Small Satellite Mission Design for Robotic Assembly and Reconfiguration of Mechanical Metamaterials

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Abstract—**In-space assembly is crucial for constructing large-scale structures for future space missions. Future lunar base construction and Martian missions may necessitate various structures, including astronaut shelters, communication towers, structural reinforcement for natural features like caves, and even landing pads. The NASA Automated Reconfigurable Mission Adaptive Digital Assembly Systems (ARMADAS) project seeks to provide an autonomous robotic solution to meet these diverse mission objectives. The project utilizes discrete lattice building blocks that offer high mechanical performance and a repeatable structure, specifically designed for autonomous robotic assembly. The robots, designed to live and work on this lattice structure, are capable of transporting, assembling, dissasembling, and fastening voxels, autonomously, to build and reconfigure a desired structure. In this work, we present the mission overview for a scaled-down ARMADAS system and detailed system requirements for a 27U CubeSat mission that would allow for a successful space mission demonstration and raise the Technology Readiness Level of the ARMADAS system.**

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1. INTRODUCTION

To further human exploration and establish a lasting presence in space, we must be able to assemble large, complicated structures in orbit or on celestial bodies. Large-scale infrastructure is essential for long-term missions, space habitats and other structures that are too large to be launched pre-assembled. Therefore, one feasible way to build these structures is to do so in space. Most notably, structures like the International Space Station [1] and the James Webb Space Telescope [2] have demonstrated that massive structures can be modified after launch into space.

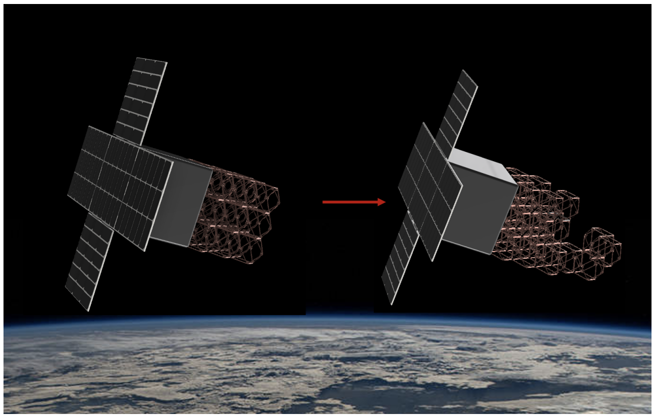

Figure 1. The mission goal is to demonstrate voxel reconfiguration onboard a 27U cubeSat. The ARMADAS robots will reconfigure four voxels into a new orientation onboard the satellite.

Mechanical metamaterials offer an innovative approach to address the challenges of in-space assembly [3]. The properties of these materials are defined by their unique internal architectures rather than their chemical composition [4] and can offer lightweight, high-strength solutions for construction in space. These materials are composed of cellular solids, or patterned lattice-like structures, whose mechanical properties can be fine-tuned by adjusting cell geometry, size, and connectivity [5]. Therefore, mechanical metamaterials create a lightweight yet robust structure, making these materials ideal for structural design, specifically for load-bearing structures [4].

The Automated Reconfigurable Mission Adaptive Digital Assembly System (ARMADAS) project has created ultralight, high strength mechanical metamaterials made from carbon fiber-reinforced polymer (StattechNN-40CF) to use as building blocks for large-scale infrastructure assembly. Recently, the ARMADAS team published their findings from an Earth-based demonstration [3], which showed that autonomous robots were able to successfully assemble, reconfigure, and disassemble discrete mechanical metamaterial building blocks, termed 'voxels,' into large lattice structures. The self-reprogrammable system separates the actuation components from the structural components in order to leverage the high strength-to-weight ratio associated with a lattice of cellular solids. The robots are designed to autonomously manipulate and assemble the lattice all within this predictable and repetitive local reference frame. The robots are therefore able to achieve high precision locomotion using fewer sensing or complex perception tools. This approach capitalizes on the advantageous strength properties of the lattice structure while utilizing robots to dynamically modify the structure as needed.

To this point, the ARMADAS system, and all programmable material systems, are exceptionally well-suited for the challenges posed by space missions. The ARMADAS system is capable of meeting high-performance strength requirements and can reconfigure to meet dynamic needs of space exploration, all while remaining ultralight. This combination of properties is indispensable for space applications, where minimizing mass is crucial for efficiency, launch costs, and overall mission success [1].

While deploying folded structures is a well-established and innovative technology, it often comes with constraints related to packaging efficiency and the complexity of deployment mechanisms. In contrast, a cellular solid approach, such as that taken by the ARMADAS project, emphasizes simplicity and scalability, allowing for more efficient use of available volume during launch and greater flexibility in design once in orbit. By constructing in situ, we can create robust and adaptable structures that can be tailored to specific mission requirements and environmental conditions. Furthermore, the ARMADAS system's voxels are ultralight, low density, and have a high specific stiffness when constructed in a lattice [3], making them an ideal choice for space applications where mass is a significant limiting factor for launches.

Our specific contributions are as follows:

1. Mission requirements and concept of operations for demonstrating an adapted ARMADAS system suited for a 27U CubeSat.
2. A proposed adaptation to ARMADAS voxels that will scale from 30x30x30 cm to a 1U (10x10x10 cm) size.
3. A proposed new robot architecture focused on deploying a greater number of robots with fewer degrees of freedom, rather than relying on a few highly complex robots. These streamlined robots shall make the system more scalable without sacrificing performance.

We first discuss related work in Section 2. To present our contributions, we then discuss in Section 3 the high level mission and payload requirements for mission success and a proposed concept of operations for a CubeSat mission to low-Earth orbit (LEO). Section 4 then presents our adaptations to the current ARMADAS system and outlines how these adaptations specifically address challenges associated with operating on a small satellite. Finally, Section 5 discusses additional implementation challenges that require mitigation strategies as the mission design process evolves, concluding with an overview of the ongoing work for this project in Sections 6 and 7, respectively.

2. RELATED WORK

On-orbit assembly has emerged as a key area of interest in advancing the capabilities of space infrastructure. Several projects have explored different methodologies, ranging from manual assembly by astronauts to semi-autonomous robotic systems.

One of the most notable achievements in this field is the assembly of the International Space Station (ISS). Built over several decades and requiring more than 260 spacewalks for assembly, maintenance, and reconfiguration, the ISS assembly demonstrated the feasibility of constructing large structures in space [6]. The Mobile Servicing System (MSS) was installed in 2001 to assist with the assembly of ISS modules, large exterior payload manipulation, and docking visiting spacecraft [7]. The MSS consists of the Space Station Remote Operating System (SSRMS) and other robot arms that are able to perform Extravehicular Activity (EVA) tasks under supervision and control from astronauts aboard the ISS as well as can maneuver astronauts to different parts of the ISS during EVA [8]. However, the reliance on human labor, high mission costs, and a long construction timeline pose significant challenges for future missions. Though versatile and equipped with the ability to self-relocate using two latching end-effectors, the SSRMS and the rest of the MSS consume significant human and financial resources, making them less suited for more flexible, scalable, or autonomous in-space assembly tasks required in future missions, where efficiency and adaptability will be paramount.

An example of potential on-orbit assembly technology is the Extended Structure Additive Manufacturing Machine (ESAMM), as part of the In-Space Manufacturing (ISM) project with NASA This technology demonstrated the capability to manufacture truss structures within a thermal vacuum chamber (TVAC) [9], indicating strong potential for operational viability in low-Earth orbit. This technology has the potential to increase launch vehicle efficiency because it can pack more raw materials that then can be used to construct structures on-orbit. In addition to being more mass efficient, the launch vehicles would require less complicated designs and simulations if they are only launching raw, printable materials. However, while this research suggests ESAMM is capable of constructing truss structures in space, there are several drawbacks. Printed structures are not reconfigurable and therefore, cannot adapt for other missions or tasks. Limitations to 3D printing, such as thermal management, material deposition, and using multiple filament containers for large prints, are challenging to address in space.

When discussing in-space assembly, it is also important to mention deployable structures, or mechanical systems that efficiently fold or collapse for transport and expand or unfold once in their desired location. Deployable systems can be highly versatile and operate as solar arrays, communication antennas, radar antennas, drag and solar sails, or instrument booms to name a few [10]. They maximize packing efficiency during launch and once deployed, these structures can improve the operational capability of their vehicle as a result of their increased surface area. However, there can be a lot of risks associated with implementing deployable structures. If a deployment mechanism fails, the entire mission could be in jeopardy, as repairs are difficult or impossible in space. Often, these are single point failures [2]. To mitigate these risks, substantial engineering, robust testing, and reliability measures are required before deployment, increasing costs and resources needed. All that being said, the successful launch and complex deployments of the James Webb Space

Table 1. Mission Requirements

Category	Description	Verification Method
System: Orbit parameters	1. The spacecraft shall be capable of operating in a sun-synchronous (SSO) low-Earth orbit (LEO) with an approximate altitude of 500-600 km.	STK analysis, thermal vacuum testing
System: Mechanical	2. The spacecraft shall adhere to the 27U CubeSat mass and size requirements (<54 kg and 34x35x36 cm)	CubeSat design specification document
System: Vibration tolerance	3. The spacecraft shall withstand vibration levels experienced during launch without structural failure. The fundamental frequency of the satellite structure shall not be excited by the launch vibration profile.	Vibration testing as defined by Launch Provider
Subsystem: Payload functionality	4. The onboard robots shall autonomously reconfigure a minimum of four voxels into a new configuration by executing a pre-computed path on-orbit.	Simulated environment testing, down-linked data
Subsystem: Payload functionality	5. The onboard robots shall fasten reconfigured voxels to the structure using commercial off-the-shelf fasteners in 0g.	Simulated environment testing, down-linked data
Subsystem: Communications	6. An on-board camera shall capture high-resolution images or videos that provide clear visibility of the voxel reconfiguration and fastening.	Spacecraft telemetry
Subsystem: Payload operation and safety	7. Each robot shall have standby, operational, and safe modes to ensure optimal and safe performance.	Successful activation and deactivation of each mode with no system errors.

Telescope (JWST) on-orbit demonstrated that, despite the intricate sequency of unfolding stages required, the JWST could surpass the capabilities of any telescope that could have fit within traditional launch vehicle constraints.

In light of these advancements and challenges in on-orbit assembly and deployable structures, the ARMADAS project presents a promising approach to enhancing the efficiency and adaptability of in-space assembly operations Proof-of-concept experimentation on Earth has already demonstrated that a team of three robots can autonomously follow pre-planned paths to assemble a large-scale, reconfigurable lattice structure using numerous building blocks [3]. The current ARMADAS robots have fewer degrees of freedom and fewer unique parts than traditional robot arms. However, this technology has yet to be tested in a space environment, which is crucial for its deployment on future missions like Artemis. There may also be applications for the ARMADAS system in the context of on-orbit satellite repairs, spacecraft docking, and modular power systems [11], making it an extremely versatile technology. Research into deployable voxels suggests that on-orbit repairs could be performed on voxel structures [12], allowing for the maintenance of structural integrity even in the event of failures. These features along with the mission design described in this paper lay the groundwork for the potential of the ARMADAS system as an avenue to achieve autonomous on-orbit infrastructure assembly on future missions.

3. MISSION OVERVIEW

Establishing clear mission objectives is the first step in the systems engineering process, as these requirements will guide the design and validation of the ARMADAS system to address the in-space assembly problem.

Mission Requirements

First, mission and payload requirements were established to define the objectives and constraints for this project. While the ground demonstration assembled a 256 voxel structure [3], this project will operate on a much smaller scale, with the main payload requirements being to reconfigure and refasten four voxels into a new shape. Figure 1 shows a hypothetical reconfiguration from a cube of voxels to extending an S-tetromino (tetris) shape of voxels off the distal end of the spacecraft. This assembly will be done autonomously by a team of robots. Images will be down-linked from a camera onboard the satellite for exhibition. Further mission requirements, along with potential verification methods, are listed in Table 1 as per the standard in the NASA Systems Engineering Handbook [13].

Concept of Operations

The mission Concept of Operations (ConOps) outlines the high-level operation of the CubeSat throughout the mission life cycle [13]. Following launch (as part of a launch provider ride-share or SLS payload), the CubeSat will be deployed into low-Earth sun-synchronous orbit (SSO), where the solar panels will deploy, the payload will move into position, and nominal operations will begin (Figure 2A). Nominal operations shall consist of a team of robots unfastening voxels, transporting them to a new location, and refastening them. The goal will be to replicate the functionality of the original ARMADAS robots, MMIC-I and SOLL-E, but on a much smaller scale in a space environment. The other key nominal operation is communication with the ground. We plan to use both sensor telemetry and visual confirmation of mission success criteria.

The final aspect of the ConOps is the Design Reference Mission to estimate orbital lifetime [13]. In order to estimate the expected de-orbit of the spacecraft, a lifetime orbital analysis was completed using the Ansys System Tool Kit

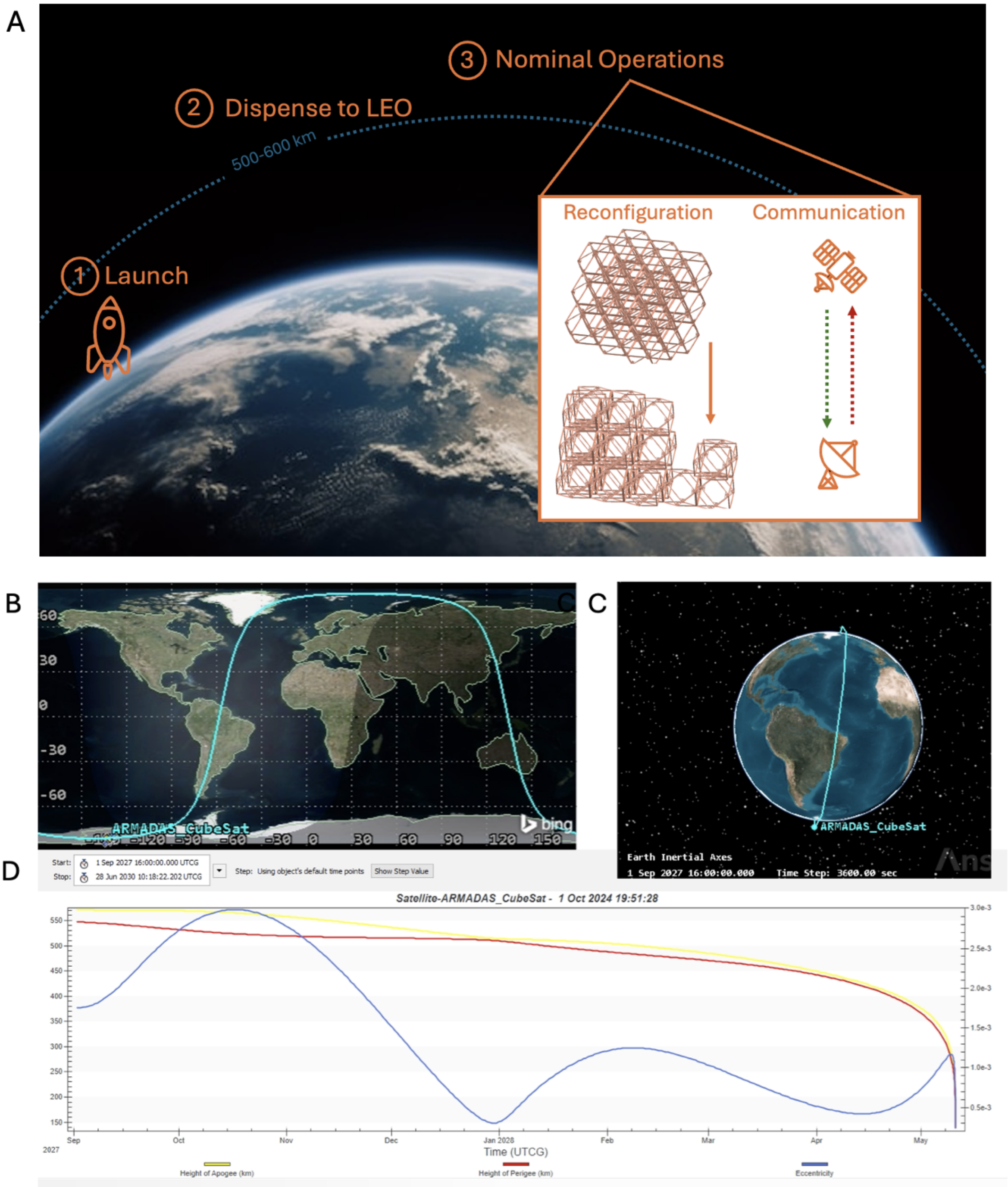

Figure 2. A) The Mission ConOps for this spacecraft involve reconfiguration and communication tasks in LEO between 500-600 km. B) The ground track progression of the satellite's orbit demonstrates the spacecraft's path relative to Earth's surface. C) The satellite will follow a near-polar SSO with an orbital cycle estimated at approximately 95 minutes. D) A hypothetical satellite lifetime analysis for circular SSO at 550km altitude shows an orbital decay after 252 days.

High-Precision Orbit Propagator. A sun-synchronous, near-polar orbit with inclination of 98% was chosen so that the nodal precession rate matches the Earth's orbital rate around the sun. Not only is it a common orbit for ride-share launch vehicles, it provides global coverage at all latitudes, consistent lighting and thermal conditions during the sunlit portion of the orbit, and a wide range of compatible altitude ranges [14]. A 550km altitude with 550km apogee and perigee was chosen, and nominal drag and reflectivity coefficients were selected for that altitude [15], [16]. The atmosphere was represented using the NRLMSISE-00 model for low-earth orbit and an example launch date of September 1st, 2027 was selected for this simulation. The CubeSat mass was generalized to the upper limit of 27U CubeSat standards at 54 kg [17]. We did not account for variations in surface area caused by the solar panels or potential differences in exposed surface areas on different sides of the satellite. These factors could influence the overall performance and behavior of the system and should be considered in future analyses once the spacecraft design and payload deployment is finalized.

Figure 2B shows the results of this simulation. Given the assumptions discussed above, the spacecraft is estimated to de-orbit (to an altitude of below 65km) after 252 days of operation. This simulation is intended to be preliminary, as we currently lack definitive details and a finalized payload design. The primary goal of this analysis is to provide an initial understanding of the potential performance of this scale of satellite in LEO, allowing us to explore various operational scenarios even in the absence of specific design parameters.

Payload Design Considerations

Though mission details are still preliminary, a mock-up CubeSat model was created (Figure 3). Special emphasis is placed on the mechanical payload design of the proposed CubeSat, which will carry the voxels and robots capable of assembling and reconfiguring a structure in low-Earth orbit. The payload mass will be kept under 20 kg, in alignment with sample requirements for a 27U CubeSat bus that is commercially available [18]. While we are not explicitly designing to this bus configuration, we used it as a baseline to estimate the potential mass available for our payload. However, we recognize that the more significant challenge will likely arise from volume constraints rather than mass constraints.

The payload was designed to be housed in a 27U CubeSat system with dimensions 34x35x36 cm, thus severely limiting the volume we have to transport voxels and robots. Initial design ideas involve putting 24, 1U-sized voxels in the payload space already connected into a cube with 3U of space available for avionics in the back (Figure 3 A).The cutaway view of the preliminary design shows the packaged voxels and avionics system within the satellite. We opted to place the avionics subsystem in the middle of the structure in order to leave the outside voxels, which will be easier to reconfigure, free for robot manipulation as needed. The robots will already be gripped to the structure, either in the open pyramid volume between voxels or completely inside the voxels. We have not included the robots in this model for simplicity. If this configuration was adopted, we would use a linear actuating mechanism to guide the voxel structure along into place. A camera will be deployed from the back of the structure after the voxel structure extends into space from the front end of the CubeSat (Figure 3 B). The cutaway view of the preliminary design shows the packaged voxels and avionics system within the satellite.

Until we obtain further details about the mission and whether we will be developing our own satellite bus in-house or utilizing a commercially available one, we cannot finalize key aspects of how the payload will integrate with the rest of the spacecraft yet. This determination will have a profound influence on the overall design and interface considerations for the payload, and it will evolve further upon approval for the mission. Additionally, the interface to the launch vehicle used, whether a CubeSat dispenser mechanism or an Evolved Expendable Launch Vehicle Secondary Payload Adapter (ESPA) ring [19], will influence the spacecraft design as well. This paper, rather, is focused on the payload itself and the considerations that must be made with the ARMADAS system to successfully perform in space.

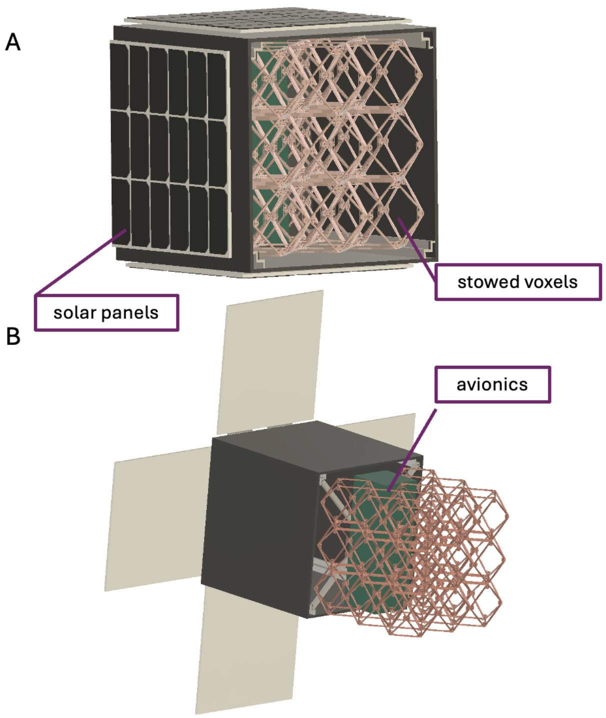

Figure 3. The payload will be stowed in the 27U satellite bus. After being dispensed into LEO, the satellite will prepare for nominal operations by deploying solar panels and extending the payload into open space.

4. ARMADAS ADAPTATIONS

Several core features of the ARMADAS system offer significant advantages for space applications and are retained in these adaptations. The first is the predictability of the lattice structure and its repeatable assembly process. This predictability significantly reduces the need for high cost components and sensors on the robotics. Since the environment in which the robots operate is repetitive and highly consistent, robots can rely on predefined, systematic behaviors, rather than continuously adapting to unknown or variable conditions.

Another key feature is the cubeoctahedral voxel geometry. Not only does this geometry allow for a predictable and repeatable assembly process, the cubeoctahedron in particular demonstrates high mechanical performance, while offering high volume clearance for robot locomotion and maximizing the amount of space for a robot end-effector to operate near the nodes [20]. When assembled into a structure, cubeoctahedron voxels balance load distribution across the structure and robotic load effects are minimized due to the number of attachments to neighboring voxels. Equally noteworthy is the inherent reconfigurability of the ARMADAS system. This will be essential for space applications, as it demonstrates the ability to dynamically adapt structures based on changing mission needs. This reconfigurability allows for effective responses to diverse scenarios without necessitating a complete overhaul of the existing design or requiring the introduction of new components.

While the ARMADAS system offers several highly beneficial features that align with the requirements for space applications, certain aspects will need adaptation to optimize performance in an on-orbit environment. The following sections will outline several necessary adaptations to the ARMADAS system, including voxel scaling, the implementation of commercial off-the-shelf fasteners, modifications to the robot architecture, and adjustments to the path planning algorithm.

Voxel Scaling

The payload design includes re-scaling of the voxels presented in the original ARMADAS demonstration to accommodate the volume-constrained payload space of a 27U CubeSat. In order to fit enough voxels on-board to actually build and reconfigure a structure, they must be scaled down to approximately the volume of a 1U CubeSat each, or 10x10x10 cm (Figure 4) [21]. However, when the entire voxel model was scaled linearly by a factor of 0.329 from the original size to the 1U size, the benefits of the node structure were not preserved. For example, the gripper bars for assembly robots to move along and grip to the structure were too small for any practical robot gripper mechanism to grasp. Furthermore, on the original voxel, there are alignment features consisting of protrusions and indentations on each node that help slot neighboring voxels into proper alignment with each other (Figure 4A). However, on the 1U voxel, these alignment features were not starkly defined, which could lead to challenges with proper alignment during assembly. These features are especially important in a 0g environment, where gravity cannot assist voxel placement or alignment. Finally, the intra-voxel fasteners were already sized for 10-32 hardware on the original voxel, meaning that the linear scaled voxel fastener holes were too small to be functional and the resulting fasteners would be exceedingly small. This suggests that modifications to the node feature of the voxel was required during the scaling process.

Though discrete lattices have been produced at a wide range of scales and from a wide range of materials [23], the design of the inter-voxel connection points typically does not scale across all size ranges. This is due to manufacturing challenges, availability of commercial off-the-shelf (COTS) fasteners, and the interface requirements of assembly robots. Though idealized cellular solid theory suggests that the specific stiffness of a given lattice of a given material should be constant across scale as long as relative density remains constant [5], the practicalities of assembled lattices means that parasitic mass at the nodes has a proportionally stronger effect at smaller lattice scales and higher relative densities. This is because the proportion of the mass at the nodes increases relative to the mass in the struts.

For the 1U voxel, we applied a scaling factor of 2.4 to the node, while the struts were scaled by a factor of 2 (Figure 4). By thickening the gripper bars and refining the protrusions and indentations of the alignment features, we were able to retain and enhance the effective alignment properties from the original voxel design. Additionally, we incorporated a clearance hole in the redesigned 1U voxel to accommodate an M2 × 0.4 mm COTS fastener, ensuring that intra-voxel connections could be made using affordable and readily available fasteners at scale.

Further work will include determining available space-rated materials that can maintain the desired specific stiffness for acceptable dynamic behavior. Before implementing the mission, further analysis on buckling and structural vibration will need to be conducted. However, it is important to note that for the purposes of an on-orbit demonstration, structural issues related to exceeding stiffness bounds are unlikely to arise.

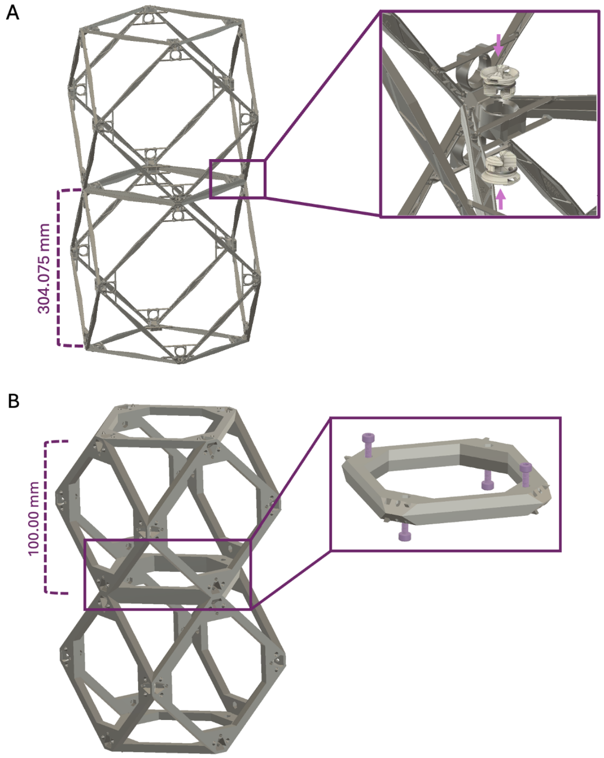

Figure 4. A) The original ARMADAS voxels are fastened together using captive androgynous fasteners [22]. These fasteners are symmetrical and do not have directionality. Sized at approximately 304 mm, the ratio of node-size to strut-size produces a high specific stiffness. B) The proposed ARMADAS CubeSat voxels are fastened with captive COTS bolts and nuts to improve generalizability. Using COTS fasteners introduces directionality to the bolting mechanism which must be account for in the bolting robot design. Sized at only 100mm, these voxels required a change in the ratio of node-size to strut size.

COTS Fasteners for Inter-voxel Connections

In the ARMADAS ground demonstration, the voxels were fastened together using androgynous captive fasteners [22]. These fasteners were designed for ease of robotic assembly via simple actuation and to relax the strict positioning requirements of the fastening robots. Furthermore, they were symmetrical, meaning that the voxels themselves were all identical in orientation, which made path planning easier. However, these fasteners were manufactured using injection molding, which made the androgynous fasteners less cost-effective than commercially available fasteners.

The new generation of voxels employ captive COTS fasteners rather than the androgynous fasteners for the reasons of having better structural performance, being more mass and cost efficient, and improving the speed and robustness of development. This architecture uses a 10-32 IP25 driven flat head bolt and nut pair. For optimal structural performance, it was concluded that the nut and bolt pair should be fastened to a torque spec of 25.5 lb.in. The bolts are held captive with a washer and the nuts are press fitted and secured into their respective locations on voxel faces. We designed the scaled voxels to employ captive COTS fasteners for inter-voxel connections for the reasons mentioned previously (Figure 4). However, this design change comes with an increased

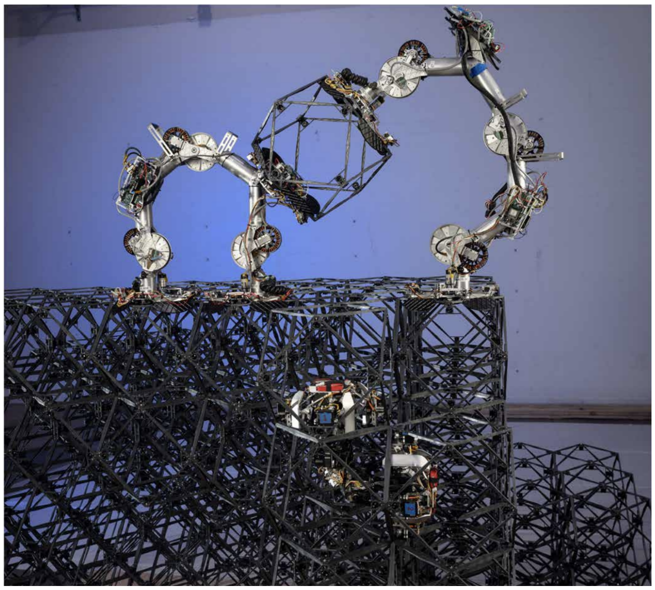

Figure 5. During a ground demonstration, the ARMADAS system was able to build a structure consisting of 256 fastened voxels [3].

algorithmic planning burden and will be discussed in a later section.

Robot Architecture

The current ARMADAS robotic architecture can be described as a series of functional primitives, or the basic tasks that the system must execute to meet the system goals [24]. For ARMADAS, these functional primitives consist of the tasks to manage voxel transportation across the structure and fasten them in the correct location. These can be split into five main actions: move self, move voxel, move friend, align/place voxel, and bolt voxel pair. The current robot team consists of two transporter robots and one bolting robot. The Cargo transporter is responsible for collecting a voxel from the depot and carrying it to the build front, which is done via a third cargo gripper on its back. The Crane transporter unloads the voxel from the cargo transporter and places it on the lattice structure [3]. Each transporting robot can locomote along the exterior of the structure without assistance. Then, once the crane robot has placed the voxel at the build site, a bolting robot (which lives inside the structure) locomotes into the voxel to fasten it to the rest of the structure.

While the current ARMADAS robots are highly effective for on-Earth demonstrations and could be applied in future applications in lunar environments, their designs present challenges when scaled down to a 27U CubeSat size. While simpler than traditional robot arms, they were designed for larger scale voxels because of COTS motor availability. Therefore, there are significant challenges for scaling mechanically. The next three sections will lay out the key ideas behind our modifications to the system that will help ensure its readiness for space.

*Voxel-transporting Robots—*Instead of relying on a pair of 7-DOF external robots to independently transport and place voxels at the build front [25], we propose a new architecture in which multiple smaller robots collaborate to move voxels across the structure. This collaborative approach reduces the degrees of freedom for each individual robot, allowing them to work together by rolling voxels along the structure. The reduced complexity in design and the fewer number of unique parts make this system both efficient and easier to scale compared to the SOLL-E robot. The robots can roll voxels in two primary ways: they can either perform a 90-degree rotation to place the voxel adjacent to its original position within the robot's coordinate axis (Figure 6A), or they can rotate the voxel 180 degrees to a new position, either above or below its original location within the robot's coordinate action (Figure 6B). This rotation could be extended to include other axes if a yaw stage were integrated, allowing the robot to flip voxels outside its default coordinate axis. The new primitives primitives for this robot would be: 1) travel/ride on voxel, and 2) roll voxel (to align/place).

A potential downside of this robot type is that they would require ”scaffolding” voxels for locomotion and to assist in positioning other robots and voxels, thereby placing an increased demand on the path planning algorithm complexity and potentially increasing the total number of required voxels in an already volume-constrained environment to achieve the target reconfiguration.

Bolting Robots— While it would be ideal for a robot to access all bolts within a voxel such as is done with the internal MMIC-I robot [26], this 7-DOF approach becomes impractical as the system scales. To address this, we propose a simplified bolting robot with fewer degrees of freedom, capable of operating along a single coordinate axis. By reducing complexity, this robot would scale far more effectively. Instead of using one robot to access all bolts within a voxel, the task could be distributed across multiple simpler robots, each responsible for bolts within a single coordinate axis. This division of labor allows these smaller robots to collaborate, with one robot managing bolts in its own axis while others handle the remaining bolts outside its range. The ability to scale this style of robot also allows the bolting mechanism to remain inside the voxel structure.

Additionally, the bolting robots could work in tandem with the transport robots, which could flip the voxel as necessary to give the bolting robot access to areas that are out of its current coordinate axis. The functional primitives of this robot mostly remain the same: 1) locomote internally and. 2) bolt voxel pairs. We add a third primitive 3) travel in voxel. This cooperative approach greatly enhances scalability, as it eliminates the need for a single robot to handle all fastening tasks.

However, the introduction of COTS fasteners introduces directionality to the voxels, adding complexity not present in the original model. As illustrated in Figure 7, the orientation of the bolts requires careful planning. For example, a bolting robot positioned inside the voxel can secure the purple nodes (where the screw heads are located), but to access the yellow nodes, it must reorient itself to bolt from the outside. This pattern alternates orientation every voxel face in one coordinate axis. This new directionality introduces both design and algorithmic complexity, but leverages the use of COTS fasteners.

Considerations on Bolting Mechanisms— The new bolting module must be designed to to bolt captive COTS fasteners. Currently, the MMIC-I robot is equipped with multiple Hitec D951 servo motors that are capable of fastening the old generation of androgynous fasteners to a torque spec of 1.5 N.m. The existing bolting mechanism also uses a Hitec D89 servo to provide a linear driving force to secure the

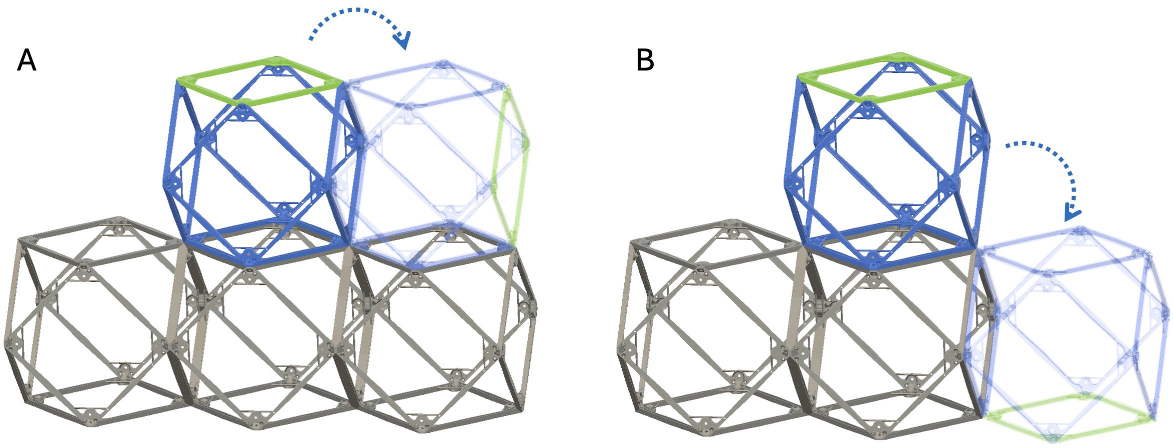

Figure 6. Voxels can be rolled A) 90°or B) 180 °by the new transporting robot system for movement along the structure. Robots gripped to the outside of the voxel can also be carried to a new location when rolled by another transporting robot. Protrusion and indentation features at the nodes of the voxels provide alignment assistance.

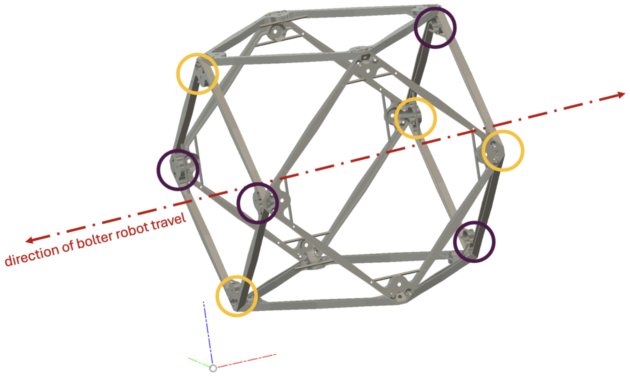

Figure 7. The bolter must reorient 90°within its coordinate axis in order to accommodate COTS fastener directionality during bolting. The new bolting robot system will have the capability of rotating its gripping mechanism to accommodate this directionality.

androgynous fasteners [26]. We initially have designed the COTS bolter mechanism discussed below to the original sized voxels and will scale down to the 1U voxel size after finalized proof-of-concept testing.

For the voxels that involve captive nuts and bolts, we have modified the Hitec D951 servos to be continuous by tuning the potentiometer and removing hard-stops inside the servo. Connected to the shaft of the servo is a spring-loaded mechanism equipped with a Wiha 25mm IP25 TorxPlus bit (Figure 8). The use of this mechanism provides two new advantages. The first is that the deployment of the bolting module can be paired with the extension of an internal robot's grippers, therefore reducing the number of necessary actuators by one. The compliance of the spring allows the Torx bit to rest on the bolt head without requiring another actuator to linearly deploy it. Furthermore, the spring passively provides linear driving force as the bolt is being fastened. The second advantage is associated improved bit alignment. There is a high likelihood that when the bolting module is deployed, the Torx bit will not align directly into the drive of the bolt head. However, when the bolting module begins its bolting sequence, the spring ensures that the Torx bit will align to the correct position.

To ensure proper fastening to ideal torque specs, the bolting module incorporates an INA219 current sensor monitored through I2C that calibrates current to torque output. While the D951 servo has a maximum stall torque of 486.05 oz.in (approximately 30.38 lb.in) [27], we have derated the servo to only pull half of its stall current to meet safety standards. Based on initial experimentation done using the modified continuous-D951 motor derated to half its stall current, the maximum torque outputted was approximately 20 lb.in. However, further tests need to be done to provide a conclusive torque value.

This new bolter design brings an additional set of challenges. The smaller size of the Torx bit and bolt head is more challenging to reason about alignment and accuracy. New passive alignment features can be developed for the bolting module to assist in guiding the Torx bit to the bolt head where the spring will do the work of slotting the bit into the drive. Furthermore, the alternating and directional captive fasteners for the new generation of voxels introduce complexities to the bolter robot and the path planning algorithms, which will be discussed in the next section. While bolting remains a complex challenge, the current mechanisms outlined here demonstrate a solid foundation for future innovation.

Algorithmic Path Planning

In addition to the modifications required for the current system architecture, we must also make significant adjustments to the current ARMADAS discrete path planning algorithm. The goal of the path planning algorithm is to first determine a state space representation of the entire system (robots and voxel structure) that represents all states that each component of the system is capable of being in at any given time [28]. Constraints on certain representations are added to ensure that all robot and voxel moves are physically feasible. With the state space representation of the system fully defined, A* path planning algorithms can be adopted and modified for this specific application to define the optimal series of steps all robots can take to complete the reconfiguration of the system. With the path planned, low level commands can then be sent

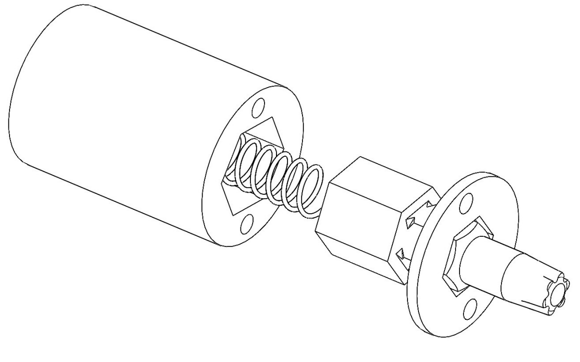

Figure 8. A new bolter design will leverage a spring loaded mechanism to ensure compliance and alignment of the Torx bit with the drive of the bolt head. This will be part of a larger gripper mechanism capable of accommodating the directionality of the COTS fasteners.

to each robot on the structure to be then carried out.

The planning algorithm for the CubeSat system will need to be modified to effectively operate within our proposed architecture. First, we will need to redefine each of the robot type's state parameterization, as the motions allowed by each design are substantially different from the original system. The voxel parameterization must also change because now the voxels have specified directionality with regards to bolting with COTS fasteners that they did not have with the androgynous fasteners. Therefore, their orientation must be considered when placing voxels at the build front and coordinating valid moves for the bolting robot to take, which will greatly increase the complexity of the state space. Finally, there will be added complexity with timing and constraints to avoid robot collision, trapping each other, etc. due to the increase in the number of robots present on the structure.

Ultimately, we can leverage a planning algorithm to assess the feasibility of the mission ConOps. This algorithm will help determine if this system architecture can generate a viable path solution that exists between the starting configuration state space and the ending configuration state space. Based on the outcomes of this assessment, we can make informed decisions regarding the number of voxels and robots required to execute viable plans. This will inform if we can fit sufficient resources onboard to complete mission tasks.

5. IMPLEMENTATION CHALLENGES

There are several challenges associated with implementing this technology on a CubeSat from a systems perspective. First, we are heavily volume constrained. Even with a 27U configuration, all ARMADAS components must be scaled down significantly. While the current implementation utilizes a number of 1U-sized voxels, the voxel size will ultimately be limited by how small we are able to make the robot components. Additionally, how efficiently the planning algorithm handles this complex scenario and distributes resources will also contribute heavily to the scalability of the project.

Power and battery management are critical challenges for the mission, as frequent battery changes will not be feasible. Previous work has used the ARMADAS system to assemble modular solar panels [11]; however, given the few number of voxels onboard, this does not address charging the robots specifically. Potential mitigation strategies include equipping the robots with solar charging capabilities, allowing them to recharge while idle or during transit. This would rely less on battery reserves and limitations associated with needing large batteries. Another option is to implement a charging voxel that can serve as a power station as part of the lattice structure, enabling the robots to make contact and recharge as needed. This would help maintain operational longevity in space, where direct solar charging might not always be feasible for every robot (especially the internal robot) due to size, orientation, or shadowing. The charger could be equipped with self-aligning connectors to ensure adequate contact is made and spring-loaded pins or pads could be used to maintain contact pressure. However, this adds a lot of increased complexity to the planning algorithm, that must now provide paths to and from the charging voxel, even for the transporter robots that require other robots to help them locomote.

Thermal management presents another significant challenge, particularly as heat will accumulate from robot motors during operation. One possible solution is to integrate thermal pads at the robot-voxel interface, allowing for passive heat dispersion through the voxel structure, which could be comprised of a conductive metal. This would minimize the risk of overheating and ensure more consistent performance in varying thermal conditions. In eclipse, however, extreme low temperatures could cause issues for the system that might need to be addressed with insulation or thermal switches to temporarily stop connection to a heat sink that would normally be required during periods of sunlight [29]. Ultimately, once the design is finalized, thermal simulations and thermal vacuum (TVAC) testing will provide insights into the system's performance during both sunlight exposure and eclipse conditions.

During nominal operations, vibration during lattice reconfiguration or robot movement could resonate through the structure despite voxel stiffness, potentially disrupting precise tasks like bolting. While modal analysis can assist in predicting and mitigating these risks, it may be sufficient to negate vibration effects by programming the robots to operate at a slow enough speed to avoid generating excessive contact forces that could induce vibrations through the structure. Additionally, to minimize vibration during operation, we could consider integrating damping systems into the robot interface with the voxels. In addition to challenges during nominal operations, considerations will need to be made for addressing launch conditions. Storage and gripping mechanisms for the robots must be carefully considered to prevent damage or misalignment due to launch vibrations. Ultimately, vibration testing of the constructed spacecraft will provide insights into how the different parts of the structure are behaving during varying vibration conditions.

6. ONGOING AND FUTURE WORK

While significant progress has been made, including the development of initial requirements and ConOps, many iterations of the design are yet to come as we refine the system. The biggest drivers on the refined payload design are going to be the ability to scale any robot design to be small enough using as few custom parts as possible and the planning algorithm that dictates the robot and voxel movements commands. While the concept of simplifying the robot design and resulting valid voxel movements is promising, there is much ongoing work needed to fully develop the robotic system, especially at scale. We need to determine the smallest possible robotic architecture we can achieve with COTS parts, such as motors. Since the goal is to drive the cost down per robot and thereby increase the total number of robots working within the system, limiting the amount of custom or specialized parts is a key design priority.

From a planning perspective, we want to find the most optimal sequence of robot and voxel movements required to get from the starting state representation to the target representation. However, the planning algorithm can be even more informative than that. We can use it to advise us how many voxels and how many of each robot we actually need to achieve the mission objectives via optimization algorithms such as gradient descent. We can leverage the planning algorithm to determine the minimum amount of resources we actually need, which is extremely important in such a volume-constrained mission. If we need fewer resources, we may be able to relax the size constrains on the robot by implementing voxels that are larger than 1U.

The next area for increased focus is the avionics subsystem. Once we finalize the spacecraft bus configuration and what kind of solar power it can generate, we will be better able to construct an estimated power budget. Currently, we are making the assumption that we will be working with the small satellite team at NASA or an industry partner for development of the power and avionics systems. Furthermore, once the specific robotic designs are completed rather than just an architectural overview, we will be able to better address power needs within the system and further refine the mission requirements. As we advance in the design lifecycle and begin mission development beyond concepts, we will be able to explore integration options for this type of payload onto a spacecraft. This ongoing process will involve iterative refinement of the design, ensuring alignment with evolving requirements and constraints [13].

Also in the scope of this project is considering additional materials for the voxels themselves. If one wanted to use the ARMADAS system to construct, for example, a modular radiator panel, perhaps the voxels could be comprised of copper to increase thermal dissipation. The voxels could be outfitted with passive radiator panels on one side that are then attached together using an active method of thermal control, such as heat pipes [29]. If the voxels are constructed from a highly conductive metal capable of absorbing and dissipating heat, such as copper, they could actively contribute to the spacecraft's thermal management system [30]. While material changes would require reanalyzing mechanical properties such as specific stiffness of the voxels, the added versatility of outfitting voxels in various ways would be highly beneficial.

With the continued sophistication of on-board computing and spacecraft development, heat generation inside spacecraft and thus the thermal control of spacecraft is crucial to a mission's success. Leveraging the ARMADAS system to tackle more complex challenges would greatly enhance its adaptability and potential applications. By adding different module types with compatible interfaces (thermal modules, solar modules, instrument modules, etc.), this system could autonomously construct, outfit, and maintain a wide variety of structures without the need for bespoke robotic solutions. Furthermore, in-space assembly offers the advantage of saving valuable launch space by allowing heat dissipation structures to be built once in orbit. This approach could be a widely applicable solution on spacecraft that lack the room for large, pre-built, and sophisticated thermal management systems.

7. CONCLUSIONS

This paper demonstrates that with careful consideration, the ARMADAS system can be adapted for a CubeSat demonstration. We defined high level mission requirements and proposed outlines for scaling the system to accommodate the highly volume-constrained CubeSat payload space. Finally, we concluded by addressing the challenges with implementing an ARMADAS fleet on-orbit as well as the ongoing work on this project.

On-orbit assembly of space structures is critical for enabling missions that require extensive infrastructure. As we move forward, the need for robots to operate autonomously in extreme environments will only grow. In the long term, ARMADAS aims to enhance autonomy, diversify construction capabilities, and scale up operations to include large numbers of robot teams working in conjunction to build even larger structures with minimal increase in cost. Future applications may include satellite repair and docking capabilities as well as the construction of permanent infrastructure on the lunar surface, like lunar radio towers or giant solar panel arrays.

This first in-space demonstration of the ARMADAS system will significantly highlight its full autonomy, ability to package compactly, and resilience to harsh launch conditions and space environment. While the initial voxel assembly may involve fewer voxels and simpler reconfigurations, this technology demonstration offers a valuable opportunity for advancing the Technology Readiness Level (TRL) of the ARMADAS project. Advancing the TRL paves the way for utilization in future missions and makes significant contributions towards large-scale in-space infrastructure.

Thus, this technology demonstration is a critical component towards advancing the ARMADAS system's capabilities and it lays the groundwork for addressing the complex challenges of large-scale infrastructure development beyond Earth.

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