Automated Construction of an Unmanned Scientific Space Platform

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With the planned decommission of the International Space Station (ISS) scheduled to occur in approximately five years, academic institutions and industrial companies are about to lose one of the only testing facilities that currently exists in outer space. The experiments previously sent up to the ISS have helped increase scientific understanding of how objects interact differently in space conditions compared to normal atmospheric conditions on the Earth's surface. With the resurgence of the focus on space settlement, a new experimental platform would greatly aid humanity in its attempt to live out in space. This paper explores the autonomous construction of a theoretical unmanned space station that would focus on replacing the ISS's scientific capabilities.

I. Nomenclature

A = Hub surface area
α_x = Absorptivity of surface x
DOD = Depth of discharge
ε_x = Emissivity of surface x
K = Trailing-edge (TE) non-dimensional angular deflection rate
P_e = Average eclipse load
n = Battery to load transmission efficiency
N = Number of batteries
$\dot{q}$ = Power generated by the hub
q_x = Radiation from source x
σ = Stefan-Boltzmann constant
T = Temperature
T_e = Time of eclipse

II. Introduction

The International Space Station is the largest human-made structure ever assembled in orbit and the most complex multi-national engineering project in history [1]. Construction began in November 1998 with the launch of the Russian *Zarya* and continued over more than a decade, culminating in the final configuration's completion in 2011. In total, the station comprises more than 100 major components delivered across approximately 40 assembly flights by the Space Shuttle, Soyuz, Progress, and later commercial flights.

Operationally, the ISS has supported a continuous human presence since November 2000 and currently accommodates rotating crews of astronauts serving expeditions of less than a year. The station hosts a diverse portfolio of scientific investigations spanning microgravity biology, materials science, combustion physics, Earth remote sensing, and

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technology demonstration. This operational record establishes the ISS as the primary reference for the scientific operations of the design presented in this paper.

In-space assembly (ISA) is the process of constructing large structures from discrete components delivered by separate launches, and it has been an active area of both theoretical research and practical demonstration since the early years of human spaceflight. The concept gained notoriety during the Space Shuttle era and as the technique to connect the disparate pieces of the ISS. The ISS assembly sequence constitutes the most extensive demonstration of in-space construction to date. Between 1998 and 2011, astronauts performed more than 160 EVAs dedicated to station assembly, totaling in excess of 1,000 hours of spacewalk time []. Key milestones included the installation of the P6 solar array truss, the integration of the *Destiny* module, and the multi-flight installation of the ITS segments. Robotic systems have played an equally important role in ISA flight heritage. The Space Station Remote Manipulator System (SSRMS), known as Canadarm2, has been instrumental in berthing visiting vehicles, relocating modules, and supporting EVA crews since its installation in 2001 []. Its demonstrated capability for precision manipulation of large payloads in a microgravity environment has motivated subsequent research into autonomous and teleoperated construction robots.

Programs such as the DARPA Robotic Servicing of Geosynchronous Satellites (RSGS) have extended this heritage to on-orbit servicing and assembly tasks []. More recent work has further expanded the technical readiness level of ISA technologies. NASA's On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1) mission, formerly known as Restore-L, was designed to demonstrate autonomous propellant transfer and hardware servicing in orbit (although the mission has been canceled) [2]. Separately, Made In Space (now Redwire) flew the Archinaut technology development effort, which demonstrated the ability to manufacture and integrate structural beams in a simulated space environment and culminated in planning for the Archinaut One satellite, intended to deploy solar arrays manufactured on-orbit [3]. In parallel, academic and commercial research groups have examined structural configurations for large ISA structures including truss frameworks [4], cable-stayed architectures [5], and hybrid tension-compression systems optimized for repeated docking operations [6].

The design of crewed research facilities in low Earth orbit (LEO) represents one of the most complex undertakings in modern engineering. From life support and power generation to structural integration and orbital maintenance, a science space station must balance stringent mass and volume constraints with the operational demands of long-duration human spaceflight. This paper proposes a conceptual design for a self-assembled reconfigurable space station station that bases scientific output off of the flight heritage of the ISS. A concept of operations (ConOps) of the self-assembly and the scientific operations is presented, along with engineering analysis for requirement verification.

III. Station Concept (ConOps)

A. Requirements

The system is composed of several different requirements based on expected use. First, Level 0 mission requirements are defined in Table 1. Additionally, requirements to support station functionality are broken down in Table 2. Additional requirements at the subsystem and component level were derived for the purpose of commonality while working on this concept, but are not included for brevity.

Table 1 Level 0 Mission Requirements

Requirement ID	Description
L0-1	The system shall enable autonomous, unmanned assembly and operation of a modular, reconfigurable research station beyond LEO.
L0-2	The system shall autonomously manage research payloads throughout their life cycle, from docking to end-of-experiment processing or disposal.
L0-3	The system shall maintain long-duration operability using autonomous maintenance and repair capabilities.
L0-4	The system shall support modular expansion using ARMADAS voxels, leveraging CubeSat-scale components.

Table 2 Level 1 Functional Requirements

Requirement ID	Description	Area
L1-1	The station shall autonomously assemble ARMADAS structural, electrical, and power-transfer voxels into the operational station configuration.	Assembly
L1-2	The station shall support autonomous reconfiguration to accommodate new modules, relocate existing modules, or isolate faults.	Assembly
L1-3	The station shall autonomously capture, install, and manage research payloads.	Experiment Life Cycle
L1-4	The station shall autonomously perform end-of-experiment (EoE) processing, including removal, containment, and disposal.	Experiment Life Cycle
L1-5	The station shall autonomously inspect structural, electrical, and thermal subsystems.	Maintenance
L1-6	The station shall autonomously identify and correct faults or degraded components.	Maintenance
L1-7	The station shall operate continuously for multi-year missions without human presence through robotic maintenance.	Operations
L1-8	The station shall ensure safe operation of robotic assets to prevent collisions, contamination, and mission-ending faults.	Operations

B. Orbit Considerations

An important consideration is the orbital regime of the platform station. Figure 1 shows potential geosynchronous orbits of different inclinations, all of which are circular and share the same symmetrical longitude as the University of Cincinnati. There is also the special case of a geosynchronous orbit, one where inclination is also zero, which is a geostationary orbit. This was done using Ansys Systems Tool Kit (STK), a commercially available digital engineering software. With further research and commercial engagement, a proper orbit can be chosen to satisfy most demands and needs.

This platform would give the ability to test these sensors in the true space environment and conditions prior to the actual mission. A prime example of this is the NOAA Geostationary Operational Environmental Satellites (GOES) [7]. These are a series of geostationary satellites that are used to monitor the weather conditions and patterns of Earth. Through being geostationary, these satellites stay over one point relative to the Earth, providing continuous coverage over the same area. The GOES use wide field-of-view (FOV) sensors that allow for most of the Western Hemisphere to be seen by one satellite. In this case, a geostationary orbit would be best for the testing platform; however, this may not be the case for every current or future sensor. If the sensor has a smaller FOV, or if a certain area is more interesting for commercial-use, then an inclined orbit would be desired instead. This would allow the station to spend more time over areas-of-interest on Earth.

C. Construction Resources

The proposed unmanned scientific space platform utilizes NASA's Automated Reconfigurable Mission Adaptive Digital Assembly System (ARMADAS) technology [8]. This system allows for a cost effective and highly precise method of autonomous assembly. The ARMADAS system uses a building-block approach where voxels are assembled by an autonomous multi-robot team into desired 3D lattice structures. The voxels are cuboctahedron frames manufactured from carbon-fiber reinforced polymers allowing for high strength at a low weight [9]. While voxels are used to form the primary structures of space assemblies, they can also come pre-integrated with solar cells, data routing, or thermal shielding depending on the desired use case. The platform station will utilize the structural, routing, and solar voxels.

Construction of the voxels is handled by a specialized multi-robot team comprised of Scaling Omnidirectional

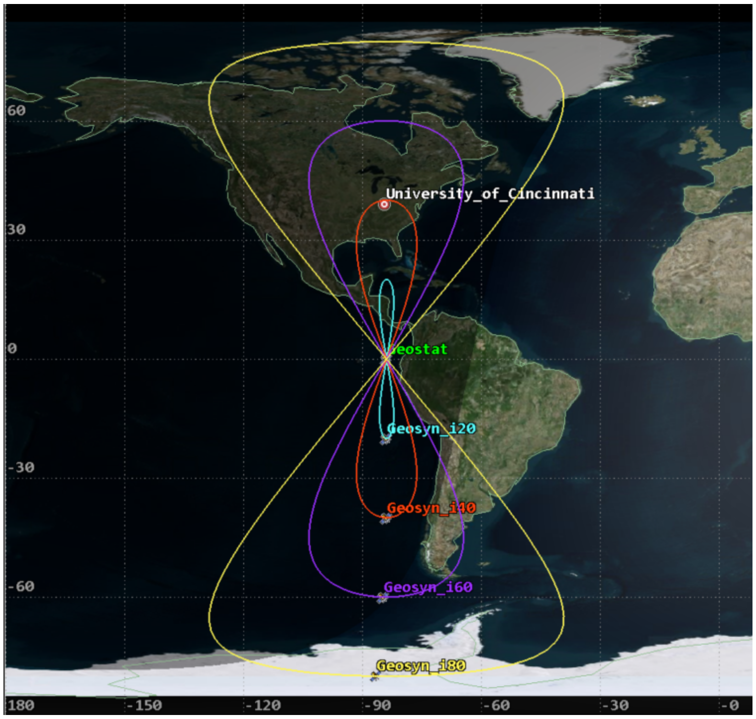

Fig. 1 Possible Geosynchronous Orbits, with No Eccentricity and Varying Inclinations

Lattice Locomoting Explorer (SOLL-E) and Mobile Metamaterial Internal Co-Integrator (MMIC-I) robots [10]. The SOLL-E robots are bipedal, inchworm-like robots that traverse the exterior of the structure. They carry voxels from a central depot to the building site and place the voxels in the correct position on the lattice. The MMIC-I robots crawl through the interior of the voxels and bolt the voxels into place using a reversible fastening mechanism. Both the SOLL-E and MMIMC-I robots, in addition to a dual-arm manipulator, are leveraged in the proposed construction of the space platform.

The ARMADAS components as well as any additional components needed for the initial assembly and first set of experiments will be launched onboard a reusable Falcon 9. The voxels will be folded and packed into "cassettes", using hinges at four of the corners to drastically reduce their volume [11]. At approximately one week MET, the dual arm manipulator will deploy the first SOLL-E arm and construction of the platform will begin.

IV. Station Design

A. Physical Layout

The station is formed around a core, which would be made from a modified geostationary satellite bus. This bus includes propulsion, attitude control, avionics, communications, and power equipment. Prior to construction, the bus will be used for transfer to the desired orbit. Several busses were assessed, and the general core mass and capability was sized based on Northrup Grumman's GEOStar-3. The core section in the graphical representation is kept as a generic octahedron for visual simplicity. As part of the modification process, several voxel sections would be permanently attached to the core to provide a starting point for the overall voxel structure.

Several motions which are outside the capabilities of the ARMADAS robots (SOLL-E and MMIC-I) are required for the station ConOps. Berthing a refueling vehicle, unpacking the voxels from their launch cassettes, and moving the SOLL-E and MMIC-I between different points which are not on a continuous voxel grid will require more dexterous, longer, and more powerful arms. A dual-arm manipulator system is included, with two circular rails allowing the dual-arms to move to many different points along the station. The arms were sized to approximately half of the range of the Canadarm on the International Space Station each. A "walking arm" concept was explored, similar to the Latching End-Effector on the Canadarm, however the additional complexity and stress on the voxel grid was decided to be less

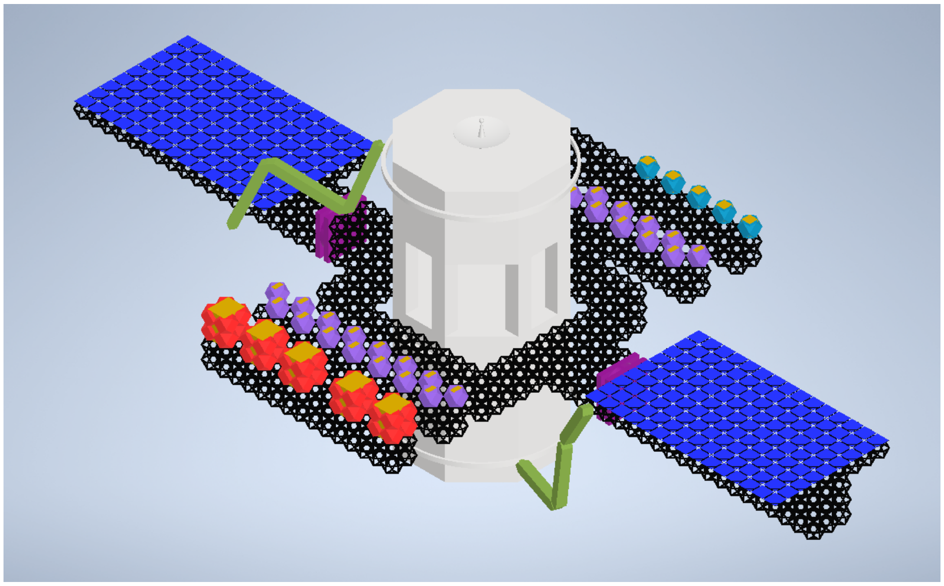

Fig. 2   Final Station Design

feasible than the rail concept. The overall station layout proposed is shown in Fig. 2.

B. Electrical System

An extremely important section for automatically running this space platform is the electrical system. As the only way to fix it would be to tear out the broken section, this system needs to be robust while also able to account for a variety of operating conditions. With many of the more power intensive systems, i.e. the external robotic arms, not needing to run at all times, the station's peak power is much greater than the average power required to operate. Even so, an electrical system was devised to support the full operation of the station through any eclipse cycle.

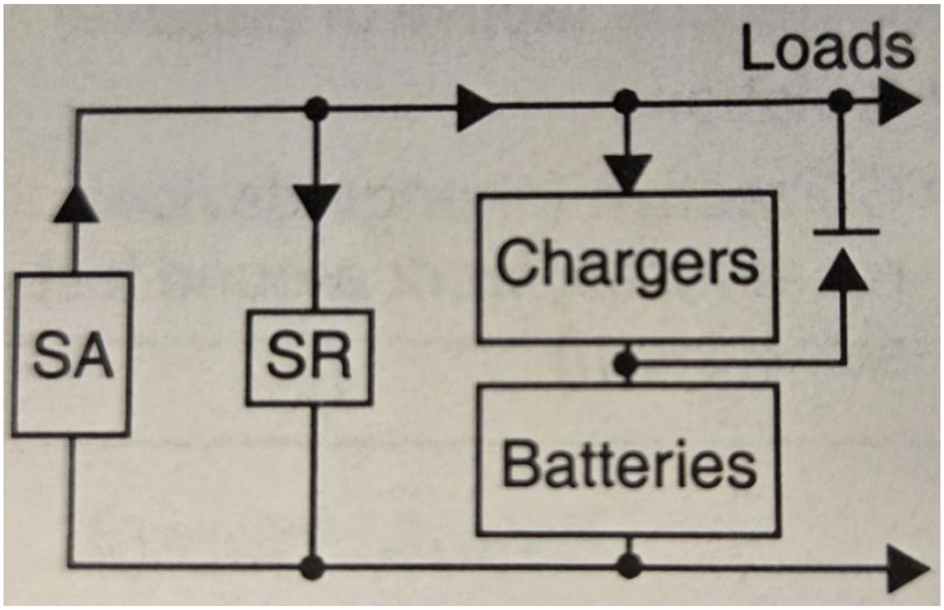

Fig. 3   Quasi-Regulated Bus with Constant Current Chargers [12]

The designed electrical system, shown in Fig. 3, utilizes a direct energy transfer (DET) with constant current chargers quasi-regulated design. A DET system is a dissipative subsystem because it dissipates power not used by the loads [12]. Where the excess power is dissipated varies depending upon whether internal or external power dissipation is desired. For this space station an external power dissipation was desired and an array of shunt resistors was included behind each solar panel wing in order to handle the power dissipation. The system being quasi-regulated means that the bus voltage is only regulated while the batteries are charging. This means that during discharge the bus voltage will gradually drop as the station continues to operate. To help mitigate the voltage drop and the power used at one time, power switches will be used to separate sections of the network that are not currently in use.

The proposed system utilizes batteries to store the required power to make it through an eclipse or any unexpected periods of darkness when the solar panels cannot generate enough power for the entire station. For this system, lithium-ion batteries were selected due to their charge density, 70-100 Whr/kg, and light weight. With each extra kilogram costing thousands of dollars to send to the desired orbit, selecting a lightweight battery can make a surprising difference in cost. The capacity of the battery bank can be calculated using Eq. (1) below.From this equation, the required number of lithium-ion batteries can be determined for different orbits provided the average load during an eclipse is known.

$$Cr = P_e T_e / (DOD) N n \tag{1}$$

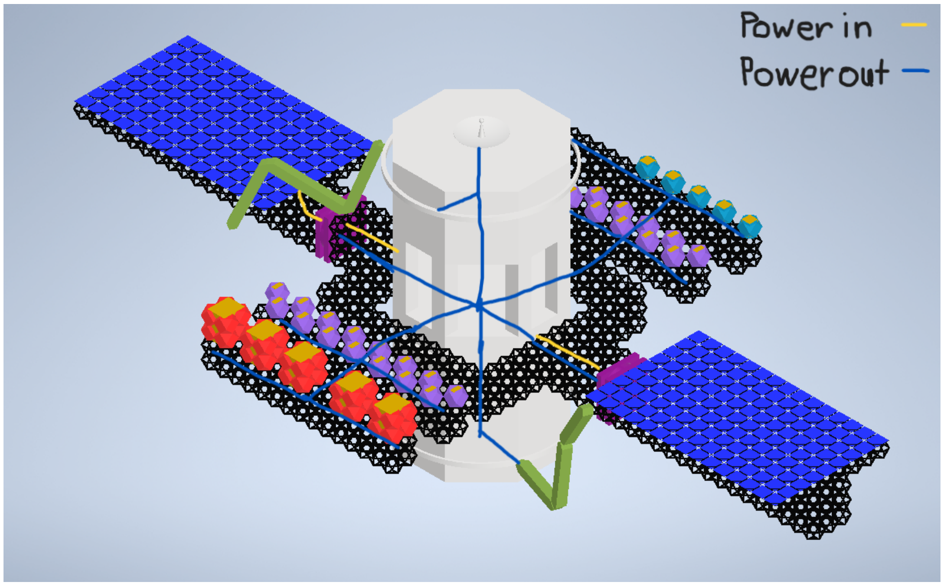

Fig. 4 Station General Wiring

The general wiring of the electrical system runs through the power and data voxels. As shown in Fig. 4, The central portion of the station contains the batteries, major electronics, and any servers and communication devices required to exchange information with a ground station on the Earth. All power is routed to the batteries and main bus from the solar panels, with the shunt arrays dissipating any excess power. The system is partially designed to operate with 2 main buses, as a fail safe in case one bus shorts or an experiment overloads one experimental wing. With the addition of power switches, this allows problem experiments to be isolated and allows the ARMADAS robots easy access to and problem areas without having to shut down the entire station. Ideally, any communication cables, which would interface with the experiments themselves, would run alongside the power system wiring to keep the cables compact.

1. Electrical System Consideration

The other power system type that was considered was a peak power tracker (PPT) system. This type of power system is designed to only extract as much power as the load, the experimental platform, requires, up to the array's peak power. Unlike the DET system that was used in the design of the electrical system, this system has a low efficiency when used with a quasi-regulated system and has no power dissipation that occurs during operation. Some advantages of the DET system over the PPT include fewer parts, the electrical system having less mass, and a higher total efficiency at equivalent operating levels.

Some alternative main bus systems that were considered for this station were a) an unregulated bus and b) a fully regulated bus. An unregulated bus has no voltage specified at any time. Instead, the main bus voltage is equivalent to the voltage stored in the batteries. The second type of power system that was considered involved a fully regulated bus, which has a defined voltage at all times. However, this comes with the drawback that the system is inefficient charge and discharge regulators. This type of main bus is typically used for low power spacecraft that require highly regulated buses. An advantage of a fully regulated bus over a quasi-regulated or unregulated bus is that when loads are connected, the system acts as a low-impedance power supply [12]. As this space station is designed to pull up to $6000W$ and to have two robotic arms that travel on external rails, both the unregulated and fully regulated power systems were passed over in exchange for the quasi-regulated bus as discussed above. To construct these buses, two different options were considered. The first involved using the proposed power and data voxels to connect all the experiments and solar panels to the central hub, which would contain the power storage. The second option was using normal voxels and then routing cables afterwards with the ARMADAS inchworm robots. Due to the risks and unpredictability of routing loose cables through voxels in space, the power and data voxels were selected as the main conduits for routing any power to the experiments that are external to the hub.

As mentioned above, the primary support for the main bus comes from the batteries that help store excess power to be used in the case of an eclipse where the solar panels cannot create energy from the sun. Primary batteries, which cannot be recharged may be useful initially as the station is being set up, but become irrelevant after the solar panels are deployed. Thus, the batteries that were looked at are classified as secondary batteries, batteries that are meant to get the station through an eclipse period. A couple of different rechargeable batteries, all nickel and lithium based, were considered before settling upon the lithium-ion batteries. The factors that were considered are a) charge density, b) mass density of the battery, and c) how the battery performed in a high radiation environment such as space. Batteries with higher charge densities were preferred due to requiring fewer to help support platform running at full capacity during any eclipses.

C. Thermal System

While space is considered to be an incredible heat sink there are many limits on the type of cooling that happens space. Due to the lack of a medium of some kind, fluid or solid, the only way to expunge excess heat is through thermal radiation, conduction and convection are only options for transferring heat internally. The amount of thermal radiation emitted from the station is directly proportional to the exposed surface area as seen in Eq. (2).

$$q = \sigma T^4 (W/m^2) \tag{2}$$

As such, this proposed station needs to have enough surface area to emit from while also mitigating the amount of radiation absorbed from its ambient surroundings. There are many different ways to decrease the required surface area, such as using a thermal paste or a reflective material. These materials are engineered to have a low absorption coefficient, α, and a high emissivity, ε, or reflectivity, ρ. The equation that describes the net thermal energy of the system is Eq. (3).

$$\alpha q_{sun} A + \alpha q_{Earth} A + \alpha q_{albedo} A + \alpha q_{deepspace} A - \varepsilon q_{station} A + \dot{q} = 0 \tag{3}$$

For simplicity, this station was assumed to use a white epoxy with an emissivity of $\varepsilon = 0.95$ and an absorptivity of $\alpha_{sun} = 0.019$ [13]. Eq. 3 uses values that assume the worst conditions for the space station. Specifically, $q_{sun} = 1418$ W/m^2, $q_{Earth} = 258$ W/m^2, $q_{albedo} = 70.1$ W/m^2, and $q_{deepspace} = 1.452 * 10^{-5}$ W/m^2, as $T_{deepspace}$ is considered to be 4 Kelvin, with the desired station temperature at 20 Kelvin helping determine that $q_{station} = 417.882$ W/m^2 and the solar panels producing their maximum voltage of $\dot{q} = 6000$ W. As such, the required surface area was determined to be only 16.49 m^2. It should be noted that this value assumes the station is not dissipating any energy through the shunt arrays located behind the solar panels in the DET power system mentioned above and that all energy is emitted from the central hub. With the aforementioned shunt arrays, this surface area decreases further.

For the internal components of the station, such as the servers, communication equipment and batteries, a passive phase change cooling system was selected, shown in Fig.5.

This system transfer heat via convection and conduction to the outer surface of the hub where it radiates off to space. However, the amount of heat radiated can be controlled by louvers on the exterior which can change their angle relative to the exterior surface. In some cases, the electronics may require heating instead of cooling. This can be accomplished by either lowering the angle of the louvers, releasing less radiation off into space, or through including a heater by the temperature sensitive electronics.

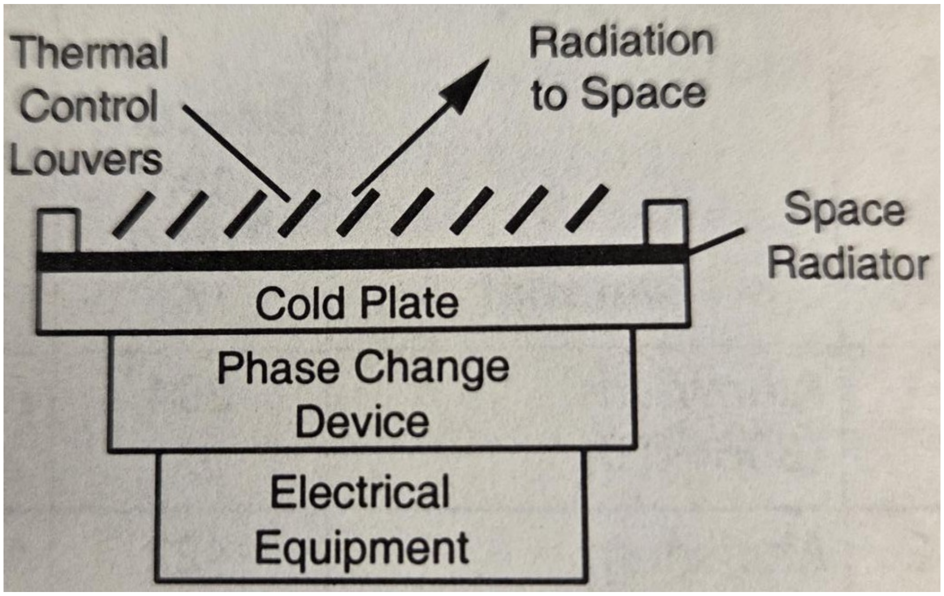

Fig. 5 Passive Thermal Cooling System [12]

1. Considered Thermal Management System

In addition to the thermal management system described above, other cooling options were considered. The first cooling system that was considered involved the use of heat pipes. Initially these heat pipes were going to be places in individual voxels for any interior thermal management and a section was going to extend into space, external to the station itself. However, due to the large area these external heat pipes would require, which may impede approach to the station or the movement of the large robotic arms, and concerns about the spreading of thermals with a modular heat pipe design, this idea was phased out early on. The second thermal management system relied on using thermal conduction strips to transfer all unnecessary heat to the exterior of the space station where it would be emitted to its surroundings. Once again, due to the modular nature of the voxels that were being used to construct the experimental wings, there were concerns with how these conduction strips would be connected to each other and how that would affect their overall conductivity. As connection points typically act as areas of higher resistance and thus lower thermal conductivity when transferring heat via conduction. This second system also did not consider how to maintain any electronics and experiments within an appropriate temperature range and would have run the risk of them becoming too cold.

D. Communication

The proposed commercial persistent platform will handle most operations autonomously, but will have capacity for remote operations, data up-links/down-links and TT& C. The orbiting platform, similar to the ISS, will rely on the NASA-managed Space Network which uses a constellation of TDRS satellites. In this structure, commands and data can be sent up from ground control to the persistent platform via the TDRS satellites. The down-link of high-rate data such as scientific experiment results, video, and telemetry can also be sent to the TDRS satellites, which then relay data to ground stations. Additionally, each payload may have smaller X-Band communication modules that each client may design and access independently from central control of the platform.

E. Autonomous Design

1. Robotics

Development of a large space station for in-space assembly demands careful consideration of the autonomous systems for fabrication. The chosen robots to enable this mission are the ARMADAS system [10]. The ARMADAS system is split into internal integration robots and external transport and material placement. The internal robot is comprised of 5 degrees-of-freedom (DOF) for locomotion and 16 DOF for end-effector maneuvering, as described

Table 3 Conceptual Design (SMAD) and Commercially Available Hardware

Parameter	Notional 50 Mbit/s Ku	AAC Clyde PULSAR-XTX
Band / freq.	Ku, ~15 GHz TX	X-band, 8.025–8.375 GHz
Data rate (max)	50 Mbit/s	10–50 Mbit/s
Required spacecraft EIRP	~54 dBW	~43 dBW with 2 W + ~11 dBi antenna (direct-to-Earth)
Antenna type & size	1.0 m Ku parabolic dish on 2-axis gimbal	Small X-band patch (~8–10 dBi)
RF output power (Tx)	~20 W RF	2 W RF (33 dBm)
Peak DC power (Tx mode)	~150 W (HPA + baseband)	< 10 W (Tx electronics))
Approx. comms hardware mass	~40–60 kg (antenna + RF electronics)	< 0.2 kg (Tx + patch antenna)

Table 4 Decision Hierarchy

Level	Scope	Overrides?
Level 4	Mission goals	All lower levels
Level 3	Scheduling/coordination	2 (within policy)
Level 2	Execution	1 (temporarily)
Level 1	Safety	All (hard stop)

in the ISAM State-of Play[14]. Similarly, the external robot is comprised of 5 DOF for locomotion and 8 DOF for end-effector operations.

While this ARMADAS system is helpful for assembly of station voxels, it cannot sufficiently serve as the only system for all other tasks. With this in mind, a rail-mounted dual arm system is considered. Each of these arms will be a 6 DOF arm capable of assisting with experiment processing as described in section III. The elaboration of this autonomous system, as seen in Figure 6, illustrates the tasks expected from each robotic entity and how they relate to overall system design.

2. Multi-Agent Coordination

With a complex system of robots and a large space assembly mission, several different components need to seamlessly coordinate for mission success. With this in mind, a decision hierarchy and data transfer pathway is needed, as described in Figure 7. These four levels determine system safety and that the right components receive the right scope of information at the right time. The flow of information starts at the high level in Level 4: Mission and flows through Level 3 to plan, Level 2 to execute, and Level 1 for safety, as described in Table 4.

The combination of tasks to build, expand, inspect, and maintain a large space station, as well as experiment handling, involves cooperation from different types. In this instance a centralized task manager advertises tasks based on type and resource demand. The agents are broken into four types:

- ASI - interior assembly
- ASE - exterior assembly
- DMR - dual arm manipulator
- INS* - inspection agents to monitor maintenance issues

While INS* agents could take the form of a specialized robot or CubeSat deputy, for simplicity we will assume this is an external assembly robot with a camera mounted. Each of these four agents can perform specialized tasks. The task types include but are not limited to:

- Voxel transport
- Voxel placement
- Experiment docking

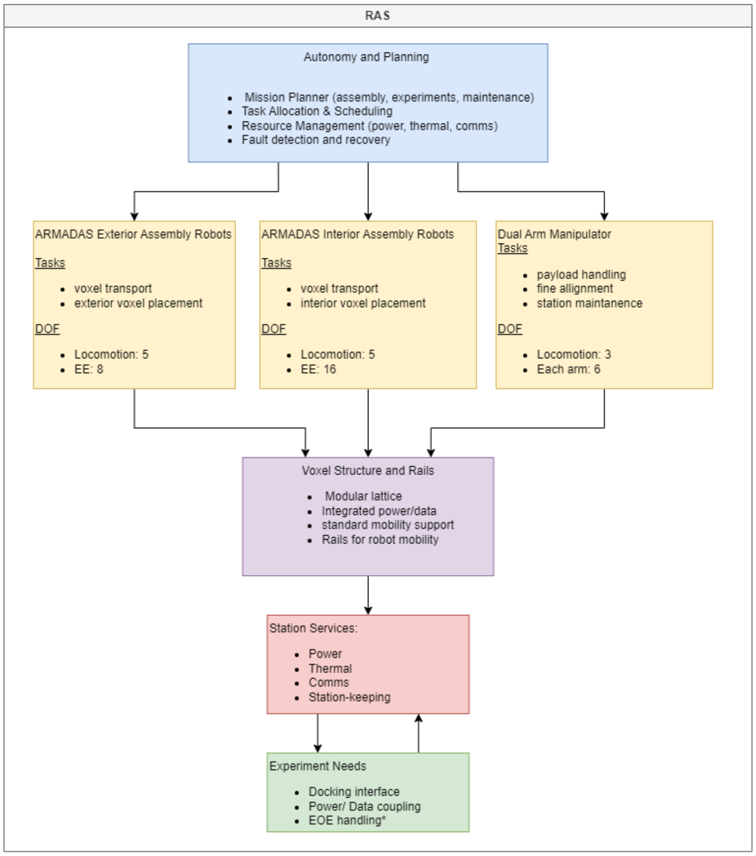

Fig. 6 Manipulator Concept and Task Delegation

- Experiment End-of-Life handling
- Inspection
- Maintenance

Each task is made up of several different properties. This includes Task-ID, Task-Type, Required-Agent-Type, Required-Resources, and Priority (optional). To verify that the agent assigned has enough resources to complete the mission, the Resource Token is included under "Required-Resources". This includes information such as Resource-Type, Quantity, and Duration. Once a task is created, the task manager checks the properties of the task and the available agents to find a match. Then the agent updates the task status as it works. Besides each agent having an Agent-Type, it also has an ID and Status (Busy or Free). This process is illustrated in Figure 8.

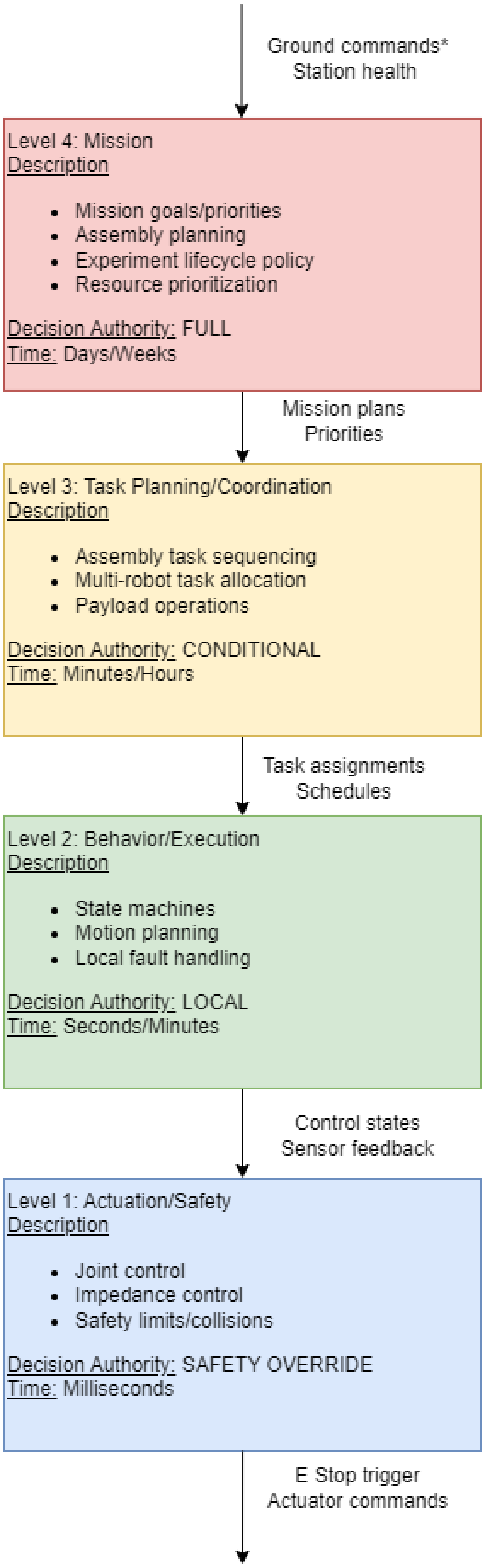

Fig. 7 Multi-Agent Task Delegation

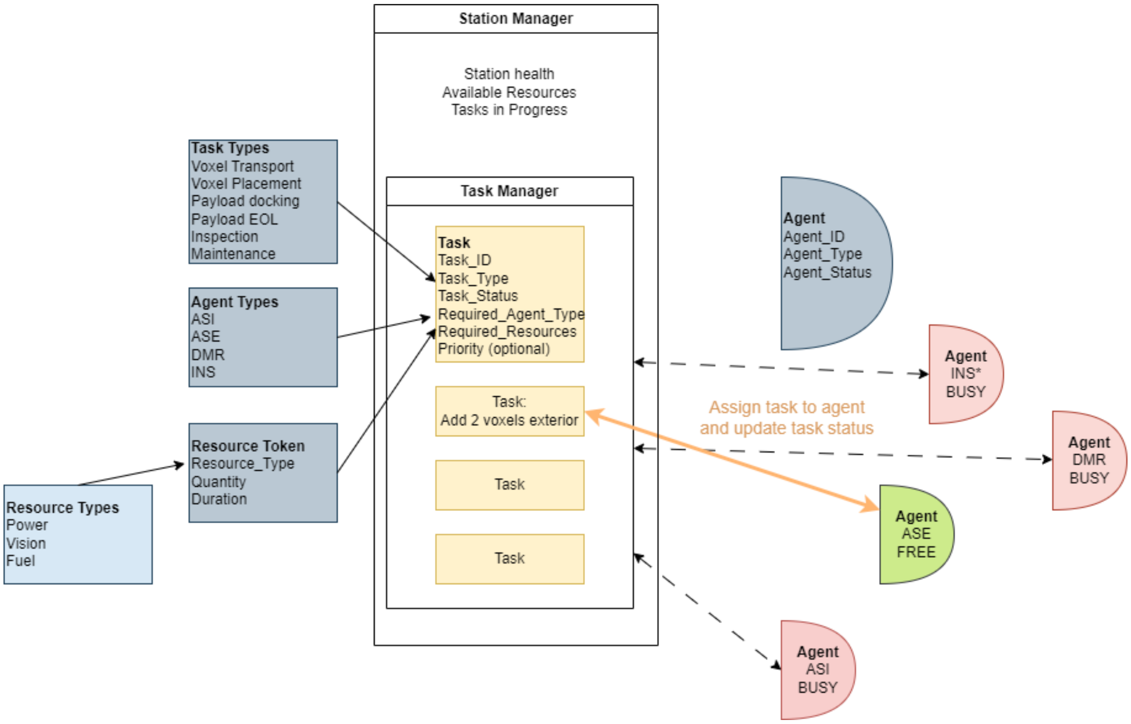

Fig. 8 Task Manager and Data Structure for Agents and Tasks

V. Life Cycle of Experiments

A payload arrives to the science station via a space delivery vehicle, is checked-out for functional verification, is brought to its assigned payload bay, conducts its experiments or mission, and at the end of its lifetime is disposed by future logistic vehicles. Details and important considerations are explained below for each step of the life cycle. The life cycle as described by this work is a proposal to create requirements both on the design of the science station and on the customers designing payloads. As detailed by NASA [15], researchers wishing to use the science station must conform to certain station requirements, such as available power, data transfer budget, servicing resources, and so on. However, due to the nascence of this proposal, customers would have the ability to also establish standards and practices for these requirements. Meaning: station operators would work with customers to determine best specific requirements. For the sake of explaining the basic requirements to have a successful experiment life cycle for every customer, the following explains in more detail.

- **Arrival Check-Out**: when customer experiments and payloads are delivered to the station they must first be inspected, have their integrity verified, and then unloaded and placed into a staging zone. Before payloads can be removed from the delivery vehicle they should undergo customer-specified readiness verification. This may include visual inspection by cameras onboard robotic station agents to verify visually the payload arrived undamaged, or could even involve powering the payload to verify successful operations. Pre-unloading payload verification is a requirement placed to ensure that payloads brought onboard the station are in functioning order. If a payload was found to be irreparably damaged on arrival to the station this would indicate that it should not be brought onboard, and would instead remain onboard the delivery vehicle for disposal. A customer could choose to go ahead with the payload berthing if the verification process partially fails, so long as communication to and from the payload is possible for troubleshooting.
- **Berthing**: careful manipulation of the payload should be used during the berthing phase in order to ensure that functioning payloads do not become damaged by station robotic agents. To this end, the delivery of payloads to their berthing bays should be planned with extreme care to keep a number of constraints in mind, such as 1) avoid multiple agents working in close proximity, 2) pre-plan optimal berthing order to meet customer requirements while managing station agent resources, and so on.
- **Station Integration Check-Out**: once a payload has been berthed in its assigned bay, it must be verified that all station interfaces are functioning correctly before the experiment mission can begin. This includes confirmation of mechanical attachment, electrical power delivery, data and communication links, and any fluid or thermal interfaces the payload requires. Station robotic agents and onboard monitoring systems should perform this check-out autonomously where possible, with results reported to both station operators and the customer. If an interface is found to be non-functional, operators and the customer should jointly determine whether the fault is correctable in situ (for example, by reseating a connector or cycling power) or whether the payload must be re-berthed or removed. Only after all required interfaces are verified nominal should the payload be cleared to begin its mission. This check is critical, as an undetected integration fault could compromise not only the customer's experiment but also neighboring payloads or station systems sharing the same power or data bus.
- **Maintenance During Mission**: payloads are expected to require some degree of attention over the course of their mission lifetime. Station operators should provide a baseline level of monitoring for all active payloads, tracking power consumption, thermal output, and communication status as a minimum. Customers may specify additional monitoring or periodic servicing tasks, such as sample retrieval, consumable replenishment, or software updates, which station robotic agents can perform according to a pre-agreed servicing schedule. When an anomaly is detected, the station's fault management system should notify the customer and, depending on severity, may autonomously safe the payload to prevent damage to station systems. Customers should be required to provide operators with anomaly response procedures at the time of payload delivery, so that corrective actions can be taken promptly without waiting for customer input. Payloads that cannot be recovered from an anomalous state and pose a risk to the station or other payloads should be powered down and scheduled for early removal.
- **End of Mission Logistics**: at the conclusion of a payload's mission, three broad disposal paths are available: return to Earth aboard a logistics vehicle, disposal via destructive reentry, or temporary on-orbit storage. The preferred path should be designated by the customer at the time of manifest and factored into station logistics planning. Payloads with recoverable scientific samples, reusable hardware, or high residual value are candidates for Earth return, and should be packaged and staged in the logistics zone ahead of the next available return vehicle. Payloads with no recovery value may be transferred to a departing logistics vehicle for destructive reentry disposal, minimizing long-term storage demands on the station. In cases where neither a return nor a disposal vehicle is immediately available, a limited on-orbit storage capability within a designated staging zone should allow

payloads to be held temporarily; however, storage duration should be bounded by a customer-agreed maximum to prevent the staging zone from becoming a constraint on incoming payload traffic. In all cases, end-of-mission logistics should be coordinated well in advance of the payload's projected decommission date to ensure that an appropriate vehicle and station resources are available.

VI. Conclusion

The concept of in-space assembly is a cutting edge idea to take advantage of "infinite" workable area for large scale space infrastructure. However, this presents unique challenges in logistics, life cycle, and maintenance of such a system. The intent of the Self-Assembled Science Station (SASS) system is to provide advanced resources to modular CubeSat type experiments to improve science experimentation outside the ISS. With this in mind, a specific orbit must be determined to maximize usefulness in addition to key system design components like layout, electronics, thermal management, communication, and autonomy. The team has evaluated a mission which has a constrained budget while still raising the TRL of several key components. Consideration of actual payload configurations for launch was included to ensure realistic component design. Given these factors, SASS demonstrates the power of assembled structures in space, while simultaneously addressing a clear, present, and marketable need.

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