Self-Assembling Space Architecture: tessellated shell structures for space habitats

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As habitation and operation needs evolve around new commercial space stations in LEO (Low Earth Orbit) and exploration missions to the Moon and Mars, space architecture must adapt to address new use-case and deployment contexts. Rather than relying on fixed, rigid shell or fixed, inflatable modules, a new paradigm for modular in-space construction can offer adaptive, reconfigurable, and re-usable outer shells. Our tessellated shell structure approach proposes multifunctional tiles (structural units augmented with sensing, guidance navigation and control, and shielding) that assemble autonomously via magnetically-mediated bonding along regular, geometric edges. We propose an extensible paradigm for in-orbit space habitat construction via quasi-stochastic self-assembly in microgravity and discuss re-purposing these shells for surface deployments as well. This 2019 AIAA SciTech paper details our v2 TESSERAE prototype design (building on the v1 system presented in our 2018 AIAA SciTech report), including the integrated sensing and GNC approach, progress on proof-of-concept prototypes with accompanying simulation models, and extensibility to other shell tessellations and multi-module space station polyhedral packing arrangements. This research serves as a technology demonstration mission, presented for this paper in the context of an upcoming suborbital deployment test.

I. Introduction

To address the changing ConOps (Concept of Operations) for space architecture, in anticipation of LEO space tourism and NASA's strategy for manned exploration missions to the Moon and beyond [1], we propose the TESSERAE (Tessellated Electromagnetic Space Structures for the Exploration of Reconfigurable, Adaptive Environments) architectural modules (see Fig. 1). This approach to space architecture relies on multi-part, modular construction from a standard suite of base units (structural sides, airlocks, docking ports, etc), that can be reconfigured on-demand with LEGO-like interchangeability. TESSERAE structures are intended to provide agile modules that can be packed flat during launch, assembled in orbit, reconfigured as needed (e.g., add a new docking port on demand, if a second craft arrives), disassembled, and transported to a new orbit or surface landing site for re-assembly and re-use. Entire TESSERAE modules can also be docked together for larger total volume space station configurations, in densely packed crystalline-like arrangements.

To achieve this level of modularity, the outer structural shell of the module must be tessellated and segmented into separate units. TESSERAE modules are designed to self-assemble in orbit from a "tile set" of regular polyhedral base units. The particular tile geometry (number of sides, tile thickness, dihedral side-slope angle, etc.) and number of units define a targeted macro structure when fully assembled (e.g., 12 pentagons and 20 hexagons form a buckminsterfullerene [2], or 8 hexagons and 6 squares form a truncated icosahedron, see Fig. 2). Our initial

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investigations and prototype tests have centered on the buckminsterfullerene ("buckyball"), or truncated icosahedron. Due to the shape's close approximation to a sphere, we can achieve a relative minimization of surface area (reducing cost and payload weight) for a given interior, enclosed volume. TESSERAE tiles snap together via magnet-mediated joints; an intentionally designed spatial map of the magnet polarities (north/south) on each bonding face ensures that a minimum number of unique joints are constructed to ensure the target shape (e.g., only two joint types—Hexagon-Hexagon and Pentagon-Hexagon—are required for the buckyball). Minimizing the number of unique joints helps increase the probability that any two neighbor tiles are compatible and can bond along their proximate edges. While early prototypes [3] explored purely stochastic systems with permanent magnet jointing, current prototypes for deployment on a parabolic flight and a suborbital test flight in 2019 rely on quasi-stochastic, "self-aware" assembly. This involves a supervisory sensor network that detects and diagnoses tile-tile bonds and actuates electro-permanent magnets to facilitate correct bonds or detach erroneous bonds. Electro-permanent magnets provide a key power-saving functionality: the tiles are constantly drawn together through the steady-state, un-powered magnetic attraction between tiles, but can be separated by pulsing current through the electro-permanent magnet units to "neutralize" the magnetic field. Custom electro-permanent magnets can be designed with tunable mass to holding strength and field strength ratios [4], and we have explored commercially available EPMs [5], [6] for feasibility at in-orbit deployment scale [7].

Sections II and III present the latest TESSERAE proof of concept prototype and discuss related work in the two distinct fields that this research merges: self-assembly and space architecture. Section IV presents preliminary modelling results in microgravity deployment contexts (parabolic flight tests and suborbital flight tests). Section V discusses the extensibility of the TESSERAE approach to other geometries (both for surface tiling and space station docking). We conclude in Section VI with an analysis of wider benefits (storage, satellite condominiums, parabolic mirrors) and future work.

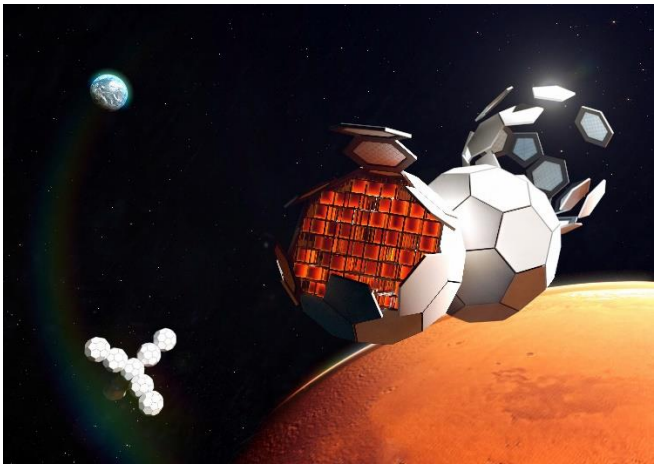


Fig. 1 Artist's render of TESSERAE concept, showing self-assembling module and multi-module space station in orbit around Mars. Image courtesy of collaboration with TU Dortmund Fraunhofer Institute.

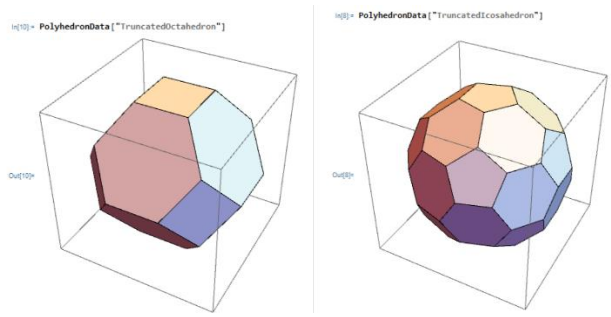


Fig. 2 Mathematica renders of the truncated octahedron (L) and truncated icosahedron (R), or buckyball. Both shapes are under consideration and testing for TESSERAE deployments.

II. System Design and Mission Operation

The TESSERAE v2 prototype design includes a multi-functional, 3D printed tile housing with embedded electro-permanent magnets (see Fig. 3), and a supervisory sensor network and rudimentary GNC algorithm for tile-tile bonding corrections (see Fig. 4). Below, we discuss the integration of these elements in our system design, and explain the intended ConOps for prototype testing on the suborbital test flight, with extensibility to a deployment in orbit.

A. System Design

The TESSERAE tile housing includes a 3D printed plastic shell of either five sides (pentagon) or six sides (hexagon), with recessed holes for two electro-permanent magnets (EPMs) on each face. A central motherboard handles: the EPM driving circuitry; wireless communication to a remote computer "downlink"; Time of Flight (ToF) ranging sensors for closing-distance calculation between tiles; an inertial measurement unit (IMU) to track relative position, rotation, and translation of the tiles; and interfacing with a peripheral sensing board on each tile edge. The peripheral sensing boards include a magnetometer (for detecting and diagnosing the electromagnetic bonding signature between mated tiles) and an RGB emitter/sensor pair to communicate between tiles bonding faces. Sensor data is gathered and analyzed through a multi-stage algorithm to actuate the EPMs as needed for control and correction (see Fig. 4). The EPMs dominate the power consumption (even though used only minimally to pulse "off" the magnetic attraction, per Section I) and an advanced lithium 9V battery has been chosen for capacity and flight heritage.

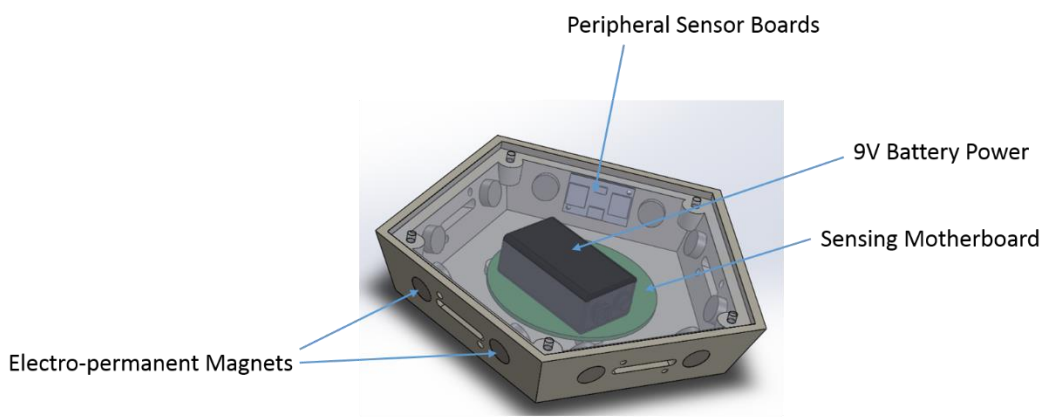


Fig. 3 TESSERAE tile prototype with transparent lid, showing interior components.

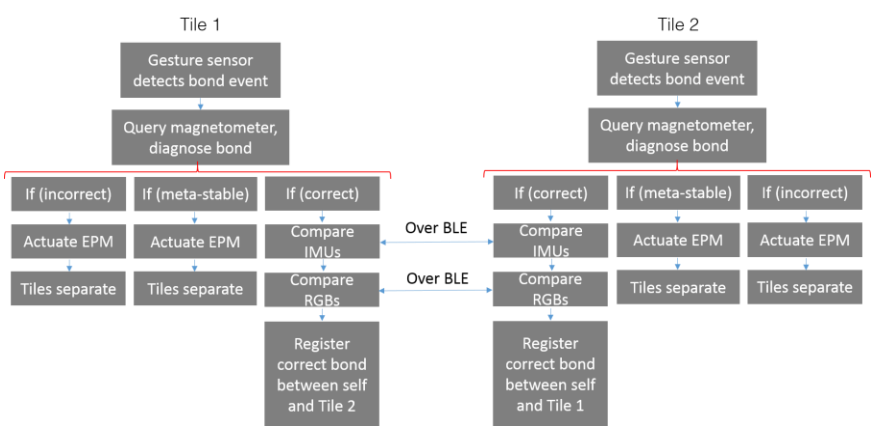


Fig. 4 TESSERAE's proposed bonding control and correction algorithm, including redundant checks to ensure incorrect bonds are not misidentified as correct bonds.

B. Mission Operation

For the suborbital launch, we are preparing the TESSERAE tiles to actuate the above GNC protocol repeatedly over three minutes of sustained microgravity. Three tiles (two hexagons and one pentagon) will be fixed rigidly against the sides of the payload locker during launch, released at the beginning of the coast period, and allowed to float free and circulate. The containment chamber will keep the tiles in close enough proximity that the EPMs need only act over small distances (inches) to bring the tiles together (thus allowing for lower field strength, lower mass magnets). At the conclusion of the microgravity period, we aim to have achieved several correct attachments and detachments, with ideally at least one observation of a "complete" three-part assembly (Fig. 5).

This test regimen has been designed to mimic certain conditions of an orbital deployment, and will thus serve as a milestone test in advance of a proposed ISS deployment (tiles will still be scaled down to fit inside an ISS science lab container). Tiles will be similarly contained in a closed volume (in orbit, this will be an inflatable membrane) during assembly, and will rely on sensing data and bonding diagnosis information to actuate EPMs (larger scale units) for on-demand buffering between tiles, selective application of torques (likely mediated with active, standard electromagnets as well), and error-correction via forced tile separation. For a full discussion of in-orbit deployment and operation (including calculations for feasibility of pressurization, power budget, magnet strength required, etc.), see [7]. While our TESSERAE prototype tiles have ranged from a few centimeters in diameter to a few inches, the at-scale TESSERAE deployment dimensions are currently proposed and evaluated for a 5ft tile edge, and approximately 30ft interior module diameter.

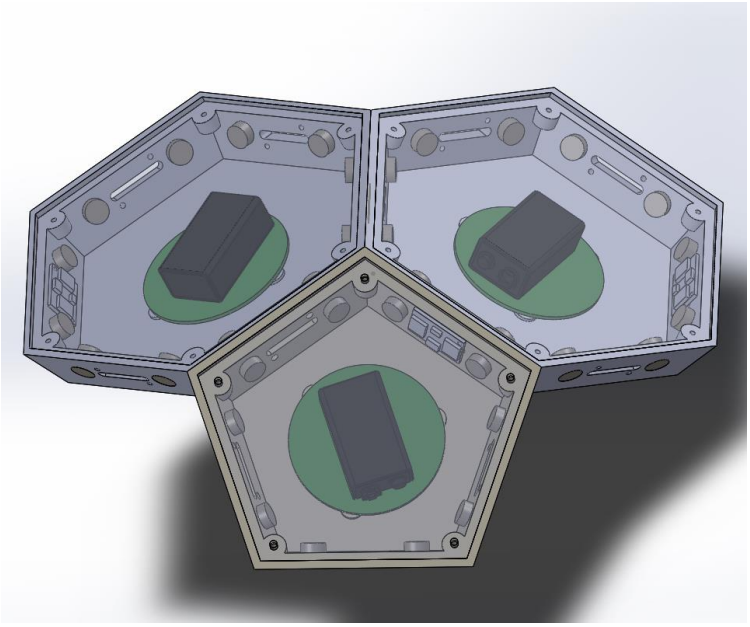


Fig. 5 Three-part sub-assembly shown as target shape for suborbital flight test (transparent lids to show internal components). The three mated tiles already begin to establish the buckyball curvature.

In support of NASA's strategic vision for a "human return to the Moon, followed by missions to Mars and beyond" [1], we have designed TESSERAE with a hybrid mission ConOps in mind. The at-scale TESSERAE mission concept begins with the Moon: a TESSERAE module "shell set" is packed flat, launched, deployed inside a containment membrane (which is later removed) and self-assembles in lunar orbit to support the Lunar Orbital Platform Gateway [8]. The TESSERAE unit can support an influx in crew numbers (as is expected with the varying, seasonal activity in LOP-G) by docking through standard attachment ports, or provide additional storage volume for supplies or science payloads. When ready for a surface deployment, the TESSERAE module can be de-pressurized and packed flat again, this time in a transit vehicle for entry, descent, and landing on the lunar surface. The lightweight tiles can then be moved from site to site by rover and re-assembled as modular architecture on the surface wherever needed; the electro-permanent magnets will aid in easy snap-assembly (with the aid of a deployable ladder and simple pulley, when in a gravity environment). Because the tiles are being designed for in-space radiation environments, TESSERAE tiles could be used creatively as shielding in combination with other inflatable or 3D printed, on-surface habitat concepts.

The ConOps design efforts necessary to realize this mission can be repurposed and reapplied in a comparable mission to Mars (MOSAIC, or Mars Orbiting Self-Assembling Interlocking Chambers) in subsequent years (Fig. 6).

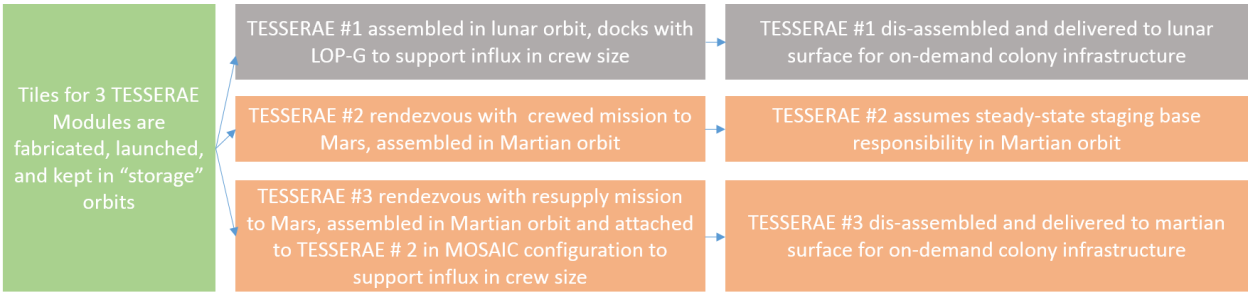


Fig. 6 Mission architecture chart showing lunar mission concept (gray bars), with a Mars continuation mission (orange bars).

III. Related Work: Self Assembly & Space Architecture

The following section outlines a condensed literature review for micro and macro scale self-assembly, from which we have drawn certain hypotheses and intuitions for the quasi-stochastic nature of our system. We also examine a range of space architecture paradigms, from fixed cylindrical shells in the tradition of ISS modules to origami-inspired deployables, to inform our design of the TESSERAE feature set.

A. Self-Assembly

We note prior work in macro self-assembly, where the geometry of each sub-part is tuned to induce accretion into the desired whole, such as lock and key physical joints or magnet bonding pairs [9], [10]. At smaller scales, self-assembly processes that are modeled after DNA molecular assembly and protein folding use an "annealing ramp" approach [11], [12]; this involves tuning inputs or "stirring energy" (e.g., vibration and shaking) to circulate units and converge a multi-part system into a cohesive whole. The TESSERAE self-assembling system combines these two approaches, as we design the tile physical geometry, the magnet polarity arrangement along tile bonding faces, and a quasi-stochastic annealing ramp via sensor-mediated EPM actuation to direct the self-assembly process into the desired buckyball configuration.

As previously noted in [7], electro-permanent magnets on each TESSERAE tile bonding face serve two purposes. In their unpowered state, they exert a constant magnetic attraction, drawing hexagons and pentagons into a particular configuration for "additive construction." 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 bonded into an incorrect configuration or meta-stable state. These additive and subtractive modes of EPM-mediated assembly have been previously explored in two dimensional, water-supported systems [13] and three dimensional "pebble" rearrangement [14]. TESSERAE uniquely combines the additive and subtractive approaches with a new polarity map (additional degrees of freedom with more magnet attachment points) and a quasi-stochastic actuation approach in three dimensional microgravity spaces. TESSERAE also builds on prior research in control algorithms for self-assembling swarms that exchange data between members [15].

B. Space Architecture

The TESSERAE assembly and in-orbit deployment plan uniquely combines several existing aerospace technologies. We build on [16], [17] for demonstrating feasibility of magnetic docking approaches, and electromagnetic formation flight [18], [19], for our magnet mediated self-assembly. A temporary, flexible membrane will encapsulate payload elements, and undergo autonomous inflation (building on various previously explored concepts for balloon inflation in aerospace contexts [20], [21]) upon reaching the intended deployment orbit. This ensures that the component tiles are kept in close proximity when released into the microgravity environment, to improve the likelihood of finding neighbors (ensuring that magnets need only act over short ranges, per the $1/r^2$ drop off in magnetic force). While we are primarily interested in solid, enclosed volumes, we note the relevant principle of joint reversibility [22] in deployable aerospace structures.

At the module level, we have drawn our previously-reported-on shell material and mass estimates from the ISS Columbus module [23], and stuffed Whipple shield [24], for a conservative (extra margin built in) mass-to-enclosed-volume ratio. We note the BEAM inflatable habitat [25] as a fellow example of architecture that can be condensed for launch via flat packing in a rocket payload fairing, and we anticipate a roughly 10:1 deployed:packed volume ratio for TESSERAE. Our modular approach yields the additional benefit of modularity and reconfigurability at the shell level, which the BEAM model does not (one cannot easily remove and change out segments of the BEAM inflatable walls, as is possible with TESSERAE base unit tiles). Beyond inflatable module concepts, we also note prior work in origami-inspired space structures (currently for open form, unfurling surfaces like James Webb [26] and Starshade [27]).

While prior art has extensively analyzed 2D self-assembly in normal gravity environments, and other examples of self-deploying space architecture have been demonstrated, we believe TESSERAE to be the first microgravity-based, three-dimensional self-assembly system; we are thus interested in modelling and simulation to fully characterize both desirable and undesirable assembly states as we tune parameters that affect quasi-stochastic behavior in three dimensions.

IV. Preliminary Results: Modelling Microgravity Deployments

Below, we present two experiment deployment contexts in microgravity (a completed parabolic flight test, and a prospective suborbital flight launch) and discuss the applicability of modelling approaches in stochastic vs quasi-stochastic contexts.

A. Parabolic Flight with Stochastic Assembly

Our preliminary results on a stochastic assembly model (passive, permanent neodymium magnets on each bonding face), deployed over 17 parabolas, validated the core concept of magnet-mediated self-assembly in microgravity. As discussed in [28], we observed that adjacent, proximate tiles reliably snap together over centimeter distances in a matter of seconds. As we progress towards a rigorous full-system simulation for TESSERAE's assembly behavior in orbit, we have calibrated an initial modelling representation in Unity 3D [29] based on our results from the parabolic flight. The table below (Fig. 7) summarizes our analysis of the correct bonding regimes and error behavior from our flight footage (over two deployed tile sets). We have been able to identify a predictable pattern of the tile-tile bonding modes and have confirmed comparable behavior (both in period of time over which tiles assemble, and physical configurations of the tiles) in our Unity simulation (Fig. 8).

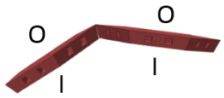
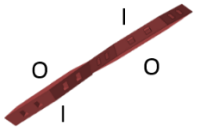
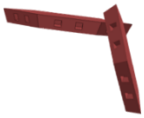
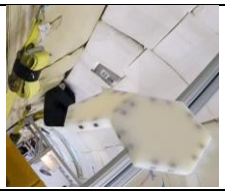
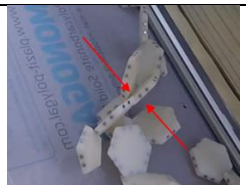
	Correct Bond	**Error Mode: inverted full bond**	**Error Mode: meta-stable**	**Error Mode: clumping**
Description	Correctly paired dyad, establishing consistent inner (I) and outer (O) surface, with dihedral bonding angle.	One tile is inverted. This is a stable error mode (based on current polarity map) that would require active intervention.	A single magnet pair attracts, leaving an uncompleted dyad pairing. This meta-stable error mode is easily perturbed and self-corrected.	Magnetic interactions outside the magnet-magnet bonding axis draw tiles together loosely. This unstable error mode is easily perturbed and self-corrected
Modelling				
Experiment				

Fig. 7 Table showing both correct bonding and error modes observed during first parabolic flight test, Nov 2017.

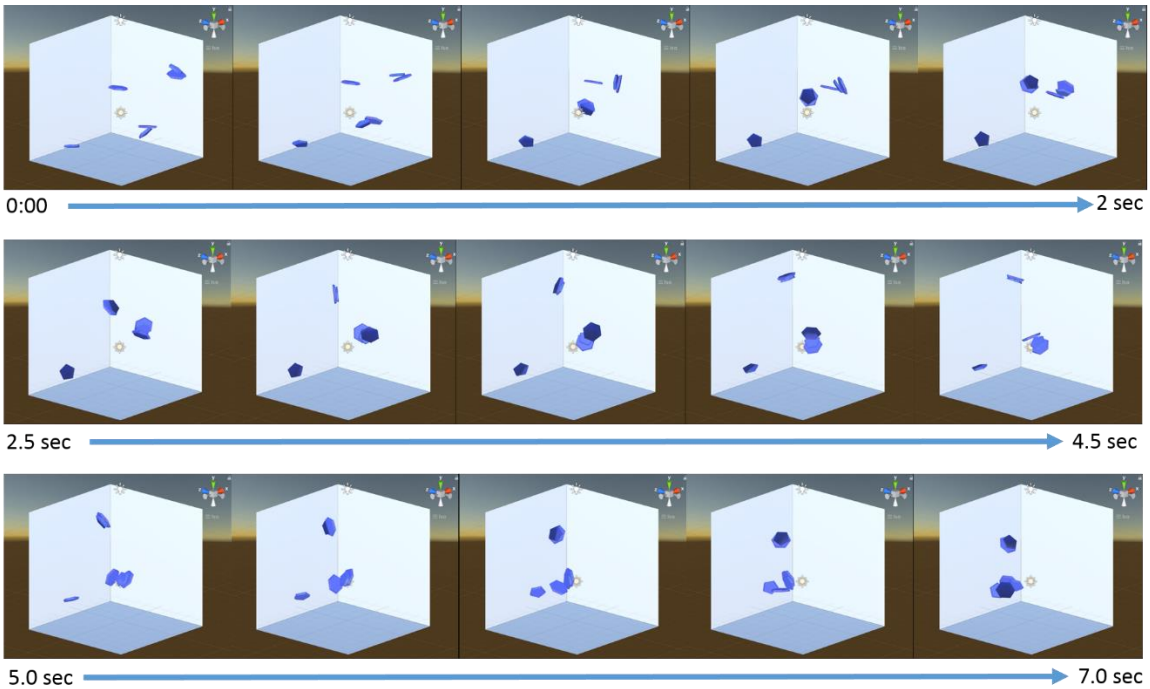


Fig. 8 Output from Unity model (screenshots from sequential timestamps) showing self-assembly behavior in simulated microgravity environment; six freely circulating tiles (initial condition for 1st frame) condense into two batches.

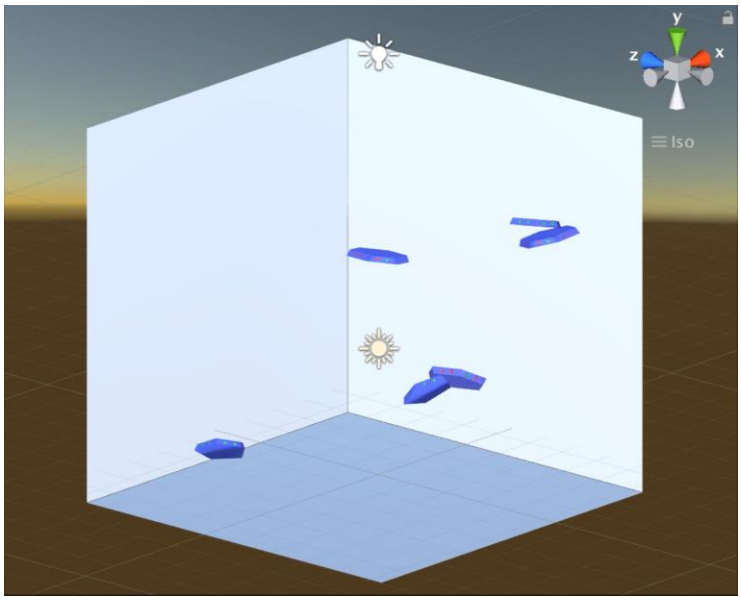


Fig. 9 Close-up of Unity modelling environment, showing red and green dot (i.e., north and south) magnet pairs embedded on the face of each tile.

The Unity simulation has faithfully produced tile-tile interactions expected from our microgravity flight experiment, including correctly bonded dyads, meta-stable states, and clumping. To provide the required precision for the rigid body collisions, we have applied a mesh collider (albeit computationally expensive) rather than Unity's standard box collider. The inverse square law formula for magnetic force is used to approximate the magnitude of the attractive or repulsive vector between the modelled magnets:

$$F = \frac{\mu q_1 q_2}{4\pi r^2} \tag{1}$$

Where $\mathbf{q_1}$ and $\mathbf{q_2}$ are magnitudes of the magnetic poles, $\boldsymbol{\mu}$ is the permeability of free space constant, $\boldsymbol{r}$ is the separation between the tile/magnet faces and $\boldsymbol{F}$ is the magnitude of the resultant force vector. Friction terms were also added to more realistically simulate tile motion and collision behavior, relying on the Nvidia PhysX engine in Unity. While this model has yielded a useful first-order approximation of tile behavior, and will be carried forward for purely-stochastic estimates of TESSERAE assembly time-scales, we are also exploring alternative modelling options including Simulink (see below) and robotic simulation for the quasi-stochastic, active-EPM control use case.

B. Suborbital Launch with Quasi-Stochastic Assembly

In anticipation of our 2019 suborbital flight research test (three sustained minutes of microgravity, three GNC-augmented tiles self-assembling and detaching), we are exploring a modeling approach for the magnetic interaction between the EPMs on the latest CAD tile design (see section II, A) using Simulink [30]. Magnetic relationships are established between tile bonding faces, with the tile properties (center of mass, inertia, geometric definitions) imported from Solidworks and augmented by Simulink plug-ins. Due to Simulink's integration with MATLAB and extensive physics libraries, this modelling environment has thus far supported the TESSERAE simulation needs: flexibility for programmatic simulation parameters (adding active control), output sensing (i.e., monitoring the magnetic forces, collision impacts, etc. between tiles), and stricter coherence with the laws of physics governing the tile assembly behavior. Figure 10 shows two TESSERAE tiles modeled and interacting in Simulink. These 2nd phase modelling results will be compared and calibrated against experimental data from the tiles' actual experience of microgravity during the suborbital test (via camera-recorded footage and the suite of sensor data described in Section II, A.)

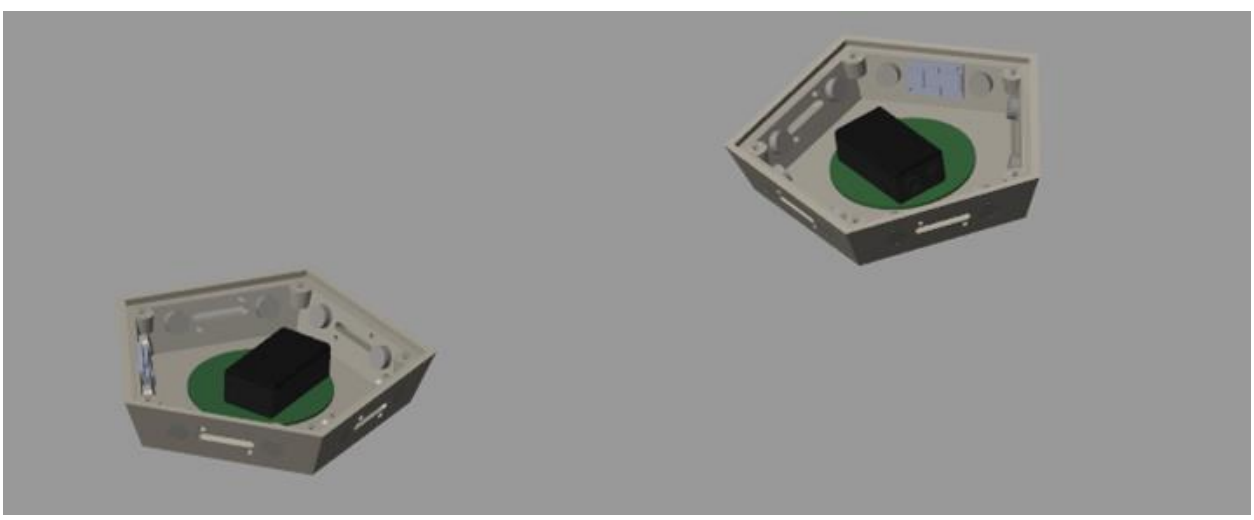


Fig. 10 Snapshot showing preliminary modeling environment in Simulink.

V. Extensibility to other Geometries

While our initial investigations into self-assembling space architecture have focused on the truncated icosahedron, or buckyball, we are expanding our modelling and simulation portfolio to also consider alternative surface shell tessellations and module-scale packing arrangements.

A. Surface Shell Tessellations

The TESSERAE ConOps, from launch to orbit to surface deployment, benefits greatly from the predictable regularity of the tile base units. While organic, cell-like tessellations of surfaces can produce similar modularity and segmentation of a surface (e.g., Voronoi tiling), the TESSERAE tiles must adhere to a regular geometry for consistency of manufacturing and interfaces, packing for launch, and predictability of assembly once in orbit. Though spheres, and sphere approximations like buckyballs, are an efficient shape for in-space habitation (maximizing usable volume, while minimizing the costly shell surface area), future space stations may be interested in other curvilinear solids, such as the traditional cylinder or a rotating torus. We can apply the same shell modularity approach to these shapes, after properly segmenting and approximating the curved surfaces. Figure 11, below, shows an approach for tessellating the torus with regular hexagons. While the sizes of the polygons do vary (requiring more than one standard size hexagon, for example), this size variation can be constrained and accounted for, yielding a repeatable "tile shell set."

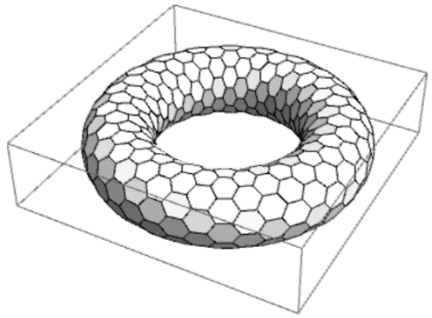


Fig. 11 Hexagonal tiling of a torus, generated in Mathematica, referencing code and approach from [31], [32].

When we consider truly generalizable tessellations, or base units that could self-assemble into any number of shapes without a fixed target in mind, we are likely to rely on triangles (building on the tradition of mesh generation that underlies most CAD software). Even still, when triangles meet at angles outside the X-Y plane, a dihedral bonding angle must be established and cut into the thickness of the tile to establish the curvature between shell units. A generalizable set of triangular tiles would not have the custom dihedral bonding angles needed for particular surface curvatures, but could be augmented with filler-material and inflatable bladders to address the internal-surface gaps.

B. Plesiohedrons and Packing: Crystalline Space Station Mega-Structures

In addition to the geometric representation of the shell surface, we are interested in solid module geometries that can be densely packed in crystalline-like arrangements. The plesiohedron class of solids (e.g., truncated octadhedrons, cubes, etc.) are able to be stacked such that they completely fill 3D Euclidean space, with no overlaps and no gaps (see Fig. 12). For our MOSAIC (Mars Orbiting Self-Assembling Interlocking Chambers) concept, we are building on the notion of plesiodedron solids to propose modular space stations that are "energy favorable" from a self-assembly standpoint and simultaneously packing-volume efficient. In particular, the truncated octahedral shape has already been explored for surface habitats [33], and we now take this notion into the context of orbiting habitats. This approach requires that the TESSERAE tile set forms a plesiohedron; these modules can then be packed outward in three dimensions to grow an on-demand, modular space station. Modules that are "internal" to the structure (i.e., landlocked,

or fully surrounded by other structures) should have at least two docking ports with interchangeable airlock doors to facilitate moving throughout the global volume. Most external modules on the space-facing exterior of the crystalline arrangement could suffice with a single docking port/air lock, and could be augmented with windows or other customized TESSERAE tiles. This decentralized approach to space station design could enable entirely new mission ConOps, where TESSERAE space station modules can separate for escape pod use, or dynamically reconfigure into a new space station arrangement on-demand.

Fig. 12 Densely packed truncated octahedrons, proposed for future space station configurations. Image courtesy of Andrew Kepert, Creative Commons.

VI. Conclusion and Future Work

We have presented our v2 prototype design (electromechanical and sensing-mediated GNC control), in the context of its mission operation plan for a suborbital flight test. We have combined the distinct fields of self-assembly and space architecture to propose an extensible construction paradigm in orbit, and have compared experimental results and Unity modelling results for a proof-of-concept, stochastic assembly version. Our quasi-stochastic, actively-EPM controlled prototypes demand a hybrid rigid body physics and robotics simulation environment, and a preliminary version has been demonstrated in Simulink. The TESSERAE self-assembly approach generalizes to other surface shell tessellations and module-scale docking arrangements, offering a wealth of creative, modular shape primitives to the future space architect.

Future work will center on modelling, to include repeated trial runs of a fully-fledged robotic simulation of the TESSERAE system to be able to accurately predict the time duration of assembly at scale, in orbit. Research into custom EPMs is underway to optimize the TESSERAE jointing system (high holding strength, low power, low mass). The v2 prototype will be deployed on an upcoming suborbital launch and second parabolic flight test.

TESSERAE's conceptual contribution consists primarily of the shell self-assembly process and accompanying mission architecture. TESSERAE is intended as an extensible platform for multifunctional use in orbit, with reusability for surface operations. While we are primarily interested in habitat-focused space architecture, we note that the TESSERAE approach could be applied to shells for other purposes (storage of mission supplies, or satellite condominium units) and open surface geometries like parabolic mirrors. TESSERAE's initial mission is targeting a human-led, hybrid orbit-and-surface operation, supporting NASA's strategic plan for both returning to the Moon and pushing out to Mars. To make TESSERAE applicable and adaptable for multiple contexts—from LEO space tourism, to lunar orbit, to Mars—we are exploring embedded, modular functionality in each tile; TESSERAE tiles should support various ECLSS (Environmental Control and Life Support Systems) approaches, astronaut activity interfaces (airlocks, docking ports), remote-sensing, and GNC orbital maneuver technologies. We are initially designing tiles to follow the radiation and debris shielding approach currently used in ISS modules (e.g., Whipple Bumper and stuffed shield [24]), with the ability to substitute alternative, advanced materials as other shielding options come available. We note a natural extensibility to multiple microgravity and surface exploration environments, and we aim to develop TESSERAE as an extensible platform for space exploration.

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