IASS 2018 BOSTON, JULY 16-20
CREATIVITY IN STRUCTURAL DESIGN

Proceedings of the IASS Symposium 2018
Creativity in Structural Design
July 16-20, 2018, MIT, Boston, USA
Caitlin Mueller, Sigrid Adriaenssens (eds.)

TESSERAE: self-assembling shell structures for space exploration

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Abstract

The future of human habitation in orbit lies in self-assembling, adaptive, additive and inflatable structures. Freed from the constraints of Earth gravity, we can explore innovative shell structures and redefine the very terms that have traditionally grounded architecture (floor, wall, ceiling, arch, et cetera). Space-based digital fabrication and autonomy in architectural assembly help us avoid gantries, mechanical assembly cranes, and the limitations of single-purpose modules. These new paradigms of construction facilitate crucial engineering benefits, from lowering launch payload weight, to reducing assembly complexity, to revolutionizing space-structure modularity. Our research proposes a multi-year effort to study, characterize, prototype, and deploy self-assembling space architecture or TESSERAE (Tessellated Electromagnetic Space Structures for the Exploration of Reconfigurable, Adaptive Environments). In this conceptual design paper, we describe the TESSERAE tile components and self-assembly shell design, we discuss at scale, in orbit deployment considerations, and we present preliminary test results from a proof of concept Zero Gravity flight.

Keywords: geodesic domes, self-assembly, stochastic assembly, space exploration habitat design, extra-planetary architecture

1. Introduction

As humanity prepares for the commercialization of Low Earth Orbit (LEO) and interplanetary civilization, we face an opportunity for a renaissance in space habitat design. Space architecture, to this point in history, has been dominated by just a few prominent examples: SkyLab, Mir, Tiangong, and the International Space Station (ISS). These structures nearly universally rely on pre-fabbed, cylindrical modules with bespoke module-to-module interfaces. Given the anticipated rise in orbital space travel ("space tourism"), the renewed focus on manned Martian exploration missions, and NASA's transition plan for space habitats from government-run to commercially-managed [1], we are faced with the prospect of a proliferation of orbiting space stations in the next decade. This beckons for a holistic evaluation of space architecture: how can we build safer, more efficient, reconfigurable and adaptable—and perhaps even inspiring or enlightening—space structures?

Modularity and re-configurability in a structure offer a promise of cost-savings (from re-using materials and interchanging a standard set of parts) and mission flexibility (ability to rebuild the structure at whim to meet updated operation requirements). We see this philosophy emerging across the aerospace industry, from reusable rockets [2] to modular space structure design [3]. Self-assembling architecture proposes one such model for the next generation of zero gravity habitats and science labs, with modularity and re-configurability inherently baked in. The new wave of space architecture will likely remain shell-based, due to the surface area-to-volume ratio benefits of avoiding corners (space deployments need to optimize enclosed volume for a given surface area, as less building material dramatically reduces launch costs) and due to the unique affordances of zero gravity (less focus on traditional weight-bearing walls). To bring autonomous self-assembly into this shell-dominated architectural context, we are exploring tessellation and multi-part structure aggregation strategies.

In particular, the mechanism of self-assembly for "energy favorable" structural configurations offers a compelling new construction paradigm. We note a growing potential for efficiently packed units that assemble stochastically or robotically, without manual, astronaut intervention. Structures need not be "purpose-built," single use modules, and should instead feature extensible units that support reconfigurable architectures by dynamically detaching and reattaching in on-demand geometries. Self-assembling architectures will be based on fundamental assembly units, or tiles, that provide enough degrees of freedom for multiple structural arrangements while retaining the required specificity to generate a predictable suite of desired shapes. Into these tiles, we can natively embed sensor networks that bring extra-planetary architecture into the realm of truly "responsive environments." Space architecture of the future should enjoy a rich melding of engaging and enlightening architectural design, flexible and reconfigurable construction modalities, and the intelligent feedback systems supported by thoughtfully integrated sensor networks.

The TESSERAE research, or Tessellated Electromagnetic Space Structures for the Exploration of Reconfigurable, Adaptive Environments, proposes a model for self-assembling, orbiting architecture built from standard base unit tiles. The "TESSERAE" name and nature of the structure hearken to the small, colored tiles used in Roman mosaics, where many standard pieces, or "tesserae," interlock to create a larger piece. We make this reference to ancient history, when designing an artifact of our space exploration future, to tie architectural elements together across scales and across millennia.

In the aerospace structures deployment context, the geometric tiles that form our TESSERAE shape will self-assemble stochastically through magnetic jointing to form a structural whole (figure 1). The tiles are designed to be released into a temporary, inflatable container and allowed to float free. Tunable magnet polarity (controlled via current coursing through an electromagnet) on the tile bonding faces mediates which tiles bond to which neighbors. By precisely controlling the beveling angle between tiles, or the "dihedral angle" in a chemistry context, we can drive the assembly towards an energy-favorable final geometry. The constituent parts then passively, stochastically self-assemble into a holistic structure, without requiring propulsion or guidance & navigation control. Embedded, custom sensor networks on each tile provide feedback on the status of self-assembly.

For our initial prototypes and space deployment launches, we have chosen the "buckyball" structure as the target assembly shape. The buckyball molecular structure recalls the architectural geodesic dome of Buckminster Fuller [4], a shape that describes both an energy-favorable configuration state in nature and a visual form that has intrigued imaginations for decades. The buckyball sphere approximation offers highly efficient space-filling options (optimizing enclosed volume for a given surface area—a key consideration for aerospace orbiting deployments). We are pursuing a hollow shell approach, to fulfill space exploration mission needs for an internal habitation area or operational staging base. An example mission concept supports Mars surface operations with multiple, interlocking TESSERAE acting as an orbiting base (Mars Orbiting Self-Assembling Interlocking Chambers or "MOSAIC") (figure 1).

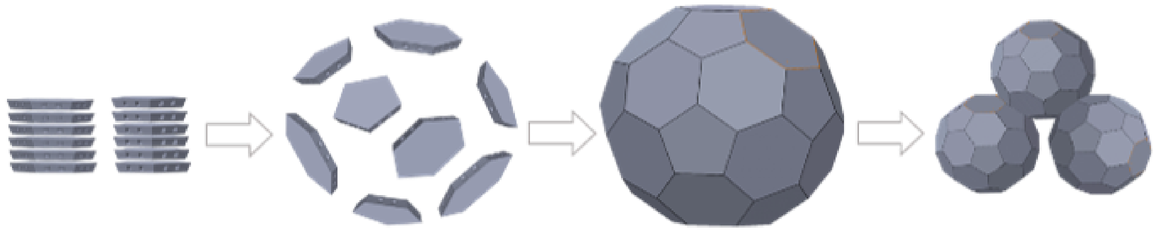

Figure 1. (L to R) Packed flat for launch → free floating tiles → TESSERAE assembly → MOSAIC

2. Background

This self-assembly architecture concept builds on prior work in several fields, including materials science, mechanical engineering, architecture and design, and bio-inspired robotics. The MIT Self-Assembly Lab explores self-assembly in a bio-inspired context, with plastic "chiral assemblies" that are shaken stochastically into final form to simulate biomolecular processes [5]. Without the need to counteract the force of gravity, we anticipate that similarly modeled base units (in our case, polygon tiles with magnet joints) will assemble in much shorter time-scales. Neil Gershenfeld's lab in the Center for Bits & Atoms has demonstrated innovative assembly and reversibility protocols for lattice structures, notably carbon-fiber reinforced units that feature reversible shear clip joints [6]. We consider a similar principle, relying instead on magnets to provide joint connection and subsequent detachment flexibility.

At habitat scale, we note several pre-existing inflatable container concepts, such as the Bigelow Expandable Activity Module (BEAM) [7] and their next generation B330, an autonomous, stand-alone space station [8]. We also note related work in origami and unfolding structures [9], and are exploring this design paradigm as a complement to the self-assembling primary structure. While our main approach for self-assembly and structure force balancing remains distinctly different from recent tensegrity-based approaches, we note extensive prior art in the area [10], and may adapt these principles for internal tensioning as discussed in section 4. While other pre-constructed geodesic dome objects have been sent into orbit for artistic or demonstration purposes, we believe TESSERAE to be the first proposal for an operational, reticulated shell space habitat, and the first proposal for a buckyball form-factor to be constructed via self-assembly in orbit.

3. System design

The buckyball TESSERAE shell can be assembled from 12 pentagonal and 20 hexagonal tiles, with several tile features to constrain the geometry and ensure a successful assembly.

The mechanism of self-assembly relies on magnetic jointing between the tiles. Each tile edge is beveled at the proper dihedral angle to establish the expected buckyball curvature, as tiles begin to bond together. This beveling establishes a flush mating surface and exposes recessed magnets on each mating edge that draw tiles together for bonding (see figure 2). The spatial configuration of North and South polarity for these paired magnets defines a system of mating joints, guiding the proper neighbor tiles towards each other, and reducing the likelihood of incorrect tile binding (e.g. matches that might lead to a partial, incorrect, or clumping shape rather than the full assembly).

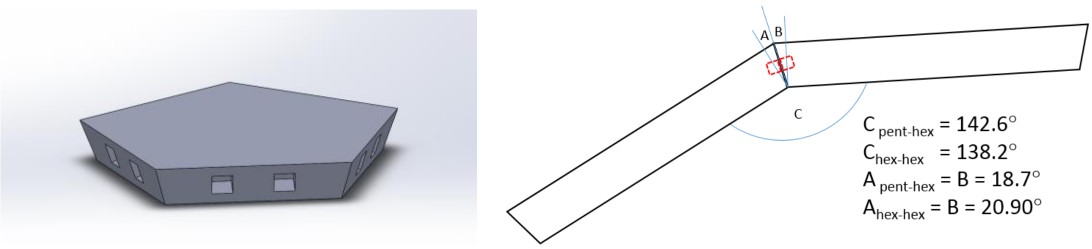

Figure 2. A sample pentagon tile with recessed holes for magnets on the bonding face (Left). Dihedral bonding angle C, with tile slope angles A & B shown in cross section for pentagon-pentagon and hexagon-hexagon tile bonding (Right). Hashed, red lines show the recessed magnet pair across tiles.

As further described in Ekblaw [11], our initial designs for the spatial magnet arrangements make use of the North-South polarity to define the minimum number of distinct joints that will force a C_{60} buckyball structure: one joint for pentagon-hexagon binding, one joint for hexagon-hexagon binding. This focus on joint-logic simplicity—finding the minimum number of distinct joints to constrain the geometry—is critical for optimizing the assembly probabilities in a stochastic system. Rather than every joint being unique, any two hexagons can bind together on certain faces and any hexagon can bind to any pentagon on the other faces (figure 3).

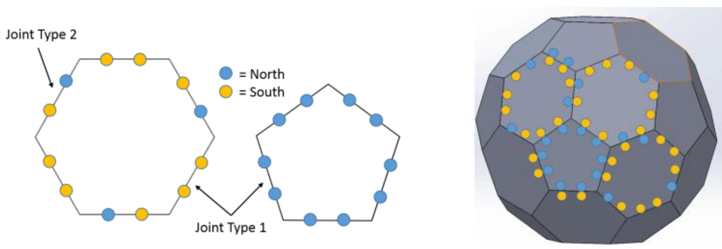

Figure 3. Polarity map for pentagon and hexagon tiles (Right). Application to 3D joints (Left).

Key to the modularity of the structure is the tunable nature of the magnet-magnet bonding: we are designing electromagnetic jointing to facilitate reconfigurable shapes. Turning magnets on or off in a controlled fashion will allow us to detach certain tiles, or reattach others, as needed for mission operations. This offers the flexibility of replacing damaged or worn tiles, replacing tiles that may be bonded to habitat functional systems (e.g., life support) in need of an upgrade, or dynamically reconfiguring the placement of interfacing tiles, such as airlocks and module-to-module mates, to allow for changes in overall space station shape and docking operation.

In addition to aiding in habitat-use flexibility, the integration of electromagnets facilitates error correction. In the event that two tiles have incorrectly bonded (e.g., due to a single point N-S bonding that does not match the buckyball shell surface topology) or a tile has been trapped inside a partial shell enclosure, we can reverse the polarity of the magnets in question and induce a repelling force to separate the tiles. When coupled with sensing to detect incorrect bonding, this error correction procedure can proceed autonomously. Akin to the magnetic levitation bullet trains, but at much lower speeds, we will be able to use tunable electromagnet polarities to guide tiles through physical space.

While we intend to keep the relative velocities of the self-assembling tiles quite low (in a contained, stochastic system), the electromagnets provide a useful buffering feature. Should two or more tiles approach each other with sufficient kinetic energy to cause destructive damage upon collision, LIDAR proximity sensing and accelerometer diagnosis data signals will automatically engage the electromagnets in question and actuate a multi-point repelling response (across all exposed, pairwise magnet faces in play) to buffer the impending collision.

Finally, the electromagnets can also aid in perturbing the system, should the stochastically-assembling tiles settle into a local minima energy state without completing assembly. By cycling the polarity of various bonding-face electromagnets (or by perhaps also including boundary enclosure electromagnets on the inflatable container surface), we can induce motion back into tiles that were at rest, and improve the continuing circulation of the swirling tile system.

We acknowledge that continuously powering electromagnets would necessitate an infeasibly large power budget. To avoid such excessive use of power, we will use LIDAR proximity sensors in a low-power, always-on operating state to detect when proper neighbor tiles have come into close-enough contact. Upon reaching close proximity, the system will deploy the "bonding activation energy" and engage the electromagnets to complete the tile-tile assembly. We use this principle of selective electromagnet actuation across the system—the default state for electromagnets will be "off", unless the system detects a correct tile-tile bonding opportunity, a need to reverse an incorrect bond, a need to buffer an impending collision, or a need to perturb the system to induce greater tile circulation. The "watchdog" software to achieve this holistic system knowledge is based on a mesh-networking design, where each tile is augmented with natively-embedded sensing and a Bluetooth Low Energy (BLE) communications chip. For a discussion of the sensor node design, communication architecture, and early sensing prototypes, please see the Paradiso Lab's recent AIAA SciTech paper [11].

4. Deployment at scale, in orbit

To explore this system in a deployment context, we model an example TESSERAE system with tiles of side length equaling 1.52m (5ft), thus yielding an interior volume of 196m^3 (6910 ft^3) with an interior open diameter of 8.7m (28.4ft) (following the formulas for volume of a truncated icosahedron). To compare this with the International Space Station (ISS) and its component modules currently in orbit, TESSERAE's proposed interior pressurized volume would be approximately 20% of the full pressurized volume available on the ISS (916m^3, 32,333 ft^3). Due to varying requirements on use of space onboard ISS, the actual "habitable" volume is only 388m^3 (13,696 ft^3), split across multiple modules [12]. A single TESSERAE module at this sample scale would therefore offer around half of the total livable space of the ISS.

In comparison, the BEAM (Bigelow Expandable Activities Module), an inflatable module attached to the ISS for a two year testing period, offers a volume of 16m^3 (565 ft^3) with a mass of 1360kg (~3,000lbs) [7]. Our proposed TESSERAE deployment would offer a twelve-fold increase on this volume, and we will continue to explore material choice and shell thickness to achieve a comparable weight. Were we to keep to the TESSERAE to BEAM volume ratio, we would aim to keep TESSERAE under ~16,300kg (36,000lbs). Realistically, TESSERAE should pursue material design choices to lower the weight even further, as we wish to continue the approach of lower-cost, flexible and adaptable modules in orbit.

Because we have decided to turn off the electromagnets after assembly, we are not counting on any magnetic attraction force contribution between tiles during steady-state operation and will instead rely on clamps. Industrial strength clamps can be powered down and still exert their holding force. The separation force due to habitat pressurization that our clamps must withstand scales with a^2, where a = length of the truncated icosahedron edge segments, thus incentivizing minimizing internal surface area.

At this scale, with tile surface area dimensions of $4m^2$ ($43ft^2$) for pentagons and $6m^2$ ($65ft^2$) for hexagons, and an interior pressurization of ~100kPa (14psi) for consistency with ISS conditions, we expect an air-expansion force ranging from 7.7×10^4 N to 9.7×10^4 N acting along each tile's bonding edge. Planning for the highest of these anticipated forces (along the hexagon-hexagon joints), and taking into account the component angles along which an example clamping device would act, we anticipate a required total clamping force per tile bonding edge of 3.0×10^5 N. Comparable clamping forces are already seen in industrial use, and such hardware could be modified for use with TESSERAE [13]. The clamping channel between the mating face of tiles will be augmented with a gasket to aide in sealing strategies. Additional sealing strategies (reversible chemical binders, or internally inflated air-tight chambers) are under consideration as well. See figure 4 below for a diagram of the simplified clamping and air expansion forces at the tile boundaries.

Sample calculations for hexagon tile:

$F_{air\ total}$ = 96.5kPa × $6m^2$ = 5.8×10^5 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 Θ = 71.3°, must exert:

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

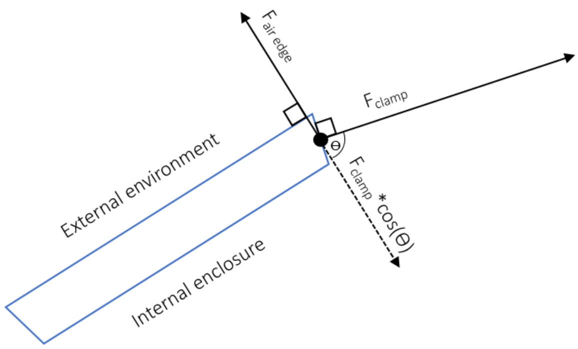

Figure 4. Showing simplified force model at tile edge, cross-sectional view. Outward force due to pressurization can be modeled as distributed evenly along the five or six edges of a pentagon or hexagon, respectively.

While the addition of so many additional "seams" or edges may at first seem an over-complication compared with the simpler cylindrical models 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 intend to be able to pop tiles on and off 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 a new mission need or incoming re-supply trajectory, et cetera. We are also exploring a buckyball skeleton frame (bars at all edge segments, empty between) where tiles can self-assemble into the negative-space slots and plug into respective hexagon and pentagon holes. If plugged from the inside, this frame and parts ensemble we will benefit from the air expansion force pushing the tiles into their frame slots, thus reducing required clamping action.

Beyond the primary focus on clamp-reinforced edges, we are exploring a second approach relying on tensegrity-tensioned cabling. Rather than affixing each tile to proximate neighbor tiles, we could tension opposite tiles along centerlines of the buckyball by attaching paired cabling. This cabling would inherently balance the forces, as opposite tiles are pulling away from each other along a shared centerline due to the internal pressurization. Fortunately, the geometry of the buckyball ensures that each tile has a perfect paired tile at a shared centerline across the sphere. This approach complicates the self-assembly process however, adding an extensive set of steps where cables must be deployed internally after the initial geometry is set, and prior to pressurization. While numerous approaches could be envisioned (autonomous deployment of cables in a controlled harpoon or grappling hook fashion, automatically extending telescoping rods, etc.), this approach raises a number of engineering challenges, from attachment point robustness concerns to order of operations for cable deployment to avoid tangling. A network of crisscrossing cables also places constraints on how the interior volume can be used, and may inhibit efficient use of the space.

While the fully expanded TESSERAE, at these particular dimensions, would constitute a large spherical volume for interior use, the individual, separate tiles can pack tightly into a condensed volume for launch. This vastly improves the prospects of deploying architecture with dimensions greater than that of the rocket fairing. This is one example of escaping the "gantry-limitation" model, where architecture can only be as expansive as the largest constraint on the building—typically a gantry or crane, or in a space context, the size of its "ride" to orbit (figure 5).

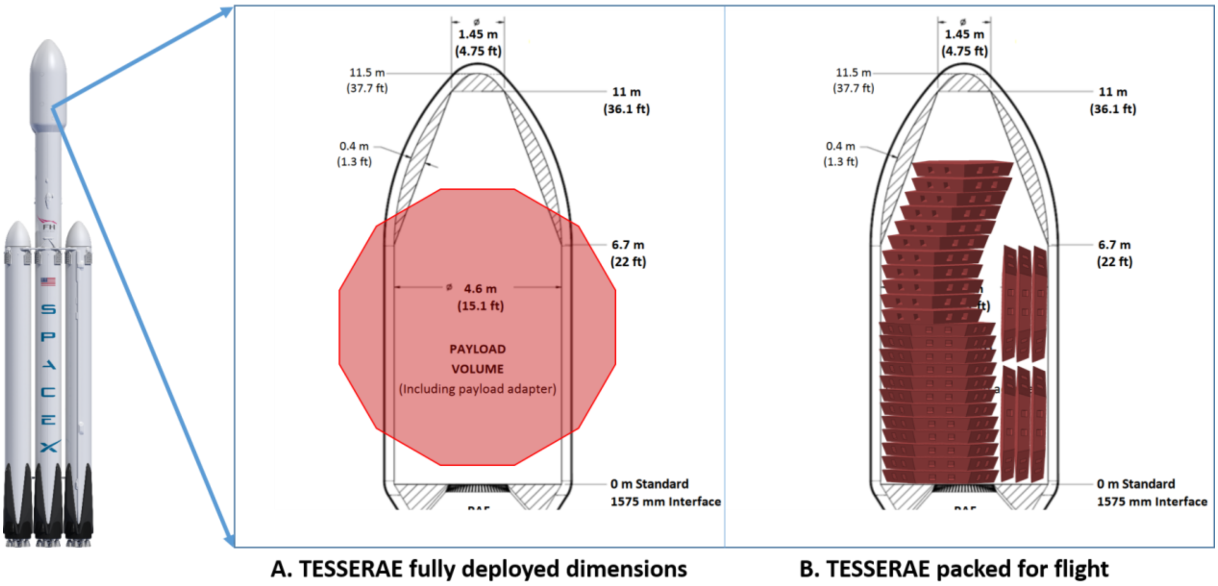

Figure 5. Scale comparison of fully deployed vs. stacked TESSERAE, in Falcon 9 Heavy [2] payload fairing.

These various estimates for deployment size and associated applicable forces are reported as illustrative examples. The first TESSERAE model deployed in orbit for testing will likely be a 1:10 or 1:20 reduced scale model, to allow the entire deployment to take place inside experimental chambers on the ISS. Though this paper primarily address the physical dimensionality and mechanical assembly approach for the TESSERAE structure, there are many 2nd order considerations to take this from a shell to a fully functioning habitat. To briefly address two key issues, both internal pressurization robustness (faith that the interior volume is safe) and radiation mitigation will be addressed in this design. Inside the enclosed volume, we envision inflating a fabric-like, air-tight chamber to provide redundancy via double containment (this presumes we have used the clamping approach, rather than tensioned cabling). For radiation protection, we are actively comparing passive materials and active radiation shielding (liquid shielding that can be directed towards a certain subsection of the shell on-demand) built into each constituent tile.

5. Preliminary testing

As we work towards deploying a TESSERAE prototype in orbit, we begin with iterative proof-of-concept tests. This testing regimen marries various operational environments with the experimental testing parameters that shape self-assembly system dynamics in the absence of gravity. For the former, we will progress through a number of increasingly applicable deployment contexts—from brief periods of microgravity on parabolic flights, to months-long deployment aboard the ISS—each with unique operational constraints. For the latter, we have identified four, key experimental parameters that influence the assembly completion percentage over a given time-scale: containment volume; "crystal seeding" or introducing group tile clusters that aid in "crystallization" and formation of correct shell geometries; extent of tile circulation within the containment volume; and kinetic perturbance approaches to combat premature settling. These parameters map closely to: boundary conditions (containment), initial conditions (seeding), system input energy (circulation), exogenous additional energy to course-correct (kinetic disturbance).

This combination testing allow us to characterize TESSERAE before investing in the hardware, team resources, and launch costs typically associated with a habitat-class space mission. In our recent Zero Gravity flight (November 2017), we tested two identical prototype tile assemblies, at a 1:53 scale to what was discussed in section 4. The tile edge length was 2.86cm, with a total volume (internal void and shell) of $1293cm^3$. Passive, neodymium magnets serve as the jointing mechanism, as testing at this stage was focused primarily on validating the mechanical concept and assembly time-scale. Experimental parameters were kept constant between the two tile assembly deployments, with the exception of volume (46cm x 46cm x 46cm for the first cube, 36cm x 36cm x 36cm for the second cube), as we intended to test the effect of containment volume on the dynamics of assembly. These volumes were selected based on the anticipated buckyball outer diameter of 18cm, to explore whether additional free space facilitates quicker assembly via greater flexibility in tile rotation and circulation exposure, or whether it inhibits assembly by providing too much space for tiles to settle away from one another.

Figure 6 shows the experimental deployment scenario, from modeling expectations to a partially-assembled structure at the end of several parabolas. Tiles are arranged in a pre-set pattern on the floor of each box, and rise up freely at the beginning of each parabola. The oscillation of the gravity environment in the plane provided an informal "kinetic perturbance" for the system, ensuring that tiles were jostled significantly into interaction with neighbor tiles. Throughout the course of the flight, we tested three scenarios: a) all tiles separate at start, b) a seeding method where 3-5 tiles were pre-assembled in groups, and c) a hole-filling test, where the majority of tiles have assumed the buckyball geometry and a few final tiles must find the remaining binding sites (shown in figure 6 far right).

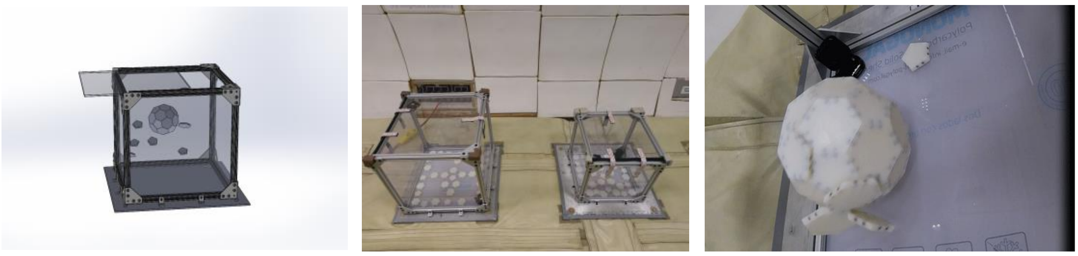

Figure 6. Experimental test apparatus for microgravity flight (Left/Center), assembly behavior example (Right).

While the Paradiso Lab AIAA SciTech paper discusses these results in detail [11], we note two key takeaways from a shell architecture perspective:

1) Baseline Performance: Even without the assistance of electromagnetics, we were able to confirm the efficacy of our magnet joint polarity design and validate the fundamental assembly mechanism. Tiles were drawn together over a separation distance of 1-2 inches, over the 10-15 seconds of true microgravity on each parabola. Longer microgravity periods will be needed to conclusively determine the optimum containment volume as a function of fully-assembled TESSERAE module volume.

2) Erroneous Behavior: While the system yielded partial-shell fragments of the intended assembly curvature, we also noted extensive clumping. This was due to magnetic interactions outside the exposed bonding face, as the force of magnetism acted through the plastic layers. Fortunately, we can mitigate this straightforward issue by thickening the tiles and increasing the distance, r, between the embedded faces of magnet that should be non-interacting. Due to the scaling of magnetic force with $1/r^2$, even a small distance increase yields a significant drop-off in attraction between tiles. The addition of electromagnets in future prototypes will also help to address this via the error correction mechanism (on-demand repelling actuation), and enable us to avoid over-thickening the shell tiles.

6. Conclusion

The shell design for the TESSERAE self-assembling space architecture habitat has been proposed, and situated in an example orbital deployment context. Preliminary testing results from a recent microgravity flight validate the mechanical self-assembly approach and suggest opportunities for refinement of the base tile units. Future work will focus on extensive modeling to understand and characterize the tiles' stochastic assembly dynamics over a range of orbiting environments, for various target structure sizes, for certain magnet strengths, and for various assembly-containment volumes. While we have initially focused on the buckyball geometry, we note many shell geometries of interest for space habitats. Rotating tori, for example, are often proposed for induced-gravity environments and the TESSERAE project will soon expand to consider tessellation approaches for these and other shapes. The next round of prototype testing will include a Blue Origin Sub-Orbital flight contracted for Fall 2018. This platform offers 3 minutes of uninterrupted zero gravity for prolonged assembly-dynamics observation. Through subsequent testing and iterative development, we aim to develop a suite of autonomously-assembling shell structures that offer modularity and re-configurability while simultaneously reducing cost and human-mediated construction risk for in-orbit space stations.

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