of the robotic mechanisms enabling the novel Archinaut manufacturing and assembly paradigm. As spiritual successors to the Space Station Remote Manipulator System (Canadarm2) and its predecessor, Archinaut's robotic manipulators establish the backbone for assembly processes that place humans on the critical path towards actualizing a future ripe for human space habitation and colonization. See Figure 5 for a diagram of Archinaut's in-space assembly capabilities.

B. ISM

In June 2017 Archinaut reached a historic milestone: successful additive manufacturing in a relevant, space-like thermal vacuum (TVAC) environment using the Extended Structure Additive Manufacturing Machine (ESAMM) technology. Demonstrating additive manufacturing of larger-than-build-volume structures in this environment is a key risk reduction for the follow-on stages of Archinaut as well as the suite of overall capabilities. Concluding the first Archinaut TVAC campaign conducted at the NASA Ames Engineering Evaluation Laboratory (EEL), this demonstration raises Archinaut technologies to a TRL of 6. Figure 6 shows ESAMM during the EEL TVAC test campaign. In August 2017, a 37.7m beam was manufactured in the MIS lab to demonstrate the additive manufacturing of a candidate structure many times longer than its parent manufacturing device.

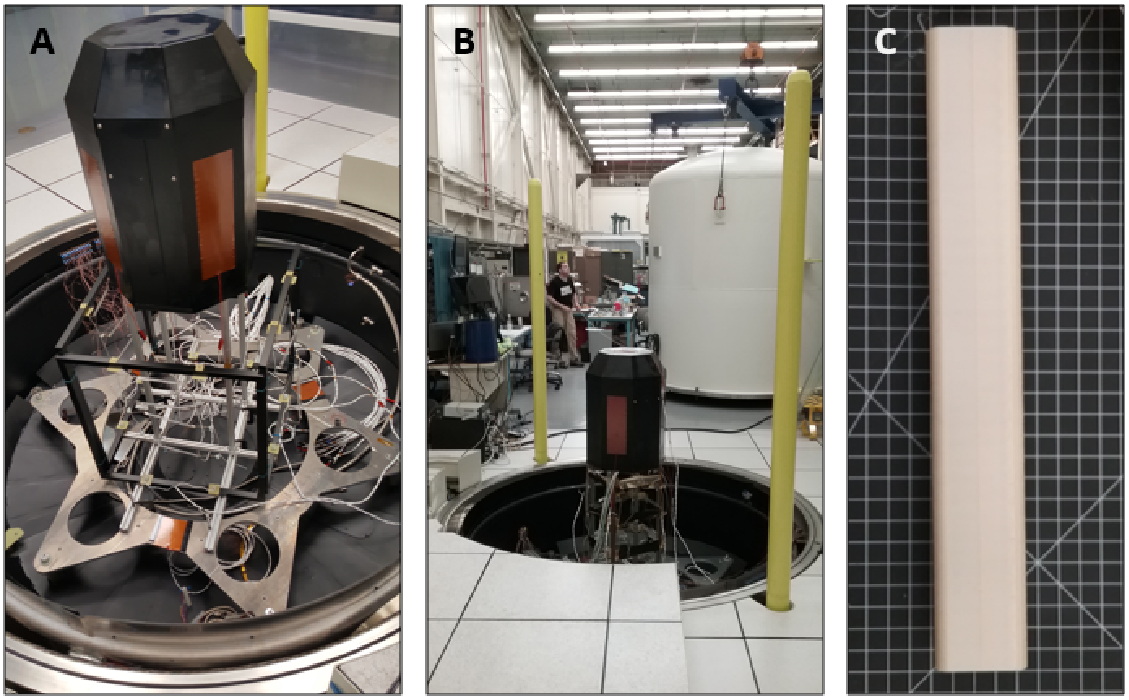

Figure 6. (A) ESAMM integrated within the EEL TVAC chamber, (B) ESAMM with TVAC chamber in background, and (C) structural element manufactured by ESAMM

V. Next-Generation Space Habitats

A. Envisioning the Next Generation

Imagining the next-generation space station begins by dissolving the current design paradigm of space-faring structures and reimagining the bounty of space as developed and utilized via Archinaut-enabled space habitats. In keeping with the current goals and visions for deep space exploration, Archinaut strives to uphold the "Design for Maintainability" philosophy foundational to the NASA ISM Program Timeline.[6]

Presently, spacecraft components undergo terrestrial assembly and upon completion are upmassed following a complex packing process to meet mission-critical spacecraft geometries. Folding and packing are necessary because launch vehicle shrouds define the launch envelope. From the perspective of a payload designer, this paradigm bounds volume and mass budgets. Once on-orbit, the concept of operations (CONOPS) corresponding to many missions under the existing paradigm entails an acrobatic display of maneuvers unpacking contorted, deployable payloads. Each step in the unfurling process represents a potential mission-ending risk.

For example, if a solar panel fails to deploy, the spacecraft can be starved of life-giving power. If an antenna fails to deploy then the subsequent disruption of communication with the spacecraft can temporarily jeopardize nominal operations or render the entire mission a failure. The deployment process itself compounds the situation with the potential for inducing unwanted torques to the spacecraft body; such torques are a dangerous prospect if they exceed the design limitations of the structure. These compounding factors dictate space systems that, assembled on Earth, must have sufficient robustness to survive the launch environment. Yet, all the effort funneled into designs ensuring launch survival is null upon arrival in the relatively benign loading cases of the microgravity environment.

B. The Archinaut-Enabled Space Habitat

Archinaut overcomes these design inefficiencies and enables a next-generation space habitat based upon a truss backbone design and drawing inspiration from the vision and technical reasoning behind the NASA Deep Space Gateway (DSG) concept. Leveraging Archinauts unique capabilities supplies a more feature-rich, reliable, and robust habitat than the planned concept, extending design space of the DSG. The next-generation habitat concept builds upon a common core of features, including but not limited to sustaining four humans for 1000 days. Pushing further, the Archinaut-enabled next generation habitat architecture supports 12 humans for the same length of time. As a Class II-habitat, the critical subsystems Environmental Control and Life Support (ECLS) and power among others are scaled DSG subsystems made compatible with proven Archinaut additive manufacturing and robotic assembly techniques.[6,7]

In addition to the initial manufacturing and assembly work, Archinaut births a novel, dynamic use case: autonomous space habitat repair. Historically, repairs such as those supporting the Hubble Space Telescope (HST) or the ISS consisted of risky EVA maneuvers. Archinaut is capable of autonomously effecting repairs upon a space habitat; think of the Archinaut platform as much as a manufacturing and repair tool as it is a space habitat (and by extension, human life) sustaining ecosystem. With this capability, the platform extends the paradigm of human space habitats, expanding their very definition. Just as a station needs solar arrays for power, this class of space stations needs Archinaut to enable and sustain new mission architectures. Archinaut is a novel and irreplaceable technology for ECLS systems.

Projecting these capabilities several decades out, a novel extension of Archinaut hinges on multiple Archinaut platforms working in unison and capable of effecting self-repair, extending the reliability of whatever space system for which they are responsible. A vision of that caliber depends on the ability to sustain a constellation of repositionable and dexterous autonomous robotic systems each equipped to analyze and infer structural and functional deficits. The space habitat possible under such a versatile paradigm is hard to imagine, but is far in excess of the facilities available to human explorers today. Further, using resources readily available in the space environment, Archinaut can leverage additive manufacturing feedstock sourced independently from earth, proving a path forward for earth-independent colonies and outposts. In-situ derived feedstock promises to close the loop on sustainable in-space manufacturing and assembly.

Refocusing on the near-term, the recently announced MIS and Axiom Space collaboration is the first step in realizing next-generation space habitats and is a springboard for fleshing out and further refining Archinaut's utility within the space habitat design space. This collaboration targets the five to ten-year time-frame for demonstrating construction of an extended platform from the Axiom Space station.

C. Mass Optimization and Risk Reduction

Archinaut enables novel mass efficiency optimizations over current manufacturing and assembly processes. Structures additively manufactured on-orbit do not need features to strengthen them for launch loads, assemblies allowing for deployment, nor face the constrains of launch fairing geometry. Optimization in this manner is nominal: Archinaut's additive manufacturing process constructs the target structure layer by layer and requires no support material in microgravity. Feedstock represents a mass repository; the potential to create and optimize a structure for precisely the environment and use cases at hand. Because nearly all Archinaut payload mass is densely packed feedstock, the volume savings coupled with structures optimized for the space environment yield a tremendous improvement in mass efficiency over current systems. The space environment is home to less harsh mechanical loading conditions than those experienced during launch and thus structures designed for space inherently require less mass for equivalent robustness and use cases.

1. Baseline Packing Efficiency

In a 2006 study, Mikulas et al concluded that a majority of space structures are significantly overdesigned for their given bending stiffness and that significant gains in efficiency are possible when utilizing certain composites, novel struts, and rods that account for certain metrics. These conclusions emphasize building for the space environment rather than the launch environment. Archinaut actualizes these conclusions. Notably, the study proposes a parameter, β, that describes packing efficiency in terms of a minimized volume for given bending stiffness.

In Figure 7, the red-dotted line corresponds to $\beta = 1$, the theoretical maximum packing efficiency where the volumes of the stored mass and manufactured mass are equal. Stowing structural material in the form of feedstock allows Archinaut to straddle the $\beta = 1$ metric and sets the stage for a next-generation of space habitats.[8]

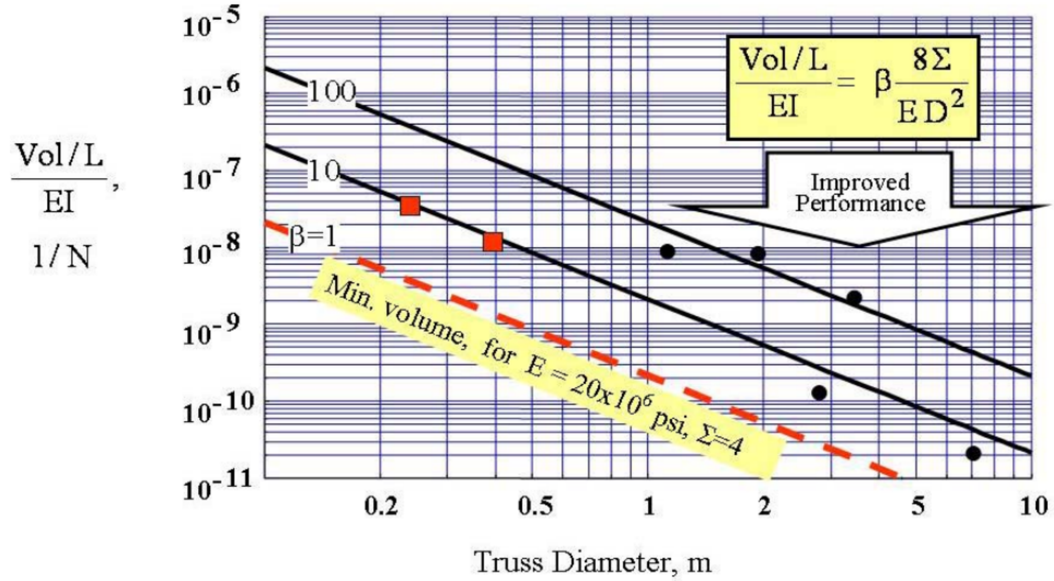

Figure 7. Packing efficiency for a given bending stifness as a function of truss diameter in meters.[8]

2. Inflatables

While Archinaut capabilities undersign the future of space habitation, in the near-term, these achievements should need not dismiss accomplishments in the field of inflatable space habitats. The Bigelow Expandable Activity Module (BEAM) is a robust capability demonstrating the utility of inflatable technology to augment Class I habitats. In terms of mass per volume ratio, BEAM is approximately 30% more efficient than the next best example (the Columbus ISS module) at 81 $\frac{kg}{m^3}$ versus 108 $\frac{kg}{m^3}$.[9,10]

Archinaut feedstock packs at approximately 1300 $\frac{kg}{m^3}$ or a 15x improvement in packing efficiency. The utility of inflatables is not in question, but long-term the mass, volume, and cost savings for an equivalent structural volume establishes Archinaut as the most capable candidate for next-generation space habitats.

3. Mass & Risk Reduction

Mass optimizations enabled by Archinaut deliver another mission benefit for space habitation: substantial risk reduction. Owens and de Weck model a number of ISM scenarios and their conclusions present a clear and necessary role for in-space manufacturing for the ISS and future Mars missions. They establish a link between the Probability of Loss of Crew (P(LoC)) and the cost of mitigating this risk as an exponential increase in a missions mass requirements. Quantitative analysis of this link reveals that it is most applicable to longer endurance missions, e.g. Mars, but nonetheless their conclusions hold even for the ISS. Owens and de Weck conclude that ISM reduces these risks by enabling use of a common manufacturing material, by allowing for robust systems, and by eliminating the constraints of the launch environment.[11] Archinaut delivers on the vision of these conclusions via its in-space manufacturing and assembly capabilities.

VI. Conclusion

Archinaut realizes a vision for more capable, reliable, and robust next-generation space habitats and promises an expansive future for human space exploration. Nestled at the intersection of bleeding-edge additive manufacturing and robotic assembly, Archinaut liberates engineers from designing solely for the launch environment and subsequently enables order-of-magnitude improvements in mass efficiency and structural sizing for space habitats. A path forward for Archinaut ISRU illuminates and circumvents the inefficient, prohibitive paradigm by which all mass necessary for human space exploration is brought to orbit via risky chemical propulsion at an unsustainable cost-per-kilogram. Actualizing a revolution in mass-dependent risk reduction, Archinaut at its core expands upon the heritage of research and development into in-space manufacturing, assembly, automation, recycling, and in-situ resource utilization as well as applied knowledge from almost two decades of ongoing ISS habitation.

Acknowledgments

The Archinaut Technology Development Project is sponsored by NASA under Contract NNM17AA02C.

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