Self-Assembling Space Habitats:
TESSERAE design and mission architecture

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Abstract—**Designs for adaptive, modular, and re-configurable space structures hold great promise for the evolving commercial space station market in LEO (Low Earth Orbit), for supporting Lunar Orbital Platform-Gateway designs, and for facilitating the first human Mars missions. We propose an extensible self-assembly paradigm for in-orbit space habitat construction, discuss mission architectures uniquely facilitated by this approach to habitat design, and present a feasibility review and preliminary results from a proof-of-concept prototype. This paper details our habitat design and deployment planning around TESSERAE (Tessellated Electromagnetic Space Structures for the Exploration of Reconfigurable, Adaptive Environments). This technology demonstration mission explores several parameters for a self-assembling system (quasi-stochastic assembly, electro-mechanical bonding, clamping processes, responsive sensing and autonomous GNC, etc.) and includes a multi-year research effort to engineer and deploy test structures. The first prototype was successfully tested on a parabolic flight in November 2017 and is now scheduled for a second parabolic flight and initial sub-orbital launch in 2019.**

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1. INTRODUCTION

We look ahead, to the technology needs of the next 10-20 years, to support Lunar or Martian exploration operations, and more broadly, the first significant waves of humans transiting in microgravity. The ease with which we can deploy, reconfigure, and adapt our habitats will directly impact the success of space missions—from lowering costs, to improving safety via fewer astronaut EVAs, to enabling agile and rapid infrastructure response for operational needs. This research proposes a multi-year effort to study, prototype and test TESSERAE (Tessellated Electromagnetic Space Structures for the Exploration of Reconfigurable, Adaptive Environments). TESSERAE are designed to function as multi-use, interchangeable, low-cost orbiting modules that can convert to surface habitats; we aim to supply transformational, practical space infrastructure for the next generation of microgravity habitats and staging bases for on-surface exploration. Unlike large scale habitats proposed for entire space colonies, the TESSERAE should be thought of as flexible and reconfigurable modules to aid in agile mission operations. The self-assembling TESSERAE modules are designed to be autonomously and sustainably constructed, reconfigured as needed without astronaut intervention (saving crew costs and time), and without propulsion (saving non-renewable resources and payload mass). A standard suite of modular tiles (structural, airlocks, docking ports, windows, etc.) are interchangeable in LEGO-style to allow for many permutations and custom mission designs at low "iteration cost." See Figure 1 for a concept diagram of TESSERAE assembly stages.

Each TESSERAE unit is designed to quasi-stochastically self-assemble from 32 tiles into a buckminsterfullerene, or geodesic dome. Electro-permanent magnets (EPMs) facilitate the bonding, while a supervisory sensor network performs bonding diagnosis and initiates error correction. We first present the TESSERAE technical design, then progress through mission architecture and ConOps (Concept of Operations), and conclude with a mission feasibility review.

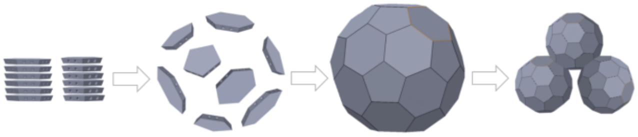

Figure 1. Tiles packed flat for launch; released for self-assembly; fully assembled TESSERAE module; multiple TESSERAE modules docked in a space station constellation configuration.

2. TECHNICAL SYSTEM DESIGN

2.1 Quasi-Stochastic Assembly

Rather than relying on large, pre-fabricated volumes, a self-assembly approaches divides the final structure into many

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constituent parts that join together under certain rules and constraints.

Prior work in macro self-assembly emphasizes embedding features into each part that induce accretion into the desired whole, such as lock and key physical joints or magnet bonding pairs [1]. Prior work in micro and meso-scale self-assembly (modeled after DNA molecular assembly and protein folding) uses an "annealing ramp" approach; this involves tuning the input stirring energy (or extent of perturbations like vibration and shaking) to circulate tiles and converge a multi-part system into a cohesive whole [2]. We combine the two approaches in the TESSERAE application, designing both the tile geometry with magnet polarity arrangement along tile bonding faces and the "stirring energy" via EPM actuation.

The initial phases of our research focus on the buckminsterfullerene [3] or "buckyball" structure as the target assembly shape. This shape is assembled from 12 pentagonal and 20 hexagonal tiles; we have beveled the TESSERAE tile bonding faces to the dihedral angles that establish the expected buckyball curvature. Magnets are embedded in a regular pattern along these surfaces to seed a successful assembly. Our design for the tile-tile bonding geometry and spatial magnet arrangement creates only two unique joint types—this increases the probability that any two neighbor tiles can find a shared bonding site. Our experimental parameters for guiding self-assembly include (several are interrelated):

- Circulation: maximizing bonding surface exposure to likely neighbors.
- Containment: optimizing the containment volume for efficient circulation (too large and tiles will settle away from one another, too small and tiles may be blocked from freely rotating to fit in proper recesses).
- Seeding: design and timely introduction of base units into a system to promote a particular shell geometry (akin to crystal nucleation).
- Stirring Energy: perturbations required to dislodge local minima and aid in circulation.
- Redundancy: exploring the optimum distribution of pentagon and hexagon tiles (e.g., adding extra tiles up until the point where crowding and resource waste creative inefficiency).
- Reversibility: maintaining ease of joint reversibility for later disassembly and reconfiguration (rather than intricate lock & key twist joints).

Because we mediate this process with EPMs for error detection and correction (see section 2.2 below), it is not an entirely passive or random system, but rather quasi-stochastic.

2.2 Electro-Mechanical Bonding

Electro-permanent magnets on each bonding face serve two purposes. In their unpowered state, they exert a constant magnetic attraction. When embedded on the TESSERAE bonding faces, this creates a polarity map that intentionally draws hexagons and pentagons into a particular configuration for "additive construction" (pentagons surrounded by five hexagons, see Figure 2). In their brief powered state, the magnetic attractions are neutralized to allow two previously bonded tiles to separate, or undergo "subtractive construction." This second functionality allows us to manage error control, when tiles may have inverted (switching interior and outer surfaces) or partially bonded into a meta-stable state. These additive and subtractive modes of EPM mediated assembly have been previously explored in 2D, water-supported systems [4] and 3D "pebble" rearrangement [5]. TESSERAE uniquely combines the two approaches with a new polarity map and quasi-stochastic actuation in microgravity 3D spaces.

The use of EPMs allows us to reduce the TESSERAE power budget on-orbit (in contrast to using traditional electromagnets that must be constantly powered to provide attractive force). Separate clamps and sealing gaskets are used to reinforce the EPMs during steady-state operation (magnets are only power-actuated during assembly and disassembly). The EPM actuation is instigated by a supervisory sensing network, described below.

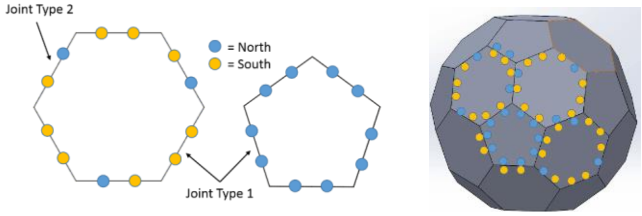


Figure 2. Polarity map for pentagon and hexagon tiles (L). Application to 3D joints (R). Presented previously in [6].

2.3 Supervisory Sensing and Swarm Response

A supervisory sensor and communication network (early prototype described in [7], mesh architecture explored in [8]) across all tiles facilitates swarm-based path planning and error correction. This can be used to pulse permanent electromagnets "off" if an incorrect tile-tile bond is detected, or for on-demand physical buffering between tiles based on proximity ranging sensor data. In Figure 3 below, we show the sensor inputs informing both local tile response and global reactive swarm response. We note prior research in scalable swarm communication architecture [9], and while our node count remains in the 30-40 range rather than 1000+, we are exploring related techniques for autonomous node management (including physical touch response, IR communication over short ranges, etc.).

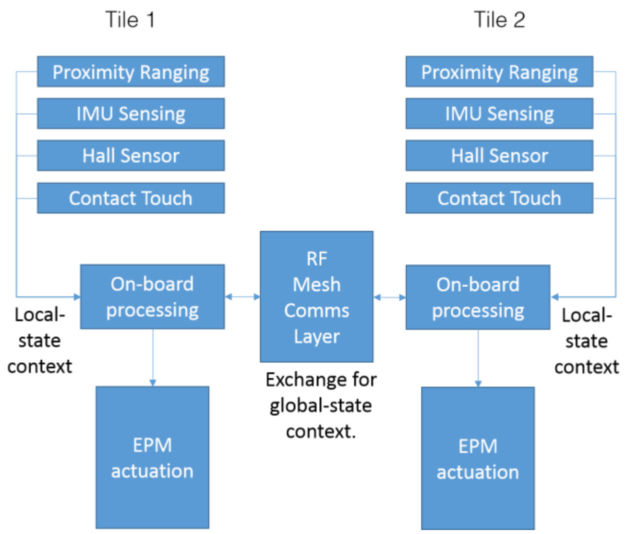


Figure 3. Tile sensing inputs are exchanged via a mesh communications layer. Multiple pairwise data exchange relationships can be established simultaneously.

3. MISSION ARCHITECTURE DESIGN

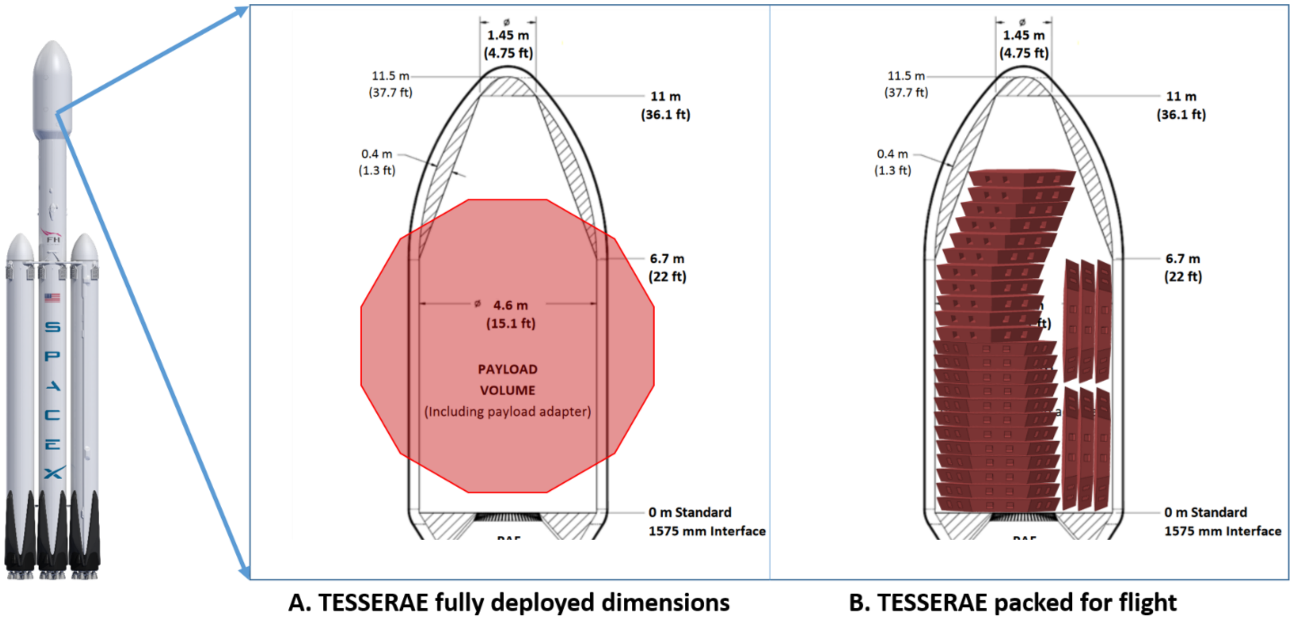
Sections below detail our prospective mission design, describing the assembly process and a subset of in-orbit possibilities for TESSERAE.

3.1 Deployment Stages and Operation

3.1.1 Initial Deployment—The TESSERAE tile units will begin the mission in a stacked, flat-pack configuration within a rocket payload fairing (see Figure 4). We anticipate fitting all 32 tiles in a single launch. Like inflatable habitat concepts, this allows us to transport structures whose final, fully-assembled dimensions are larger than the fairing's volume boundaries (in contrast to the ISS fixed-shell modules).

A temporary, flexible membrane will encapsulate payload elements, and undergo autonomous inflation upon completing orbit insertion and ejection from the payload fairing. This ensures that the component tiles are kept in close proximity when released into the microgravity environment. Current TESSERAE mission design envisions a holster-actuated process, where tiles are released one at a time from a dispensing structure to allow for incremental assembly in "accretion" style (much like a crystal nucleation process).

Released tiles then circulate quasi-stochastically throughout the confined membrane volume and self-assembly begins. As tile bonding edges pass near one another, tiles are brought together and snap into place via the EPMs on each bonding face. As explained above, this process proceeds passively without active control until an incorrect bond is detected. The supervisory sensing network and bonding diagnosis algorithm detects incorrect bonds (which should already be minimized due to optimized design of the tiles' EPM polarity map), and selectively pulses the EPMs off to free tiles for circulation back into the assembling pool. This approach builds on magnetic docking of space assets [10], [11] and active control for electromagnetic formation flight and space structure deployment [12], [13]. Actuation of the EPMs can also be used to selectively apply torques to certain tiles (e.g., for forcing bonding faces into planar alignment), to dynamically buffer tile-tile interactions (e.g., two tiles approaching each other at incorrect bonding angles, or coming in with excessive velocity vectors), and to aid in the application of stirring energy (e.g., to perturb two tiles that



A. TESSERAE fully deployed dimensions **B. TESSERAE packed for flight**

Figure 4. TESSERAE tiles packed for launch in sample payload fairing. Fully deployed dimensions (L), versus stacked concept (R). Presented previously in [6].

may have settled away from the accreting structure, or into a local minima configuration).

After the full structure has assembled and any remaining extra tiles have been gathered separately, a series of autonomous structure-finalization tasks begin. Each tile-tile bonding face executes a clamping sequence, where tiles are latched together firmly (pressed against sealing gaskets). These latching-style clamps (providing a hold force without ongoing power draw) are used as a complement to the EPMs that are providing their own, continuous, unpowered holding force. To provide a second layer of sealing for mission robustness, an internal bladder is inflated within the TESSERAE shell, which will ultimately contain the pressurized air and living space accommodations. Various options exist for actuating this internal bladder deployment; one proposal involves the bladder unfurling from within a given tile's compartment and inflating from stored air tanks (comparable to the Bigelow Expandable Activity Module air inflation process [14]). Given that this internal bladder will separate payload items (like frames and racks) from the external shell where they would be traditionally anchored, we intend to augment the bladder with rigid tie-in points.[1]

3.1.2 Re-configurability—One of TESSERAE's unique advantages lies in the inherent re-configurability of a modular structure. All "structure finalization" tasks as described in 3.1.1 are reversible. The structure can be depressurized, unclamped, and de-bonded (by pulsing current through the EPMs to neutralize magnetic attraction) back to individual tiles. This separation could be executed around a single tile or small group of tiles for targeted replacement, repair, or re-design (e.g. where a window tile was yesterday, now an airlock or additional docking port is needed). In addition, the entire structure could be disassembled for habitat relocation.

3.1.3 Dual Use On-Surface—In addition to providing orbital habitat volume, TESSERAE tiles could be used for planetary surface shielding and habitats. While the self-assembling nature of TESSERAE construction works best when least-constrained in microgravity, the ease of snapping TESSERAE tiles in place can facilitate quick, modular construction in normal and reduced gravity environments as well. TESSERAE tiles could be disassembled from their orbital configuration (e.g., a staging base), packed flat in an EDL (Entry, Descent and Landing) transfer vehicle, and re-assembled with human or robotic assistance on the surface of the Moon or Mars. The EPM polarity map allows tiles to be intentionally assembled like a puzzle set without the need for quasi-stochastic assembly, when an agent is present to take over the assembly process. Again, due to TESSERAE's re-configurability, the shell tiles could be assembled as a habitat for initial use at a landing site and then disassembled, moved by rover, and reassembled elsewhere to meet evolving mission needs.

3.1.4 Habitat Operation—Our work on TESSERAE focuses primarily on the creation of the shell as an extensible platform for multifunctional use in orbit, with reusability for surface operations as well (per 3.1.3). We do not intend to proscribe a particular habitat function—rather, we aim to make TESSERAE applicable and adaptable for LEO space tourism, Lunar orbit in conjunction with the Lunar Orbital Platform-Gateway, Mars-Phobos orbit to support on-surface missions, et cetera. To do so, we will explore embedded, modular functionality in each tile such that TESSERAE units can be retrofitted for various ECLSS (Environmental Control and Life Support Systems), remote-sensing, and Guidance and Navigation Control (GNC) orbital maneuver technologies. Tiles will be initially designed with radiation and debris shielding comparable to systems currently used in ISS modules (e.g., Whipple Bumper and stuffed shield [15]), with tests on alternative, advanced materials conducted as feasible.

We envision multiple, interlocking TESSERAE structures joining together to form larger space stations on-demand. This figures prominently in our design for agile mission operations. One particular instantiation of this concept, the Mars Orbiting Self-Assembling Interlocking Chambers (MOSAIC) constellation, would allow for dynamic creation of new habitable volume to meet waxing and waning crew needs in orbit. A single TESSERAE sphere could accommodate the first orbital crew, then dock with additional self-assembled modules as additional crew arrives, then detach and condense back to a single module in orbit as other units are disassembled, packed flat, and shipped to the surface for re-use as a land-based habitat.

3.2 Deployment Scale

While TESSERAE could be deployed at varying volume scales by tuning the size of the standard hexagon and pentagon tiles, we propose the following scale for initial mission design and feasibility review.

3.2.1 Dimensions—We model an example TESSERAE system with tiles of bonding-side length 1.52m (5ft), thus yielding a total truncated icosahedron volume (shell and enclosed area) of 196m^3 (6910 ft^3) with a span diameter of 8.7m (28.4ft), as shown in Figure 5 below. In comparison with current in-orbit architecture, TESSERAE's proposed interior pressurized volume would equal ~40% of the pressurized, habitable volume on the ISS (388m^3, 13696 ft^3) [16] and over 10 times the habitable volume of BEAM [17]. As a geodesic dome, TESSERAE benefits from the sphere-approximation geometry, with maximized volume for a given closed surface area. Based on preliminary test results (see section 4.7), we are currently anticipating a membrane containment enclosure no larger than two times the TESSERAE module diameter (to maintain tile proximity during self-assembly, without over-constraining the available volume for tile circulation).

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[1] An alternative solution uses magnetically attractive payload elements that could be reversibly bonded to the inner walls of the TESSERAE shell, acting through the membrane material depending on final material composition.

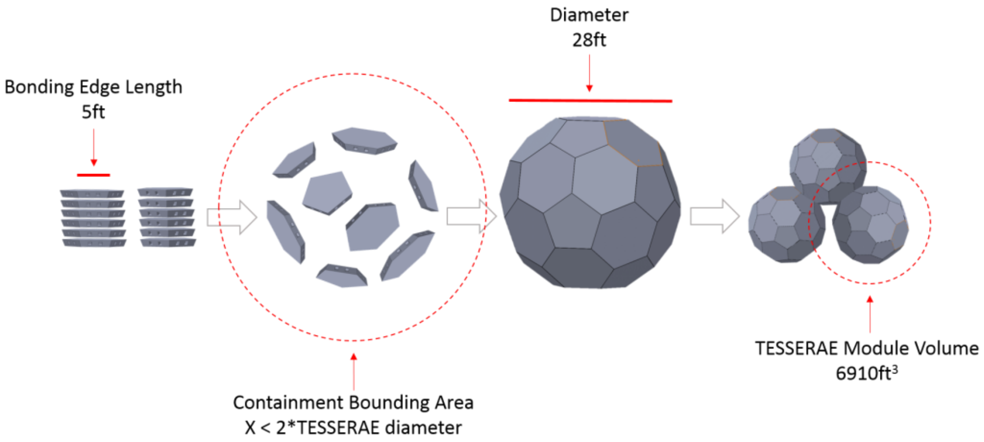


Figure 5. TESSERAE assembly stages, at orbit deployment scale.

3.2.2 Mass—While a fixed TESSERAE mass has not been determined at this scale (as the final value will depend on material choice and shell thickness), we can extrapolate from the published Columbus Module specifications to approximate the mass due to several layers of stuffed bumper, thermal and aluminum shielding. Taking the 14.7g/cm^2 area density of the 7.9cm (3.11in) thick Columbus Module [18], we would expect an upper cap of ~23,000kg (~50,000lbs) for the TESSERAE shell mass. Keeping consistent with Columbus Module thickness, the interior usable TESSERAE volume would then be approximately 175m^3 (6180 ft^3). Per the table below in Figure 6, this suggests that TESSERAE would offer a more efficient mass to usable volume ratio than comparable ISS modules (as we would expect from the optimized geometry). While BEAM's mass to usable volume ratio is far more efficient, we project that TESSERAE's advanced functionality (re-configurability at the shell level), condensed packing for launch, and rigid, protective shell offer sufficient benefits beyond the inflatable model.

	Mass (no payload)	Interior/Usable Volume	Mass to Volume ratio
TESSERAE	**23,000 kg (max cap, could be lower)**	**175 m^3**	**131 kg/m^3**
ISS: Columbus Module	10,275 kg	75 m^3	137 kg/ m^3
ISS: Destiny Module	14,500 kg	104 m^3	139 kg/ m^3
ISS: BEAM	1,413 kg	16 m^3	88 kg/ m^3

Figure 6: ISS modules specifications drawn from [19]-Columbus, [20]-Destiny, [17]-BEAM.

3.3 Deployment ConOps Comparison

In addition to the shell-mass to volume ratio benefits that TESSERAE offers, the system architecture enables unique functionality and facilitates entirely new mission ConOps. Per the comparison chart below (Figure 7), TESSERAE is not only modular at the space station scale (e.g. adding additional entire TESSERAE modules to form the MOSAIC, comparable to adding Destiny or Columbus on to the ISS) but also reconfigurable at the shell layer. The BEAM inflatable habitat comes closest to TESSERAE's feature suite, but does not fully autonomously assembly (astronauts completed the air inflation process [14]) and the fabric layers cannot be removed, replaced and exchanged in the way that TESSERAE tiles can be reconfigured.

	Modular at Space Station Level	Packs Flat for Launch	Autonomous Assembly	Re-configurable at the Shell Level
ISS	✓			
BEAM	✓	✓	✓	
TESSERAE	✓	✓	✓	✓

Figure 7. Mission feature comparison between ISS modules, BEAM, and TESSERAE.

4. MISSION FEASIBILITY ANALYSIS

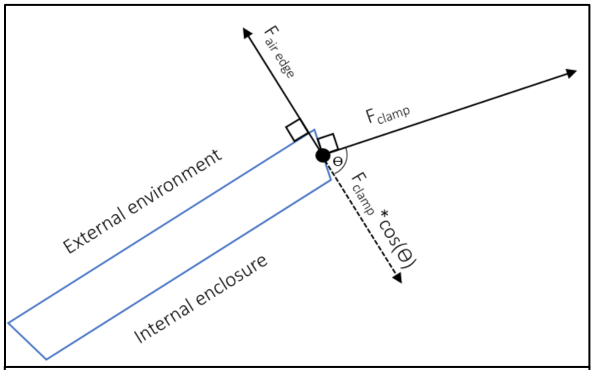
Below, we address several categories of large space structure feasibility questions to demonstrate TESSERAE's practicality in orbit.

4.1 Ride to Orbit

At a max cap of 23,000kg for the TESSERAE structure, we can confirm that there exists a launch vehicle that can deliver this mass (and stacked volume) to LEO. We note the Falcon 9 Heavy specifications, confirming an allowable payload weight of 63,800kg to this orbiting altitude range [21]. While yet to fly a demonstration mission, SpaceX's BFR [22] and Blue Origin's New Glenn [23] both offer stated capability that would allow us to fly multiple sets of TESSERAE tiles to orbit, to facilitate self-assembly of more than one shell module in parallel.

4.2 Pressurization in Orbit

As discussed previously in Ekblaw [6], we have modeled the force due to air pressurization on the TESSERAE tile joints and have confirmed that industrial clamps exist at the required hold force regimes. Our clamping system is intended to provide full redundancy in the case of EPM adhesion failure, and thus we have designed TESSERAE to withstand the full 14 PSI (for consistency with ISS conditions), or up to $9.7x10^{4}$N of air-expansion force along a tile's bonding edge (Figure 8). The tile bonding surfaces will be augmented with deformable gaskets to allow for press-sealing upon actuation of the clamp. Clamps will latch closed, without requiring constant power to maintain fixed position. This approach is comparable to the 16 connecting bolts used to secure the latching mechanism for the Common Berthing Mechanism (CBM) on the ISS [24].



Sample calculations for hexagon tile:

$F_{air\ total} = 96.5\text{kPa} \times 6\text{m}^2 = 5.8 \times 10^5$ N

$F_{air\ @\ edge} = F_{air\ total} \div 6 = 9.7 \times 10^4$ N

For force balancing, $F_{air@\ edge} = F_{clamp} \times \cos(\Theta)$

Therefore, a clamp system acting normal to the bonding face, where $\Theta = 71.3°$, must exert:

$F_{clamp} = 3.0 \times 10^5$ N (repeated at each edge)

Figure 8. Shows simplified force model at tile edge, cross-sectional view. Outward force due to pressurization can be modeled as distributed evenly along the edges of a pentagon or hexagon, respectively. Presented previously in [6].

While the clamping of many additional "seams" may at first seem an over-complication compared with the unibody cylindrical modules currently deployed in orbit, we explicitly accept the challenges that these seams present in an effort to preserve the re-configurability and modularity of the structure. We aim to be able to detach and re-attach tiles as needed—to replace damaged wall segments, trade out sub-systems that may be attached to these tiles, re-position operational mission elements like air-locks to meet an incoming re-supply trajectory, et cetera (as described in [6]).

4.3 Power Budget

We anticipate covering the outer surface area of each TESSERAE tile with solar panels to supply power for EPM actuation, sensing and clamping during assembly. Additional wing arrays of solar panels can be deployed outward, away from the structure (in the model of the ISS arrays), to support power draw for life support systems and other habitat functions.

The outer surface of TESSERAE yields 169m^2 of available area. We will assume only 90% of this area can be fully templated with solar cells, leaving a total working area of ~150m^2 (or 5.4m^2 each for 20 hexagons, 3.6 m^2 each for 10 pentagons). Assuming comparable energy yield to the ISS in W/m^2 (84-120kW out of 2500m^2 of array, gives ~33.6-48.0 W/m^2 [25]), and working with the surface area on individual tiles, we would conservatively anticipate between 120-173W for the pentagonal tiles and 182-260W for the hexagonal tiles.[2] While tiles will harvest varying levels of energy individually due to varying incident sunlight angles, an approach for maintaining electrical connection through the magnet bonding pairs will allow us to transfer power between tiles and redistribute as needed to batteries.

At this level of power generation, with modest onboard power storage for each tile, we can supply the necessary power draw for intermittent actuation of the EPMs (see section 4.4) and always-on low power sensing (see Ekblaw [7]) during self-assembly. To supply the power needed for the clamp actuation after structural assembly is complete, all tile batteries will need to recharge over 1-2 orbits (in LEO) before executing the latching tasks, depending on final battery selection.

4.4 Electromagnet Mass and Strength Considerations

When analyzing the feasibility and practicality of embedding electro-permanent magnets (EPMs) on each bonding face of each tile, we must consider both mass and holding force (minimizing the former, while maximizing the latter). As prior ESA analysis on inter-satellite coulomb forces [26] has shown, micro-Newtons are sufficient to effect satellite swarm configurations and gradually move objects in a microgravity environment over tens of meters. This is comparable to the max distance expected between TESSERAE tiles while assembling,[3] with the containment membrane keeping the tiles within this bound. We have identified several widely available, industrial EPMs with holding forces in the hundreds of Newtons, and mass under 1kg [27], [28] (testing underway to determine field strength and force of attraction at various distances). EPMs can also be custom designed, tuning the magnetic material, cross sectional area and other

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[2] The quoted energy yield is a conservative estimate, given advancements in photovoltaics since deployment of the ISS solar panel cells.

[3] Because TESSERAE units are not uniform, idealized spacecraft units as described in the ESA report, we do anticipate needing slightly greater force to effect translations between tiles; this should not be mass-prohibitive to achieve however, given commercially available EPMs and options for custom development.

parameters to achieve high capacity adhesion and attractive forces [29]. At this mass order of magnitude, all 12 EPMs on a hexagonal tile would contribute less than 1% of the tile's total mass (based on the mass estimate using Columbus module shell density, section 3.2.2). The sample EPMs in question draw power in the 30- 70 Watts range and would be pulsed "on" (thereby de-magnetizing the unit and breaking away from any currently bonded element) only briefly during error state management and disassembly (as described in Mission Architecture section 3.1.1, and 3.1.2). This commercially available magnet line and prior examples of magnetic docking and electromagnetic formation flight (cited previously in 3.1.1) suggest we can design a custom EPM for TESSERAE that will be low in mass and power draw while still having ample strength for actuation and assembly purposes.

4.5 Guidance, Navigation, and Control

While TESSERAE, by design, does not require active propulsion navigation nor extensive attitude control during assembly, certain control systems are still needed to shepherd the tiles towards desired configurations (hence the "quasi-stochastic" label). Rather than conventional GNC hardware (CMGs, reaction wheels, etc.) we intend to employ a supervisory sensing algorithm (section 2.3) and swarm-based adaptive control of the tile interactions via on-demand actuation of the EPMs. As described in section 3.1.1, we can use the EPMs to selectively apply torques, buffer tiles away from each other, and correct meta-stable error states. For example, we propose to address entrapment (tiles trapped inside a nearly-closed module) by exchanging both local and global state information between tiles, detecting and diagnosing the entrapped state via proximity sensors and tile-tile bonding logs, detaching tiles to make an escape path and actuating torques to induce motion of the trapped tiles back through the opened hole. Ideally, entrapment can be avoided from the beginning via the holster deployment method that facilitates accretion piece by piece into the desired topology. While less deterministic than using propulsion and active control to guide tiles, the TESSERAE adaptive swarm architecture approach entirely avoids the payload weight and consumable-resource-constraints associated with traditional GNC systems. For more on our evolving swarm communication approach, please refer to [8].

As a brief aside on the GNC issue of tiles colliding destructively—we are designing the tile release mechanism and elasticity of the containment membrane to keep tiles at standard docking speeds (e.g. around 0.0325 m/s [30]) relative to each other. Further design studies will be undertaken to determine whether single-material or multi-material elasticity gradients can be used in the construction of tiles to provide buffering upon first collision, while maintaining an overall rigid body.

4.6 Timescale of Assembly

To serve as a practical space structures deployment protocol, the TESSERAE system must be able to self-assemble efficiently. We are currently targeting assembly completion in under 8 hours. In parallel to the physical prototype development and system engineering, we are undertaking extensive modelling and simulation to accurately predict the timescale of assembly in orbit (discussed in future work in section 5). Small scale tests in short microgravity periods (parabolic flight test discussed in more detail in 4.7) show that proximate TESSERAE tiles within a few centimeters distance from one another snap together in a matter of seconds. A paper on 2D stochastic assembly out of the Bachelet Lab [2] shows that a system of 18 custom-joint blocks self-assembles in 1-2.5 hours with 50% reproducibility, even while fighting gravity. In this system, exact neighbors must find each other; we take a more bonding-favorable approach, working with the minimum number of unique tile joints (currently only two types) to ensure each tile has a high probability of finding a neighbor tile with which it can pair.

It is a well-known behavior of stochastic systems that the last 10-20% of the assembly can take 80-90% of the assembly time (essentially the "hole filling" problem). We note several mechanisms by which to address this: a) as the final step, hole-filling can be achieved by reserving one tile in the dispensing holster, released and directed toward the remaining area to be filled, b) through selective use of the EPMs, we could torque and direct both the tile and the partially-assembled module towards each other, c) design the annealing ramp conditions to produce two halves or four quarters that can come together easily without producing a hole to fill, d) introduce extra, redundant tiles into the assembling system, so that a final hole is not waiting for a single tile to circulate nearby.

4.7 Preliminary Test Results

As discussed in Ekblaw [6], a scaled-down, proof of concept TESSERAE prototype was deployed on a parabolic flight over 20 parabolas (Figure 9). One set of 32 TESSERAE tiles was deployed in Box 1 (46cm cube), and a second set deployed in Box 2 (36cm cube) to test the effect of containment volume (as a function of TESSERAE module diameter) on self-assembly behavior.

This test validated the feasibility of stochastic, magnetically-mediated, microgravity self-assembly in a contained volume. Our test results established a clear pattern of 3D self-assembly error modes and meta-stable states (see Figure 10) that we can now preemptively design against in our quasi-stochastic prototypes. While prior art has extensively analyzed 2D assembly and characterized geometric bonding patterning [31], [32], [33], [2], we believe TESSERAE to be the first microgravity-based, three-dimensional self-assembly system; we are thus interested in fully characterizing both desirable and undesirable states as we tune parameters that affect stochastic behavior in three dimensions.

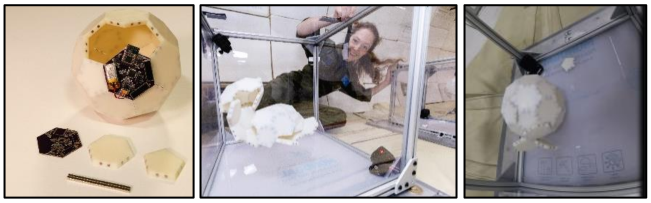


Figure 9. Proof of concept hardware model with sensing prototype (L); Tiles loose and assembling in zero g (middle); Tiles near-full assembly (R).

Speaking to the time-scale of assembly predictions, we noted that both self-assembly tile systems (Box 1 and Box 2) reached an equilibrium state after two-three microgravity parabolas (~60 seconds of microgravity total); the tile bonding pairs and clumping groups established by this point did not materially change through subsequent parabolas. This suggests two conclusions: first, that the magnet-mediated self-assembly bonding progresses rapidly to an energy favorable state when adequately contained; second, that active error control must be included to correct for local minima structures and keep the assembly progressing towards the desired topology.

With favorable implications for future on-surface deployments, we were able to fly two Martian gravity (~1/6 Earth gravity) parabolas and observed that proximate dyad pairs (a pentagon and hexagon) were able to snap together from resting position on the floor surface. While tiles could not further combat gravity to accrete upwards on the structure, this base-level attraction speaks to the ease with which magnet assembly can facilitate on-land construction (provided the force of magnetic attraction is strong relative to the force of gravity acting on the tile).

The next evolution of TESSERAE hardware, testing responsivity and the EPM actuation, will be deployed on a second parabolic flight in March 2019 and on a suborbital flight (3 minutes of continuous microgravity) in Q2 2019.

5. CONCLUSION

The engineering system design, ConOps mission design, and mission feasibility review have been presented for the TESSERAE self-assembling space architecture research. Comparative analysis with existing ISS modules and the BEAM inflatable habitat shows that TESSERAE offers newfound mission flexibility through re-configurability at the shell layer, autonomous in-orbit construction and easy of re-use for on surface habitats. Through efficient flat-packing of the modular tiles, TESSERAE can transform from a highly-efficient, closed volume in a rocket payload fairing or EDL craft to a much larger, spacious operational volume. TESSERAE's reliance on a quasi-stochastic process saves on mission cost and complexity by avoiding Astronaut EVAs, propulsion and fuel payload weight, and traditional GNC; we project that, even without these deterministic control approaches, TESSERAE can self-assemble in an efficient

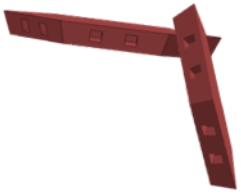
3D Error Modes	Description	Diagram
1	Correct tile-tile bond, but one tile is inner/outer surface inverted (forming a flat dyad, rather than sloped curvature, with bonding faces co-incident but an inner surface facing outward). Stable, requires active intervention or alternative EPM polarity map.	 Left: Correct (outer and inner surfaces are consistent) Right: Error mode (outer and inner surfaces are flipped)
2	Metastable (one magnet from each side bonds, leaving tile bonding faces co-planar but not co-incident). Easily perturbed and intermittently corrected by physical collisions; best to address with active intervention for efficiency of assembly.	
3	Clumping (magnetic interactions outside the magnet-magnet bonding axis allow tiles to lightly clump across other surfaces; this behavior is not observed in gravity environments). Easily perturbed, effectively addressed by magnetic shielding on non-bonding surfaces.	

Figure 10. Error mode descriptions for TESSERAE stochastic assembly (without EPM error correction).

and mission-practical timescale.

Ongoing work focuses on modelling and simulation to predict on-orbit assembly dynamics over a range of deployment contexts: various target structure sizes and tile dimensions; varying magnet strengths and polarity arrangements; various assembly-containment volumes; and tunable “stirring energy” perturbations.

Future work will explore generalizable, microgravity self-assembly for different shapes (e.g. tori). Testing will progress through parabolic flights, suborbital and orbital environments. Through the TESSERAE research, we aim to create a new paradigm for space architecture that can support a growing human presence in space and respond with agility to evolving mission needs—one that leverages self-assembly and efficiently-designed stochastic processes. We hope to contribute a suite of novel technologies that brings innovation to space structures development in the near term, while also shaping a bold vision for human life and work in orbit--wherever our orbits may be.

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