Robotic Infrastructure Construction and Maintenance Systems for the Moon, Mars, and Other Missions

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ABSTRACT

Building infrastructure in the extreme environments of space is exceptionally challenging, creating a need for lightweight, durable, economic, and remotely deployable initial infrastructure to pave the way for future activities on the Moon and Mars. Autonomous construction systems will be necessary to develop infrastructure in the remote and extreme environments encountered in space exploration. The NASA ARMADAS system of autonomously assembled modular structures presents the opportunity for building infrastructure that is both suited to transportation constraints and mission adaptive through inherent reconfigurability. NASA and M3 are developing the capabilities and near-term application of this system towards a deployment-ready solution for in-space infrastructure development.

This work and similar projects will become the foundation for robotic construction standards, illustrating that this can be scaled from modest to immense structures. This work will also increase domain knowledge of commercial and flight specific robotic design requirements for system integration with in-space manufacturing and sustainable massless space exploration goals.

BACKGROUND & INTRODUCTION

The Case for Autonomous Construction

Terrestrial industries for resource extraction and industrial fabrication have brought construction activity into ever more remote locations, increasing the demand for innovative solutions and methods of safely providing infrastructure in the most challenging environments on Earth. Similarly, as space exploration and industry expand, a demand for infrastructure built in extraterrestrial environments continues to grow.

As the construction sector expands into increasingly remote and inhospitable environments, construction also becomes more extreme. The inherent risks of such environments make traditional construction work hazardous, inefficient, and cost prohibitive compared to construction in moderate climates. Traditional methods are already resource-intensive in terms of labor, time, space, power, water, and material supply chains, and increasingly, communication networks. The logistics of adequately providing material resources and supplying human needs in remote areas complicates even basic building endeavors, often creating necessary restrictions on labor productivity, through either physical constraints or high capital costs. Safe construction is time consuming and poses unavoidable limitations for work and exploration both on Earth and in space. By utilizing autonomous construction systems, human presence for the construction phase of infrastructure deployment can be reduced, improving both mission costs and the risks associated with human spaceflight, enabling faster mission deployment.

Robotic and autonomous construction solutions are emerging in the conventional construction industry. While early results of these initial applications are promising, there remain key challenges in overcoming a complete shift towards robotic construction. The first is a disconnect between the emerging scientific research and engineering of robotic design, and the execution of infrastructure construction. This disconnect results in a general underappreciation & frequent over-assumption of robotic capabilities. Another key challenge is the rapid pace of advancement in construction technologies outpacing the rate at which the construction industry can adopt it.

Bridging the divide between robotic system design and construction requires interdisciplinary partnerships. Practical collaborations between roboticists, infrastructure engineers, and contractors are essential to address the challenges that robotic construction pose, particularly for projects with challenging environmental conditions. The ARMADAS system developed by NASA represents one such effort; designed to be reconfigurable, resilient, and tailored to mission specific needs through the robotic assembly of a modular frame, ARMADAS is primed for collaborative development with the construction industry. The following sections outline the collaborative efforts between NASA Ames Research Center and M3 Engineering & Technology Corporation to develop and advance autonomous, modular construction technologies for off-world and remote terrestrial applications.

The ARMADAS System

The Autonomous Reconfigurable Mission Adaptive Digital Assembly System (ARMADAS) project is an autonomous lattice construction project by the Coded Structures Lab at NASA Ames Research Center aiming to develop a robust and scalable autonomous robotic construction system for high-performance lattice structures. Prior work by the Coded Structures Lab matured discrete lattice structures, a material approach that applies concepts from programmable matter and architected cellular solid literature. Using assembly and a limited set of structural components, the team demonstrated the construction of high-performance and tunable structures from mass-manufacturable assembled lattice components (Cramer 2019). Such structures have been demonstrated at many size scales (from mm scale to meters scale unit cells) out of many different materials (metal, continuous carbon fiber, injection molded chopped fiber composites) and with different geometries (Jenett 2016, Jenett 2018, Jenett 2020, Gregg 2018). The goal of the ARMADAS project was to automate assembly of these building-block structures for scalable space infrastructure.

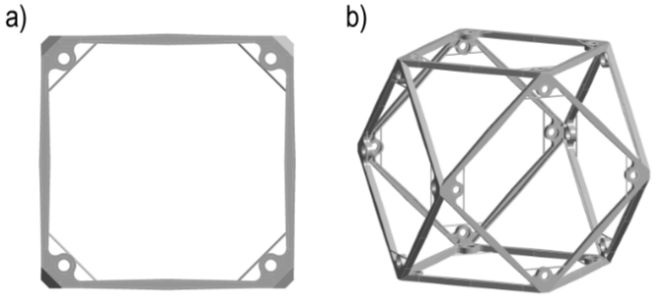

Figure 1 – Cuboctahedron Voxel: A) Single Face, B) Assembled Unit Cell

The ARMADAS system utilizes a cuboctahedron unit cell constructed from 6 square faces connected at their corners (Gregg 2024). Each face is injection-molded from chopped carbon fiber-reinforced polymer and pre-assembled using conventional bolts. The cuboctahedron unit cells are called voxels, short for volumetric pixels. The voxels are connected face to face using custom genderless reversible fasteners captive in the voxel face and actuated by the robots, and the fasteners apply a pre-load to the inter-voxel joint. Multiple frames autonomously self-configure through the use of robotic agents, making the system programmable and reconfigurable. Large structures are achievable through the assembly of many voxel units, creating a modularly scalable system.

The ARMADAS approach relies on the concept of relative robots to achieve scalable, reliable, and accurate construction from moderately simple robots with limited metrology. Relative robots are robots that locomote on the structure they are building, using the lattice structure itself for their indexing and metrology (Carney 2016). This allows small robotic agents to assemble structures larger and more precise than themselves, crucial for scalability of construction for space applications where launch fairings and payload accommodations restrict payload sizes. The ARMADAS system features two assembly robots: a robot that locomotes external to the structure performing transport and placement functions (Park 2023) and a robot that locomotes internal to the structure performing component attachment and fastening functions (Formoso 2023). Since the robots use the structure for their metrology and localization, each robot is commanded using a small set of pre-programmed trajectories that allow the robot to move to neighboring voxel faces and perform connection functions. In this way, each robot can locomote and build in 3D space with limited feedback (limit switches to detect successful grasping of the structure and joint encoders) and no global metrology system, simplifying autonomy. The precision of the structure arises from alignment features on the unit cells themselves, reducing the requirements for robotic precision and manipulation. The system has demonstrated autonomous construction of a 256-unit lattice structure, with autonomous fault handling that required extremely limited external intervention (>95% success for prototype system) (Gregg 2024). No computer vision systems were used. Subsequent experimental work demonstrated the installation of functional solar panels with electrical connections, and the capability for the internal robot to route wiring through the lattice structure (Formoso 2024).

Project Team

NASA Ames Research Center (NASA) and M3 Engineering & Technology Corporation (M3) have partnered to advance off-world infrastructure prototypes composed of modular structural components assembled by autonomous robotics. NASA Ames and M3 are collaborating to develop the ARMADAS technology toward a deployment-ready structural system for near-term applications on earth as proof of concept for in-space infrastructure development. The partnership leverages M3's experience and expertise in the design and construction of remote, large-scale scientific and industrial infrastructure with NASA Ames' expertise in system integration of robotics and autonomy for coded structures to jointly develop durable, lightweight, and modular structures suitable for autonomous robotic assembly of both on-Earth and off-planet construction.

Following recent prototype demonstrations of NASA's ARMADAS project, the goal of the partnership is to expand upon the capabilities and applications of such an autonomous system through virtual simulation of the real-world integration of autonomy with remote construction of large-scale infrastructure in austere environments. The team will further evaluate the system for constructability and mission integration through development of a Concept of Operations applicable to deploying the ARMADAS system to any remote site. These tasks will illustrate how autonomous and modular robotic construction might operate within other mission frameworks and conventional building operations.

ARCHITECTURAL EXPLORATIONS

Conceptual Design

A qualitative analysis of the architectural forms and the means of ordering them that is achievable by ARMADAS is required to inform and complement the ongoing structural analysis and development of a concept of operations. The ARMADAS system presents two exciting challenges to the architectural design of a lattice-based voxel structure: the modular constraint of the building block, and the mobile capability of the robotic assembly agents. Experimentation with macroscale integration of the modular voxel unit considers which conventional structural forms are compatible with the ARMADAS system and which unconventional forms arise as ideally suited to the unique geometry of the voxel module. These explorations consider key material properties of the larger latticed network, suitable applications for the system, and produce rough orders of magnitudes for how many units would be required to construct at various scales, useful to evaluate expected structural loads and enabling planning logistics for future missions.

A defining feature of ARMADAS is reconfigurability; deploying and re-deploying a generic building block to form any structure. This is advantageous for missions in challenging sites as mission directives evolve over time. Reconfiguring infrastructure to adapt to mission needs allows for efficient use of the limited resources on hand, saving on mission expenditures in the future. However, this characteristic of reconfigurability presents an architectural challenge: how to design for adaptability without sacrificing performance optimization or future reconfiguration. The end use-case of a structure often determines its final form, as per the architectural adage "form follows function". Questions of purpose, scale, permanence, and environment are all considered to be architectural basis of design aspects, and factors in realizing a functional design for any structure. Different activities require different spatial considerations. Designing without consideration of the end use-case results in generic architectures, which can be efficient to produce and deploy, but often lack the functional efficiency of a purpose-built environment by imposing modularity upon the ideal spatial demands of a function.

To address the architectural and structural differences inherent to various specific use-cases, NASA and M3 are developing four application typologies with unique structural systems to study:

1. Superstructures that can be built upon assumed foundations such as towers, space frame structures, and solar arrays.
2. Supporting structures, such as scaffolding, cavern supports, and soil retaining structures.
3. Mobility infrastructure to aid in crossing variable topography, such as bridges, ramps, and culverts.
4. Protective or sacrificial large-span structures, including trusses, vaults, and domes. Each of these types can house a variety of use cases, scales, and interaction methods.

M3 is iterating through macroscale architectural arrangements for each structure type to find designs responsive to the structural needs of each type and variable inputs. These typologies allow us to explore how the ARMADAS construction system can be integrated into these critical infrastructures without sacrificing the design responsiveness inherent to the reconfigurable voxel structures by defining a single end-use for a structure.

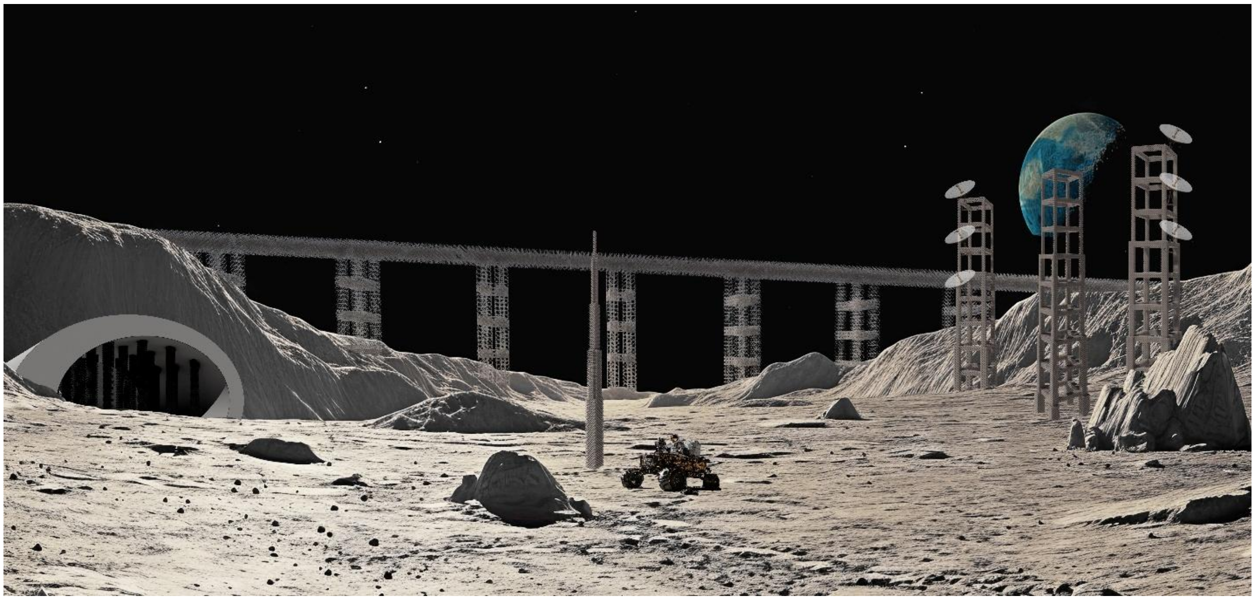

Figure 2 - Artistic Concept of ARMADAS Applications (Credit: M3)

Technical Modeling Approach

The team is method-testing by experimenting with different modeling approaches and applying these methods to different forms and complex geometries within the selected structure types, assuming the current voxel geometry, size, material composition, and associated robotic agents as defined by ARMADAS are optimal. The ARMADAS system follows a set navigation grid, with each module being placed orthogonally to one another. The system does not allow for partial units, overlapping units, diagonal connections, or connections along strut edges or cube corners. Each module is to connect to another on at least one face. To find materially efficient structural forms that conform to the modular rules, parametric and computational design is necessary, preventing the manual placement and analysis of thousands of individual parts with unconventional system properties. The first challenge in creating parametric form algorithms is to create “flexible” geometries that consistently followed rigid modular rules yet provide responsive architecture. A second challenge to modeling parametric algorithms is determining the limitations of importing large-scale geometries from modeling software into structural analysis software.

M3 is using a visual programming language, interface, and plugins within industry standard computer-aided design (CAD) applications to develop generative algorithms for parametric models of the aggregated metamaterial lattices; this method allowed for rapid visualization and intuitive iterations of complex geometry. Computational design in architecture has been a proven tool for contemporary construction methods, allowing for increasingly complex forms of architectural expressions and new applications of conventional building materials. Computational and parametric design tools allow for the automation of geometry documentation that could not be manually drafted in two-dimensional drawings and helps construction professionals manage the multitudes of custom components effectively from first concepts to final fabrication. ARMADAS’ modularity and unconventional assemblies make it an ideal candidate for computational design work. Given the dynamic nature of ARMADAS and many undefined context variables, it is advantageous to work in a program that allows for “plug and play” slider inputs rather than rigid, manual modeling. Optimizations are made to the voxel geometry to expedite model run-times, and the resulting geometry is exported through industry standard file formats to structural analysis and rendering software. Other result processes will ultimately export to logistical programming and simulation software to generate robotic tool paths for the assembly systems to execute.

With each of the form-typologies programmed, the challenge of designing without known end-use functions for the structures remains. Architectural pre-design questions are incorporated in the form of parametric controls, allowing adjustable responses to environmental and structural variables as needed. This allows for the resulting forms to be easily changed as critical factors become known and prevents time consuming manual redesign of thousands of parts.

Outcomes

The studies resulted in modular superstructures generated through voxel-based modeling that consider both the voxel building block and autonomous execution. Using a voxelization algorithm, curved and twisted frames emerge and respond to parameters such as rotations, tiers, and dimensions. These test structures demonstrate both adaptability and limitations, showing how the system accommodates bends, overhangs, and alignments while also producing floating or misaligned clusters. The outcomes point to strategies for optimization, including lightweight, hollow, or tiered designs that reduce voxel counts, ease material logistics, and lessen structural weight.

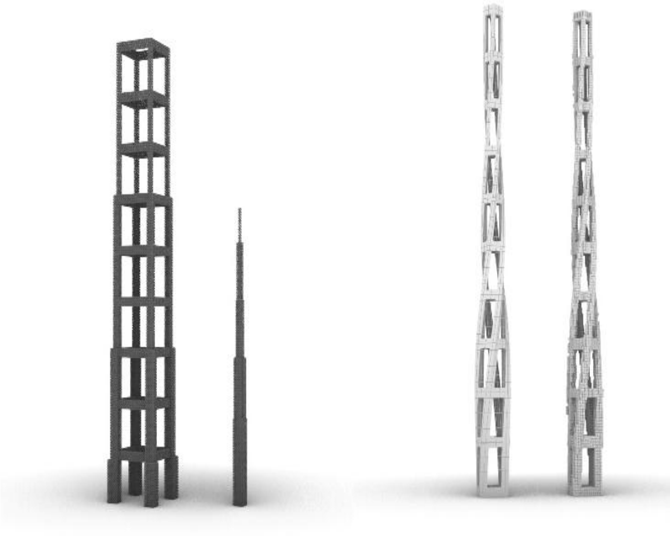

Figure 3 – Modular Frame Test Structures

The research also investigates reinforcement structures and mobility infrastructure. Reinforcement models are able to closely adapt to irregular site geometries like cavern ceilings or uneven hillsides, creating scaffolding, piers, and retention systems, though challenges remain in addressing survey inaccuracies and anchoring on rough terrain. Mobility infrastructure experiments focus on parametric bridges, where roadways and piers adjust dynamically to inputs but face constraints from digital file size.

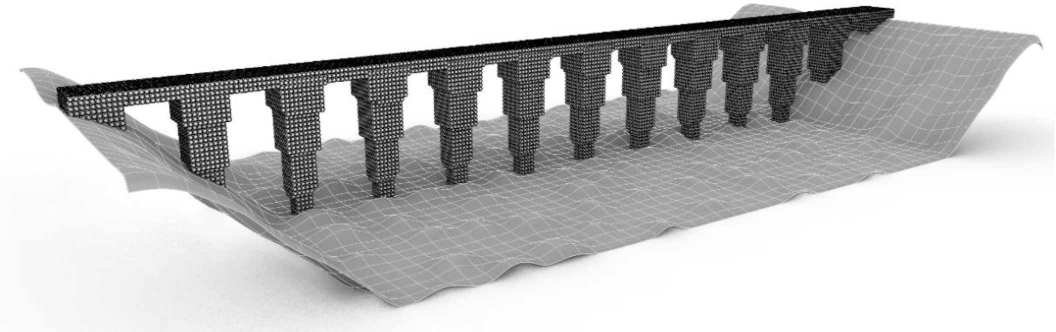

Figure 4 – Parametric Bridge Study Model

The progression of architectural explorations is highly dependent on developing an understanding of the material properties and structural performance limitations of the networked voxel frames. As structural ability is evaluated, there will be more data on the structurally required dimension parameters. Once these parameters are known, the programmed designs can be updated to conform to structural constraints of spanning ability and mechanical strength, producing forms that more closely resemble possibilities for future voxel construction. The next step would then be to design for specific use cases and integration of building systems to work towards enclosing and enhancing constructed frames.

STRUCTURAL ANALYSIS

Discussion

In conjunction with architectural explorations, the robotic assembly system is being evaluated for structural performance. Engineering of structural frames is essential regardless of purpose; structures need to remain standing. However, given the intent for this system to be autonomously constructed and to operate in high-stakes extreme environments with limited options for maintenance or repair, an especially robust structural system is needed. Failure of the mission is simply not an option.

The engineering of lattice structures is not conventionally taught in universities and lattices themselves are unique among structural functions; used primarily on Earth as custom architectural features rather than strictly structural applications. Creating a lattice structure for off-planet applications would be an engineering challenge by itself and is compounded by the geometry of the voxel module and arrangement constraints placed by the robotic system parameters. The voxel module was chosen and optimized for its integration with robotic agents, resulting in a unique structural building block with unconfirmed structural ability. The novel system will require investigation in order to discover its structural behavior and understand specific construction needs before it can be a mission-ready system.

As the individual and system structural behaviors are analyzed and understood, the discrete rules for placement programmed into the robotic assembly system will need to be updated with a new set of “rules of modularity” based on structural behavior of modular aggregation. These modular constraints will regulate placement configurations of the voxels in response to understood structural uses, such as spanning distances, support piers, and constructing cantilevers, helping to ensure inherent structural stability. Engineers will need to develop typical subassemblies of voxels with known behaviors to respond to pre-determined generic load cases. These subassemblies can then be used as a modular “kit of parts” for future reprogramming of a voxel structure towards a revised use case, reducing the need for manual re-engineering of the structural frame and lattice assemblies for each future reconfiguration of voxels.

To support further design of modular robotically assembled structures, NASA and M3 seek to mature modeling and structural analysis of voxel-based structures. Prior art has examined how to model various prior examples of voxel structures (Gregg 2018, Jennett 2020), validated by experimental design. However, prior research also suggests that differences in overall truss geometry, node geometry, strut cross-sectional geometry, material, and manufacturing process can all contribute to potential differences in global behavior and failure modes. Ongoing work looks to capture these design-parameters in computationally efficient models that are validated by experimental results and can be used for architectural design.

Finite Element Analysis

Traditionally, structural analysis of three-dimensional structures is performed using computational software such as SAP2000, RISA 3d, or similar programs. For practical purposes, they typically represent frames as bar elements, which allow engineers to model complex structures more easily. Once global behavior is understood, local design is typically completed using prescribed methodologies developed for common connection types. This approach is governed by a well-established body of analytical and experimental research, the assumptions of which consequently constrain the geometries that can be quickly evaluated. As geometries and model requirements deviate from traditional frame systems, solid body analysis provides greater flexibility.

In an effort to develop less computationally expensive methods for evaluating the performance of large assemblies, analytical modeling is approached with two methodologies: a simplified configuration of beam elements and a full solid body analysis. The motivation for a dual modeling approach stems from the distinct advantages and disadvantages of each method. By reducing the fidelity of each voxel strut into a single element, a beam element model enables computational resources to be extended to larger assemblies that would otherwise be impractical with solid body elements. In contrast, a solid body model allows the influence of hardware connections and contact interfaces to be directly captured in the performance of an assembly. Therefore, solid body analysis serves as a high-fidelity reference for calibrating beam element models. Comparing results between the two methods provides information on how different aspects and configurations of the unit geometry contribute to the behavior of both individual voxels and the overall strength of the networked structure. This further informs how engineers can balance computational cost reductions with model fidelity.

Ongoing work by both NASA and M3 includes both beam element analysis and solid body analysis of voxel behavior. Solid body analysis is performed with ANSYS Mechanical 2020 R1 using a simplified voxel geometry based on the current geometry manufactured for the ARMADAS program. For the purposes of current modeling, the complete voxel is treated as a single component and is evaluated in a 3x3x3 matrix assembly (27 voxel components).

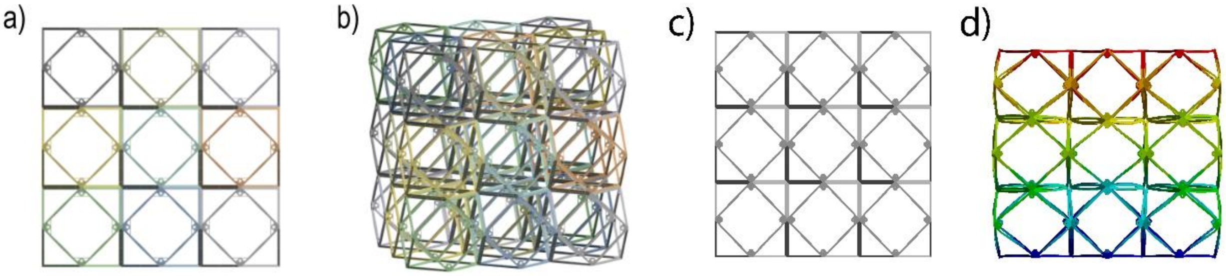

Figure 5 – Voxel Assembly: a) Front view of 3x3x3 matrix; b) Isometric view of 3x3x3 matrix. c) Non-deformed matrix d) Deformed matrix

To capture granular structural details with the solid body model, many small solid elements are required to accurately approximate the structure's response to loading. Each additional element contributes to the complexity, length, and computational cost of the analysis. To mitigate this issue, beam elements can be used to create a simpler and less computationally expensive model. Beam elements gain this computational advantage by making assumptions about the geometry they are representing. The accuracy of the model depends on how well those simplifying assumptions equate to reality. For our particular use case: structures made of slender strut voxels; the core assumptions are valid, giving us a powerful tool.

An ongoing beam element analysis is being performed with Abaqus 2024. As with solid body analysis, a matrix of 3x3x3 voxels acts as the sample structure. The tapered geometry of the voxel struts is approximated with U-shaped beam elements of varying dimensions. The structural geometry of connection points for fasteners between voxels are approximated through a series of beam elements in the shape shown by Figure 6.

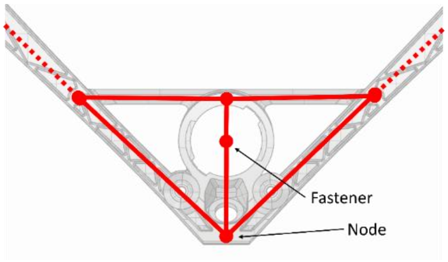

Figure 6 – Connection Geometry Diagram

Experimental Work and Certification

In addition to the finite element analysis (FEA), an experimental test program will be developed to calibrate and validate the computational models. Given the novel nature of voxel assemblies as structural components, the program has two primary objectives: first, to establish practical evaluation methods using simplified beam element models with defined margins of safety, and second, to position the systems for future product certification through recognized agencies such as the International Code Council (ICC). Initial testing will replicate the loading conditions applied in the simulations, subjecting the voxel assemblies to pure axial and pure bending loads. Once acceptable correlations are established, the program will progress to larger, more complex assemblies, including frame and truss configurations. As a catalog of assemblies develops into reliable building components with predictable performance, full-scale structural applications for specific use cases can be pursued. Physical tests will also serve to explore the relationship between fabrication methods and structural failure modes.

CONCLUSION: AREAS OF FURTHER INVESTIGATION

A critical area of further development for ARMADAS will be the integration of site logistics at the time of construction. This includes how the modular system interacts with uneven topography, methods of anchoring the modular structure to foundations, and the logistics of autonomously deploying the voxels from transport vessels. Proposed solutions for optional "foot" attachments for the base-layer modules are currently manually installed on demonstration models and will require more development to integrate with the autonomous robotic agents. Similarly, further research and development are required to materialize a fully autonomous deployment system. This system would need to perform initial arrival and deployment tasks including managing the payload of modular voxels, coordination of multiple deployments, and logistic coordination of receiving “refills” of material components. Large structures (such as bridges) may require hundreds of thousands of parts, and it is currently unfeasible to pack and transport the full material of a structure in a singular vessel. Resupply to the deployment system or a coordinated series of deployments will be a necessary component of large or complex builds, requiring development of designs compatible with phased robotic construction to allow for material logistics.

As the system matures in its autonomous capabilities, there will also be opportunities to refine and develop variations of the voxel module. An exploration of reinforced voxel geometries, compatible with the robotic agents, to respond to high demand load regions in assemblies would benefit the structural performance of the system. Ongoing explorations of material fabrication methods suitable for efficient, quality, and scalable manufacturing of durable voxel modules will require prototyping and quality assurance testing.

To further a wider use-case application of the ARMADAS system, research and development of enclosure systems integrated with the modular voxels will be necessary. Depending on the degree of development and application purpose, an enclosure system can range from a simple covering up to a fully sealed and insulated envelope system suitable for an extreme environment. Modular exterior cladding panels should be developed to pair with individual voxels and the robotic agents that place them. Exterior cladding will make the structure more robust and can serve a variety of mission directives such as solar power generation, dust control, and protection from environmental factors. Exploring cladding options will be the first step in moving the system beyond building bare structural frames towards the construction of fully habitable structures. Working through cladding and envelope design will pave the way for future integration of mechanical and electrical systems, another key component of habitable structures. That said, the challenge of determining how such systems will be constructed, and the degree to which autonomous robotic agents can participate in the construction of envelope systems is ongoing. Creating cladding and envelope designs compatible with robotic construction will require significant research and development but will contribute to the success of autonomously building complex infrastructure.

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