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Space Habitat Reconfigurability: TESSERAE platform for self-aware assembly

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Abstract

As we prepare to venture into deep space, from NASA's priorities for a lunar-orbiting gateway station to private industry prospective Mars missions, we face an inflection point for self-aware, autonomous control of space structures. Can we free space architecture from static, single-use module design and instead enable dynamic, modular space structures that "grow" and evolve over the course of a mission? This paper presents the TESSERAE platform (Tessellated Electromagnetic Space Structures for the Exploration of Reconfigurable Adaptive Environments): a set of self-assembling, multi-functional structural tiles with natively embedded sensing and quasi-stochastic guidance, navigation and control. The TESSERAE research area aims to enable a new class of rapidly reconfigurable, adaptive space architecture with a novel "growth-focused" design theory for space architecture.

Keywords: space architecture, space structures, self-assembly, distributed systems, design theory

Acronyms/Abbreviations

EPM – Electro-Permanent Magnet
MVU – Minimum Viable Unit
TESSERAE – Tessellated Electromagnetic Space Structures for the Exploration of Reconfigurable Adaptive Environments
MOSAIC – Mars Orbiting Self-Assembling Interlocking Chambers
ISRU – In Situ Resource Utilization

1. Introduction

The pursuit of space exploration presents us with what appears to be an irreconcilable conundrum: at once a mysterious and majestic domain for human exploration, while also a domain of unrelenting dangers that are fundamentally at odds with our evolved biology. The noble mission of space architecture is to answer our yearning to experience and investigate the cosmos, while we retain our current human form.

Despite decades of space architecture science fiction, bridging three centuries, we have yet to realize the grand, inspiring structures so fondly envisioned in our storytelling. Where are our space hotels, our sprawling ringworlds, our space megastructures?

To a first degree, we still require core technological development in the obvious three gatekeepers: heavy lift rockets (making the transportation to space of our Earth creations more feasible), in-space material sourcing and manufacturing (ISRU), and environmental control and life-support systems. Sustainable human life in space, at the scales of architecture we are discussing—from outposts, to colonies, to space cities—will also require advances in the sourcing of power and energy storage densities. Yet even with renewed and expanded commitment to these technical goals, we still face archetypal barriers to space architecture and systematic, scaling challenges.

Space architecture has traditionally been hampered by capricious political whims, where one generation's investment in lofty space exploration goals can be swiftly washed away by the election of a new administration. This might be crystallized into a single observation: the infeasibility of deploying and maintaining cost-sink behemoths. To address this, we can fundamentally change the paradigm of how space architecture is conceived: instead of summoning resources for a pre-determined megastructure, let us start small and grow iteratively and organically (a "spiral" theory of development). A fully formed tree does not burst forth from the ground, nor is the precise final form of the tree known at the seed stage; the tree evolves over decades, responsive to its environment, in an indeterminate pattern of growth requiring only modest resources at any one moment in time. So too, have our cities traditionally grown, by fits and starts with incremental additions that add to the "fractal density" [1].

As humans continue to make progress in the gatekeeper technical areas raised above, we will still need a means of scaling habitation in Low Earth Orbit and beyond. Our Earth-based approach, heavily dependent on manual labor and human design oversight, simply cannot be extrapolated to the space environment. The risk of astronaut EVAs (Extra Vehicular Activities) and limitations of single-design, single-use architecture would continue to unnecessarily rate-limit progress. We strive to answer this call for space architecture that builds itself, through transformative self-aware assembly— adaptive, "living structures" that follow principles of fractal self-similarity [2] to scale elegantly from common base units to modest, multi-part and modular space stations, to ultimately a family of mega-structures.

The domain of space presents us with grand—and as currently known to our models of physics, unyielding—spatial scales and timescales. Our future space architecture should commune with these scales, designed as a complementary feature of its environment, rather than in opposition to it. This suggests we should think of space architecture not as a temporary, technological artifact of its time, but as a fully embodied, sentient and self-aware complex system in symbiosis with its human designers and inhabitants; as an organism in its own right, responsive and robust, accreting and evolving over the long time horizons native to traversing the expanses of our cosmos. This leads us to the research question that guides the development of several experimental hardware platforms and design paradigms that will be discussed further in this paper:

How can we design, induce, and scale self-aware[*] *assembly to grow*[†] *space architecture, natively, in orbit?*

2. Space Architecture: A biomimetic design theory

Humanity stands at the cusp of interplanetary civilization. As we prepare to venture into deep space and establish steady-state habitats, we can begin by exploring how to enable dynamic, self-aware space structures that are informed by both inorganic and organic growth processes from complex Earth systems. The future of human habitation in outer space lies in "living structures": self-assembling and adaptive, following principles of self-similarity to scale elegantly from common base units to robust, modular structures. To unpack these terms, the self-assembling adaptivity depends on pervasive sensing built into interior and exterior shells of the architectural base units—from proximity sensing, to environmental sensing (e.g. light, radiation), to nearest-neighbor mesh networking and swarm-inspired communication protocols. We see examples of such systems in nature—self-organizing animals with collective intelligence, or swarms, where intentional, targeted macro configurations can evolve from embedded behavior and local interactions among constituent members of the group [3]. This dynamic, multi-agent responsive sensing facilitates actuators that tune self-assembly from a purely stochastic process as found in nature (say, the accretion of small particles into a clump through Brownian motion), into guided, convergent assembly managed by certain global rules and local interactions between neighbors. Principles of self-similarity, drawn from the mathematics of fractals [2], help us select base unit geometries for modules. We seek module geometries that will dock in energy-favorable assemblies for modular space stations that can continue to grow larger and adapt beyond the designer's original conception.

Such an approach yields immense practical benefit in the reduction of traditional "control" mechanisms—less need for propulsion and thrusters for path-planning, less planning for GNC (Guidance, Navigation and Control), and less human or robotic-mediated "agent-based" construction. In addition, this self-assembling and adaptive paradigm inherently supports redundancy and repair—when damaged modules can be reliably jettisoned and standard, interlocking modules added in their place, we can achieve on-demand, in-situ repair of space assets. In this context, we draw on biomimetic inspiration from the repair of nucleic acids. DNA exists in a veritable soup of G, T, A, and C nucleotides and when the strands of DNA are damaged, these base pairs can be slotted in to match the bonding site in question [4]. We envision a similar definition of space architecture modules that be slotted into standard macro-geometries of space stations for ease of reconfigurability and repair.

Finally, this paradigm of adaptive, self-assembling, modular space architecture also provides decentralized control and modest part-by-part growth; this may free us from the constraints of fickle funding and political whims that limit long term, consistent progress towards megastructures. If the modularity and interchangeability of the architectural base units is preserved for backwards compatibility (even as hardware iterations and tech maturity will inevitably lead to new versions), then the ability to expand the structure to house more humans depends on a small, iterative resource allocation rather than a large budget for an entirely new station. Instead of needing to build an entirely new structure from scratch, we simply add a new wing onto our house. We are now facing such a challenge with the International Space Station, as plans for its retirement or transition to private ownership are discussed [5]. This example of space architecture—a monumental achievement in its own right—cannot scale and grow

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[*] In this context, we use self-aware to mean sensor-mediated and responsive to the local environment (e.g. proximity sensing, neighbor-neighbor mesh communications, et cetera). We are not using "self-aware" to imply a sense of habitat-scale consciousness in the tradition of Strong AI—though perhaps advancements in neural networks, deep learning, and applied artificial intelligence will bring us closer to the latter vision, long predicted by science fiction.

[†] We focus here on models of growth to emphasize that space architecture, particularly structures in microgravity, might be constructed in energy-favorable pathways that mimic growth patterns in nature.

indefinitely. To prepare for space tourism and a democratization of the countries and citizens involved in space exploration, we are already facing needs for larger space stations, built anew. A major effort in our research centers on designing a proof of concept Minimum Viable Unit (MVU) for modular, reconfigurable space architecture; while many different candidate geometries and ConOps exist, and ultimately we hope to see a rich ecosystem of MVUs, we must start by analyzing the feasibility and architectural lifecycle of at least one candidate. Our TESSERAE prototype will be discussed in sections 3 and 5.

Our design theory for growth paradigms in space architecture relies on three core principles, phrased as dichotomy priorities. The first two explore the physical features and topologies of growing systems (both in-organic and organic); the third bears on energy flows and non-equilibrium phase transitions that govern how such growth is induced and guided. Together, they fall under an “indeterminate” growth philosophy (best known to us in botanical examples, where growth continues throughout the lifetime of an organism rather than stopping at “maturity”). This provides an opportunity to grow and adapt space structures over timescales more suited to space travel (long, vast distances. Can we build space architecture that keeps on growing (Figure 1)?

1. Accretion over Construction
2. Seeding over Erecting
3. Cascades over Dams

2.1 Accretion over Construction

Let us start small, with the minimum viable units of space architecture (e.g. the cells of a larger structure) and grow organically. Like mussels accreting to a pier, we can start with feasible base units, impose form constraints to enable a reasonable level of deterministic outcome, and allow the structures to self-assemble and evolve into these boundary conditions.

2.2 Seeding over Erecting

Traditional “erecting” modes of architecture yield smooth (at macro scale) outer shells. A seeding process allows greater variation to evolve without all detail requiring individual, manual execution, while still being responsive to certain initial conditions that govern the nucleation period and surrounding environment. We pull from the formal definition of “fractal dimension” as a mathematical framing for condensed, highly-textured, branching structures. Fractal “self-similarity across scales” can be used as a guiding concept for self-replication and continuous growth of the structure without extensive human/agent intervention. A single base unit can be replicated, bonded to an ever growing structure, and continue expanding in a seeded-pattern (e.g. self-aware) through open “bonding sites” that continue the self-similar pattern at a larger scale. Self-similarity and fractal branching structures are also shown to increase resiliency of certain systems [1]. This can be combined with our polylithic, reconfigurable systems approach (decentralized, multi-part structures), for robust, life-like space craft that are self-aware, self-healing, and easily dispersed for independent function.

Both seeding and accretion processes require in-situ resources—while this can be achieved in the short term by adding redundant base units to our enclosed self-assembling systems (e.g., a “swarm” of generalizable, re-mixable units to draw from with LEGO-like interchangeability), we also consider the merging of our research work with in-situ resource utilization technology development in the future.

2.3 Cascades over Dams

Drawing on Eric Smith’s hypothesis for the earliest origins of life on Earth [6], we are interested in finding the non-equilibrium phase transitions or energy driven-processes that would govern elegant evolution of space architecture structures. This means identifying and designing *with* the flows of available energy (cascades), rather than designing against them (dams). In designing and building space architecture, we should take explicit advantage of the physics of microgravity and the “native” environment of the vacuum: capitalizing on swirling circulation dynamics for quasi-stochastic self-assembly (no gravity, no air drag to counteract); explore radial space structures (building on Thompson’s radial coordinates projections [7]), where we can build outward in all directions; or energy-actuated systems based on inflation (air pressure leads membranes to expand out into the vacuum) or solar-radiation (solar sails, panels etc. for energy capture from incident rays unabated by an atmosphere). These choices are akin to the “native” growth paradigms of the Earth & Sea, to clearly motivate “design by and for” the unique affordances of the space environment.

Ultimately, we aim to define cellular space architecture, or minimum viable architectural units, that can be assembled into complex structures through the application of the three design principles (accretion, seeding and harnessing cascading energy flows), tying the biological base-unit scale to the space urbanism scale.

Fig 1. L to R: Mussels accreting, crystal growth, and a waterfall serve as organic and inorganic examples of growth paradigms and energy favorable processes after which we can model aspects of space architecture (images courtesy of creative commons).

3. TESSERAE: a proof of concept model for self-assembling space structures

How will we build the coming generations of Space Architecture—the modules, spaceships, and space stations that will ensconce our space-faring species? Can we move beyond the 20th century paradigm of cylindrical tubes in orbit, to geodesic dome habitats, to microgravity concert halls, to space cathedrals? The next generation of space architecture should delight, inspire, and protect humanity for our future in the near, and far, reaches of space.

The space industry's habitation and operations needs are rapidly evolving 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-cases like influxes in crew sizes, space tourism and new agile deployment contexts. Rather than relying on astronaut Extravehicular Activities (EVAs) and deploying solely fixed hard-shell or fixed inflatable structures, we can lower payload weight for a given volume, reduce assembly complexity, and introduce transformative space-structure modularity by implementing quasi-stochastic, "self-aware" assembly for aerospace structures. This paradigm shift will enable entirely new mission architectures for in-space construction, from LEGO-like interchangeability of structural components to ease of autonomous repair and servicing, to re-use and re-purposing of a single "shell tile set" for multiple mission contexts.

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 self-aware space habitat construction via quasi-stochastic self-assembly in microgravity. We then present an approach for re-purposing these shells for surface deployments (e.g., Lunar settlement) and multi-module space station polyhedral packing arrangements (e.g., mega-structures).

As previously discussed in [8], our research proposes a multi-year effort to study, characterize, prototype, and deploy self-assembling TESSERAE (Tessellated Electromagnetic Space Structures for the Exploration of Reconfigurable, Adaptive Environments) modules. Each TESSERAE structure is made from a set of tiles. These tiles are tuned to self-assemble into a particular geometry in microgravity. In our initial prototypes, we have focused on the buckminsterfullerene (20 hexagonal tiles, 12 pentagonal tiles). 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). Each tile at minimum includes a rigid outer shell, responsive sensing for bonding diagnosis, electro-permanent magnets (EPMs) for dynamically controllable bonding actuation, and an on-board power harvesting and power management system. The geometric tiles that form our TESSERAE shape will self-assemble quasi-stochastically via electro-permanent magnetic (EPM) jointing to form a closed surface (building on [9], [10] demonstrating feasibility of magnetic docking approaches). Our process employs an energy-favorable "annealing ramp" approach where stirring energy and kinetic perturbances are tuned to induce accretion of many separate parts (inspired by the self-assembly of DNA coils and validated at macro levels in [11], [12], [13]). Habitat-scale TESSERAE tiles will also include clamping and sealing for pressurization.

The self-assembling TESSERAE modules (Figure 2) can be autonomously and sustainably constructed and reconfigured as needed in orbit, 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 designed to be interchangeable in LEGO-style to allow for many permutations and custom mission designs at low "iteration cost," in both microgravity and on-surface contexts.

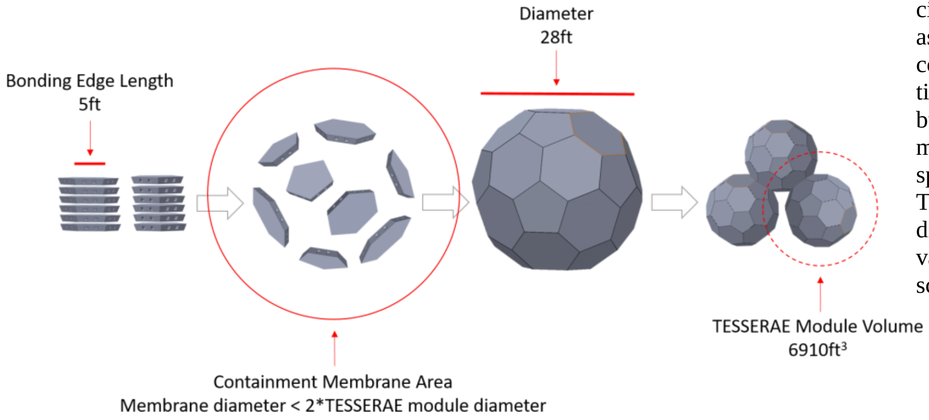

Fig 2. L to R: TESSERAE tiles packed flat for launch; circulating for self-assembly inside a containment membrane; tiles assembled into a single buckyball; TESSERAE modules docked for larger space station configuration. These preliminary dimensions are prospective; variations on the physical scale are expected.

TESSERAE construction can offer adaptive, reconfigurable, and re-usable outer shells to meet evolving mission needs. The closed TESSERAE modules, once assembled from tiles, can be joined together to form custom, decentralized space stations of varying geometries. This enables numerous architectural and spatial arrangements (see Figure 3 in Mission Architecture), and dramatically improves safety (ease of escape pod release in orbit) and robustness (avoiding single point of failure via many modular components to a larger space station).

TESSERAE was intentionally named after the small, colored tiles used in Roman mosaics, where many standard pieces, or "tesserae," interlock to create a larger image. We are now applying this tesserae notion not just to the external shell construction and self-assembly, but also to the modularity and packing of the interior elements of a space habitat like galleys, ECLSS, experiment racks, and sleeping quarters. An example mission concept (described below) supports Mars orbit and surface operations with multiple, interlocking TESSERAE acting as an orbiting base: "MOSAIC" (Mars-Orbiting Self-Assembling Interlocking Chambers). We have also proposed a ConOps architecture for TESSERAE in service of the expedited Artemis 2024 mission, providing dual orbit and surface habitat capacity. We aim for TESSERAE to support NASA's strategic plan [14] for both returning to the moon and pushing out to Mars. We note a natural extensibility to other microgravity self-assembly contexts, including re-purposing the key technical contributions for autonomous self-assembly of satellites, telescopes or parabolic mirrors, and other in-space infrastructure for space exploration; for the purposes of this paper, however, we remain focused on the habitat application.

4. Condensed Literature Review

This research attempts to marry two domains into a whole that is greater than the sum of its parts: growth mechanisms across inorganic and organic subjects, and extra-terrestrial space structures. Due to the vastness of the former domain, we focus here on the most relevant subset, with particular attention shown to growth mechanisms (e.g. self-assembly, accretion, crystal nucleation, etc.) and scaling paradigms that can be intentionally employed as structural design tools. For the latter, we build on prior innovative concepts for foldable, expandable and otherwise "deployable" structures for aerospace habitats.

4.1 Growth mechanisms and self-assembly in nature

To inform a new design theory for space architecture, one built on self-aware and iteratively scalable growth, we build on a mathematical grounding that can tie "organic transformations" together across vast scales—from minute organisms to a metropolis. D'Arcy Thompson's application of the physical laws of nature to describe biological growth, form and evolution [7] help us extrapolate these same concepts into an entirely new environment and architectural context. Bringing this framing into conversation with Geoffrey West's arguments for the approximate universality of certain scaling relationships [1], we can rigorously describe a model for dynamic, self-aware space structures that are informed by both inorganic and organic growth processes in complex, Earth systems. Our goal is to realize "indeterminate growth" space architecture, an entanglement between both natural and artificial processes [15], across a time horizon that is both immediately present and long enduring—one might say the Long Now [16] for vessels of our Space Exploration future.

This work builds on research in the emerging coupling of biology and architecture [17], [18], and biomimetic approaches for material design and fabrication [19], [20]. However, the inspiration drawn from nature and biology for this research lies primarily in the evolution and responsivity of structural form—a new genetic code for the assembly of space architecture—rather than in literal biological material choice (as the latter would not survive against outgassing in the vacuum).

We note prior work in macro and meso scale self-assembly [21], 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 [22], [23]. At smaller scales, self-assembly processes that are modelled after DNA molecular assembly and protein folding use an "annealing ramp" approach [24], [25]; 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 self-assembling sample prototype system for this research program, TESSERAE, combines these two approaches, as we design the tiles' 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. Additive and subtractive modes of assembly have been previously explored in two dimensional, water-supported systems [26] and three dimensional "pebble" rearrangement [27]. 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 [28].

4.2 Space Architecture & Aerospace Mechanisms

The TESSERAE assembly and in-orbit deployment plan uniquely combine several existing aerospace technologies. We build on [9], [10] for demonstrating feasibility of magnetic docking approaches, and electromagnetic formation flight [29], [30], 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 [31], [32]) 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 $1/r^2$ to $1/r^4$ drop off in magnetic force). While we are primarily interested in solid, enclosed volumes, we note the relevant principle of lattice joint reversibility [33] in deployable aerospace structures, and recent proposals for hierarchical assembly of spacecraft [34].

We note the BEAM inflatable habitat [35] as a fellow example of architecture that can be condensed for launch via flat packing in a rocket payload fairing. Our modular approach yields the additional benefit of modularity and re-configurability at the shell level, which the BEAM model does not (one cannot easily remove and change out segments of the BEAM fabric inflatable walls, as is possible with TESSERAE base unit tiles). At the multi-module scale, when planning for the aesthetic, radiation shielding and interior use considerations that must come into play for a functional space habitat, we note Sherwood's analysis on the reality of how such structures will be used in lunar urbanism contexts: "they will be densely populated, hermetic, shielded and interior but kinesthetically expansive and visually lightweight" [36]. We take this guidance to shape our architectural interior design for both microgravity and surface-based applications of TESSERAE.

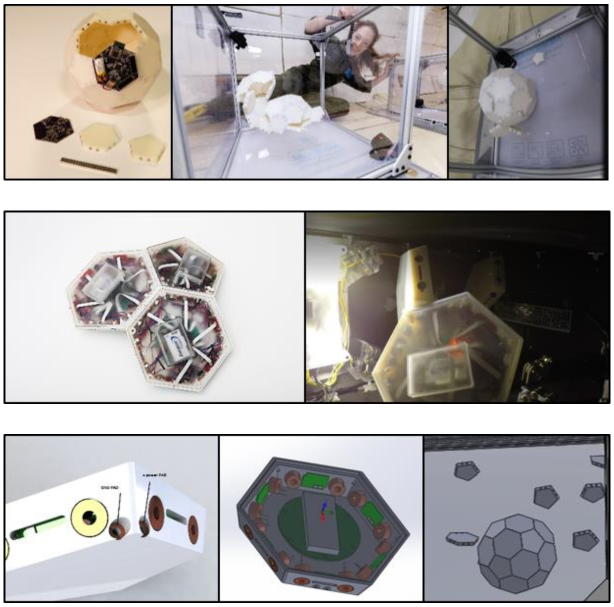

Fig 3. Top row: 2017 parabolic flight hardware and deployment test; Middle row: 2019 TESSERAE responsive tiles for parabolic flight and suborbital flight; Bottom row: newly developed tiles for miniaturized proof of concept deployment on ISS in March 2020.

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 proposal for a microgravity-based, three-dimensional, agent-less self-assembly system. Our research builds on the prior art discussed above to both a) offer a technically rigorous engineering approach to realize self-assembly of space structures and b) adapt best practices in space architecture design and ConOps to make TESSERAE a feasible near-term solution for space habitats.

5. Prototype Development for Technology Demonstration Missions

We are deploying early TRL proof of concept prototypes on microgravity flights (two flights completed in 2017 and 2019, one additional confirmed charter for 2020) and suborbital launches (one completed with Blue Origin, April 2019), see Figure 3. Our November 2017 parabolic flight successfully validated the magnet-based stochastic assembly, with tiles drawn together over centimeter distances in a matter of seconds. These flight results motivated the need for error correction and control for disassembly. Our August 2019 zero g flight and suborbital launch validated a proof of concept tile set (in miniature) with responsive, live sensing between tiles, EPM actuation, and control code. We are now preparing for a confirmed ISS launch in March 2020 with a set of 10 tiles (the highest number flown to date) to test the swarm coordination and mesh communication protocol over 30 days of sustained self-assembly and disassembly tests in microgravity.

The final PhD thesis for which this work was commenced will also include fabrication of two life sized tiles (approximately 5' bonding edge-lengths on each tile) for an at-scale demo of the EPMs and a sample clamping mechanism between tiles. Via an external collaboration, these life sized models are also under active design for re-use in analog resource constrained environments on Earth—natural disaster recovery areas and refugee camps, for use as robust, modular, low-cost and easily assembled architecture. For full discussion of prototype testing and results, please see our paper in IAC 2019 session C2.9 (“Responsive Space Structures: modular, re-configurable tiles for microgravity self-assembly”). In addition to prototype development and iterative testing, we are completing mathematical simulation modeling to predict the timescale of assembly on-orbit and technical trade analyses for the core TESSERAE subsystems (e.g., power budget, link budget, mass budget, ECLSS integration, radiation shielding, thermal management and radiators, etc). For the modelling, we are working to characterize both desirable and undesirable assembly states as we tune parameters that affect quasi-stochastic, self-aware behavior in three dimensions.

6. Mission Architectures

As previously discussed in our prior work [37], we have designed TESSERAE to support a hybrid mission ConOps in support of NASA’s strategic vision for a “human return to the Moon, followed by missions to Mars and beyond” [14]. A TESSERAE module “shell set” is packed flat, launched, deployed inside the containment membrane (which is later removed) and self-assembles in orbit to support either existing structures (e.g. the Lunar Orbital Platform Gateway [38]) or begin a modular space station anew. See full page Figure 4 below, detailing the order of expected operations and flexibility in deployment status of a TESSERAE module. The TESSERAE unit is designed to support an influx in crew numbers (as is expected with the varying, seasonal activity in LOP-G, for example) by docking through standard attachment ports, or it can provide additional storage volume for supplies or science payloads. When ready for a surface deployment, the TESSERAE module could 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 (Figure 5). While initial TESSERAE prototypes have focused on the buckminsterfullerene structure for optimization of volume given a single unit, the geometric base tiles could be re-designed to form truncated octahedra which are optimized for multi-unit packing (see Figure 6) and have been explored for use in surface habitats [39].

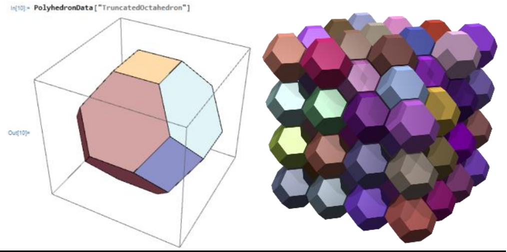

Fig 6. Left: truncated octahedron, a type of pleisohedron or space-filling solid. Right: plesiohedron mega-structure (truncated octahedrons), illustrative of efficient space station module packing options with TESSERAE approach (*src: creative commons*).

6.1 Two models for interior use

In our effort to extend our “self-aware” self-assembly concepts to pragmatic habitat designs, we have identified two models for interior use. The first addresses near-term scenarios where, due to limited resources and constrained operating support, space habitat structures must still be filled by optimizing space allocation for mixed needs within a single volume.

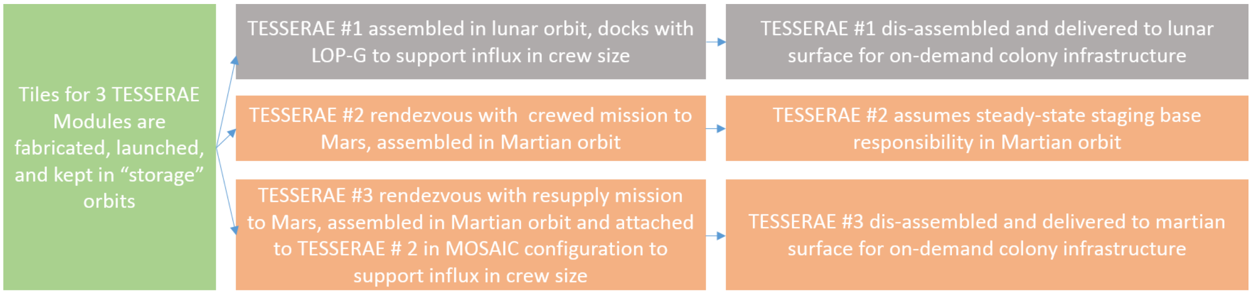

Fig 5. Mission architecture chart for lunar (gray) and Mars (orange) missions, originally presented in [37].

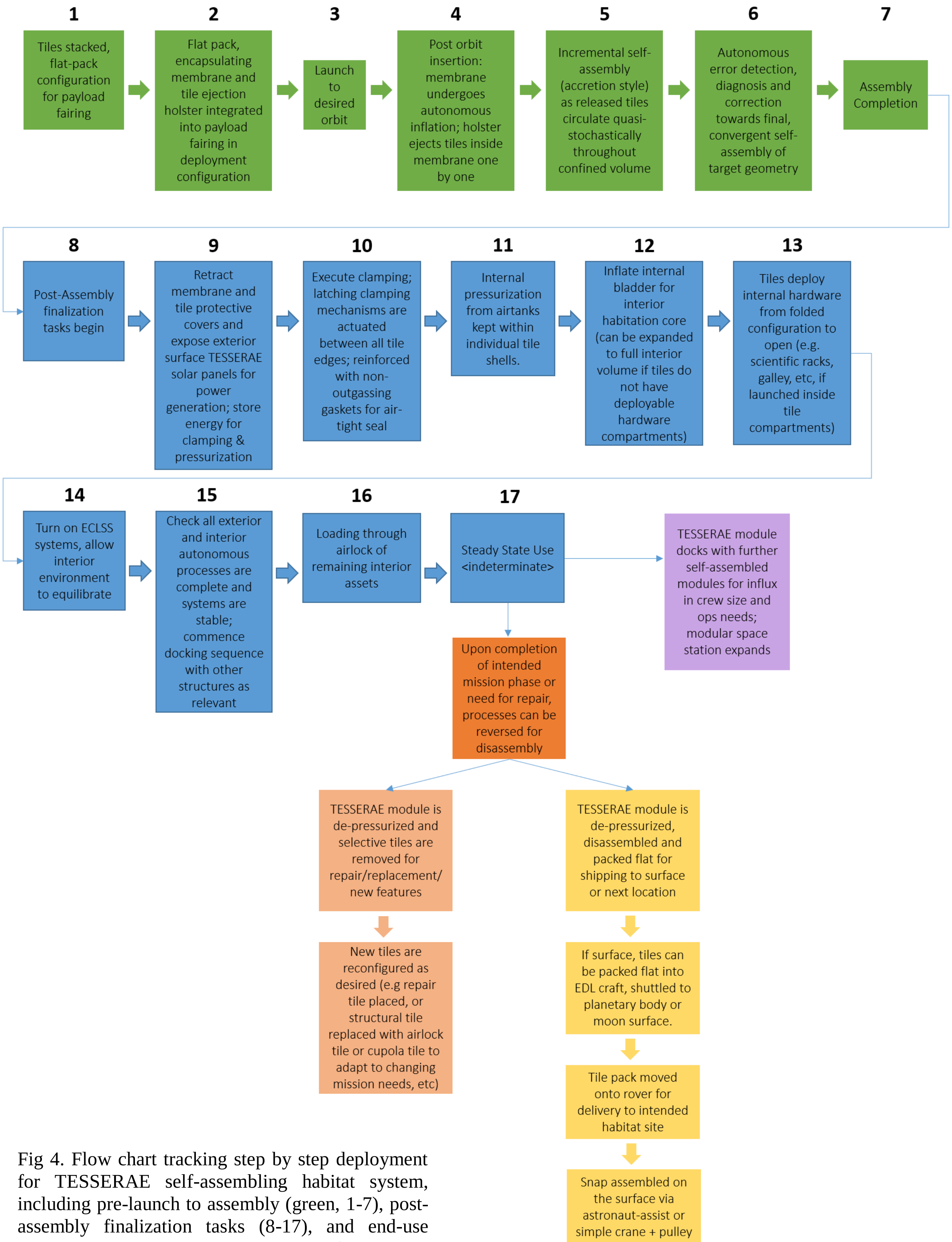

Fig 4. Flow chart tracking step by step deployment for TESSERAE self-assembling habitat system, including pre-launch to assembly (green, 1-7), post-assembly finalization tasks (8-17), and end-use cases in orbit or on a planetary/moon surface.

6.1.1 Near-term, space limited

For model A, shown below in Figure 7A, our interior design includes several functional spaces, assuming we must meet the usual suite of required astronaut support areas (sleeping quarters, galley, research racks for scientific exploration, entertainment, a window and mental health meditation corridor, etc.). We utilized the largest possible configuration of tiles allowable by near-term rocket payload fairings to facilitate comfortably hosting up to an eight person crew (these dimensions assume a 20% increase in the original TESSERAE at-scale dimensions shown in Figure 2). Our aesthetic choices drew from Japanese architectural display, in particular, the integrity and modularity of Metabolism—a post-war Japanese architectural movement that fused ideas from architectural megastructures with those of organic biological growth [40]. Our design also borrows from the idea of shoji, a room divider consisting of translucent paper, for mixed-use space utilization. Having proposed the buckminsterfullerene shape, a relatively new geometry to space architects (in comparison to the many designs proposed for cylindrical habitats), we have had to develop new design primitives for the interior life subdivisions. The diagrams and functional spaces discussed below are a preliminary attempt and part of ongoing work to marry our adaptive, self-assembling shell concepts with the practical needs of a crew of eight.

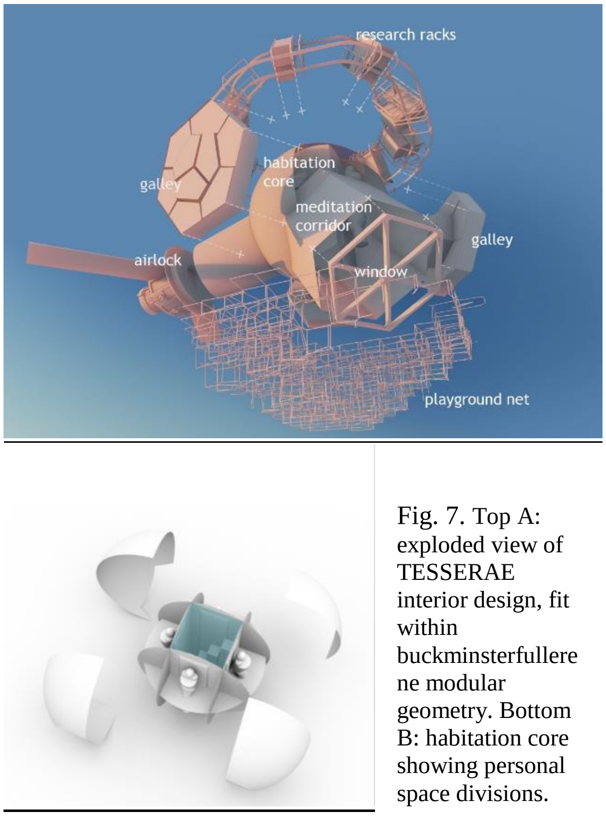

Fig. 7. Top A: exploded view of TESSERAE interior design, fit within buckminsterfullerene modular geometry. Bottom B: habitation core showing personal space divisions.

<u>Habitation Core</u>

Located in the middle of the module, the Habitation Core ensures convenient access to any location within the capsule while providing the privacy needed for sleeping and personal tasks (Figure 7B). The private quarters are equally divided by partitions, with personal belongings storage located in the center division (shown in teal). Each inhabitant can enjoy a virtual projection experience projected on the curved containment wall by their berth for recreation, per feedback from our astronaut user research sessions where open-space projection was preferred to VR headsets. The habitation core is centered in the volume of the TESSERAE module and therefore more protected, should the crew experience a micro-meteoroid impact or other external danger.

<u>Racks</u>

For scientific racks, we based our design on the "Random Access Frame" reconfigurable racks of the Jet Propulsion Lab's (JPL) space architect Scott Howe [41]. The design provides a multipurpose and flexible system of racks for use by life support systems, research equipment, and storage. We further optimized the frame shape to better fit into the fullerene geometry without any gaps. Ideally suited for the fullerene station, the rack system is easily repairable, reconfigurable, and lightweight, which makes it a practical choice for space design. Utilizing already existing rack systems, with some optimization, saves time and allows for cheaper production costs.

<u>Galley</u>

Every cubic inch is vital in this near-term model of a space habitat. For efficient construction of a galley, we employed a cabinetry tessellation to ensure fully optimized use of physical space. We investigated various types of tessellations and ultimately chose the tetragon tessellation as it mates well with both TESSERAE tile shapes—pentagons and hexagons. To maintain storage packing efficiency, any angle of a package should not be less than 60 degrees. The hexagonal tile best allows this, and thus, the hexagonal tile properly serves as a galley cabin that can be fully stowed for launch and then deployed inside the closed habitat after assembly has completed.

6.1.2 Medium-term, intermediate space constraints

A secondary, medium-term approach to space habitats will allow for longer sightlines and open spaces, where a single TESSERAE module may be devoted to a single purpose—say the command and operations bridge of a spacecraft, or a large and expansive entertainment area. We spend less time proposing this model in this paper, as this use case is likely more than a decade away, but present below an artist's conception of the TESSERAE modular architecture shell with this use case (Figure 8A).

Finally, we present an exterior view of the TESSERAE concept, showing self-assembly of several TESSERAE modules in parallel around Mars to support an on-surface mission; see Figure 8B, below, for MOSAIC (Mars Orbiting Self-Assembling Interlocking Chambers).

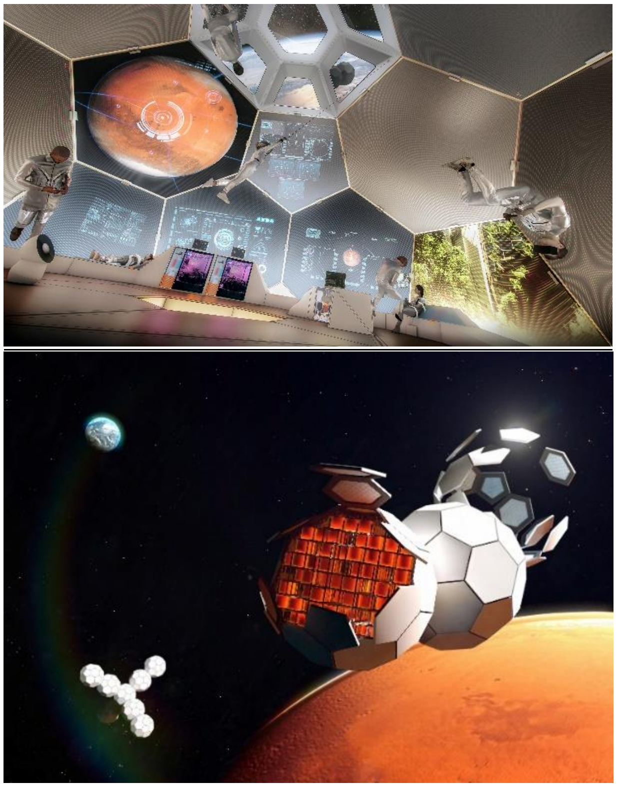

Fig. 8. Top A: speculative TESSERAE interior in medium-term conception of physical space allocation (post current survivalist period, pre-Stanford Torus period). Image courtesy of Igor Neminov. Bottom B: artist's conception of MOSAIC concept, image courtesy of TU Dortmund Fraunhofer Institute.

7. Conclusions

The TESSERAE project serves a dual mission—to both reimagine the future of space architecture through growth paradigms and "self-aware self-assembly" writ-large, and to realize near-term, practical incarnations of these concepts as space habitats. The TESSERAE tiles described in this paper are one example of a proof of concept, model platform by which we can achieve discrete, guided self-assembly, in the category of programmable matter at space scale. Our continuing and future work explores discrete, unguided self-assembly in the model of crystal growth or accretion chemistry (modelled by the space-filling plesiohedrons discussed in section 6). We also note an interest in continuous self-assembly or growth of structures without requiring the discretization of parts, such as extrusion and inflation—though these types of continuous self-assembly generally require an in-situ feedstock and explicit ISRU. Our hope, through this work, is to suggest a compelling model for indeterminate growth of space architecture. We aim to design, test and deploy modules that can grow, stack and expand throughout the expansive physical scales and long-duration time scales associated with space exploration, rather than only across the short time scales known to scoped funding programs at the mercy of changing political winds. This paper has discussed a novel design theory for "growing" space architecture through agent-less self-assembly, presented a condensed literature review of the giants on whose shoulders we stand, offered a view into our prototype engineering and space environment testing, and closed with our preliminary mission ConOps and interior design work to adapt our structures to the real constraints of human habitation.

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References

[1] West, Geoffrey. *Scale: the universal laws of growth, innovation, sustainability, and the pace of life in organisms, cities, economies, and companies*. Penguin, 2017.

[2] Mandelbrot, Benoit B. The fractal geometry of nature. Vol. 1. New York: WH freeman, 1982.

[3] Bonabeau, Eric, Directeur de Recherches Du Fnrs Marco, Marco Dorigo, and Guy Theraulaz. *Swarm intelligence: from natural to artificial systems*. No. 1. Oxford university press, 1999.

[4] Sancar, Aziz. "Mechanisms of DNA excision repair." *Science* 266, no. 5193 (1994): 1954.

[5] International Space Station Transition Report. NASA. 2018 [Online] Available: https://www.nasa.gov/sites/default/files/atoms/files/iss_transition_report_180330.pdf

[6] Smith, Eric, and Harold J. Morowitz. *The origin and nature of life on Earth: the emergence of the fourth geosphere*. Cambridge University Press, 2016.

[7] Thompson, Darcy Wentworth. "On growth and form." *On growth and form.* (1917). [Page numbers from Cambridge University Press, 1942 edition]

[8] Ekblaw, Ariel, and Joseph Paradiso. "Self-Assembling Space Habitats: TESSERAE design and

mission architecture." In 2019 *IEEE Aerospace Conference*, pp. 1-11. IEEE, 2019.

[9] Jing Pei, Luke Murchison, Victor Stewart, James Rosenthal, Drew Sellers, Mark Banchy, Adam BenShabat, Ryan Elandt, David Elliott, and Adam K. Weber. "Autonomous Rendezvous and Docking of Two 3U Cubesats Using a Novel Permanent-Magnet Docking Mechanism", *54th AIAA Aerospace Sciences Meeting, AIAA SciTech Forum*, (AIAA 2016-1465).

[10] Howard, N. and Nguyen, H.D., National Aeronautics and Space Administration (NASA), 2010. *Magnetic capture docking mechanism*. U.S. Patent 7,815,149.

[11] Falvello, A. and Tibbits, S. (2013) “Biomolecular, Chiral and Irregular Self-Assemblies,” In *Proceedings of the Association for Computer Aided Design in Architecture 2013: Adaptive Architecture*, Waterloo, Canada.

[12] Hacohen, Adar, Iddo Hanniel, Yasha Nikulshin, Shuki Wolfus, Almogit Abu-Horowitz, and Ido Bachelet. "Meshing complex macro-scale objects into self-assembling bricks." *Scientific reports* 5 (2015): 12257.

[13] Domingos, Jorge LC, François M. Peeters, and W. P. Ferreira. "Self-assembly of rigid magnetic rods consisting of single dipolar beads in two dimensions." *Physical Review E* 96, no. 1 (2017): 012603.

[14] “NASA Strategic Plan 2018.” NASA. [Online] Accessed 11 November 2018. Available: https://www.nasa.gov/sites/default/files/atoms/files/nasa_2018_strategic_plan.pdf

[15] Hillis, Danny. "The enlightenment is dead, long live the entanglement." *Journal of Design and Science* (2016).

[16] The Long Now Foundation. http://longnow.org/

[17] Oxman, Neri. "Material-based design computation." PhD diss., Massachusetts Institute of Technology, 2010.

[18] Oxman, Neri. "Templating design for biology and biology for design." *Architectural Design* 85, no. 5 (2015): 100-107.

[19] T. McNulty. Adapting Biomimicry for Designing Aerospace Materials. Lecture Presentation. NASA NIEA 2017.

[20] Keating, Steven John. "From bacteria to buildings: additive manufacturing outside the box." PhD diss., Massachusetts Institute of Technology, 2016.

[21] Whitesides, George M., and Bartosz Grzybowski. "Self-assembly at all scales." *Science* 295, no. 5564 (2002): 2418-2421.

[22] Falvello, A. and Tibbits, S. (2013) “Biomolecular, Chiral and Irregular Self-Assemblies,” In *Proceedings of the Association for Computer Aided Design in Architecture 2013: Adaptive Architecture*, Waterloo, Canada.

[23] Tibbits, Skylar, and Kenny Cheung. "Programmable materials for architectural assembly and automation." *Assembly Automation* 32, no. 3 (2012): 216-225.

[24] Hacohen, Adar, Iddo Hanniel, Yasha Nikulshin, Shuki Wolfus, Almogit Abu-Horowitz, and Ido Bachelet. "Meshing complex macro-scale objects into self-assembling bricks." *Scientific reports* 5 (2015): 12257.

[25] Grzybowski, Bartosz A., Adam Winkleman, Jason A. Wiles, Yisroel Brumer, and George M. Whitesides. "Electrostatic self-assembly of macroscopic crystals using contact electrification." *Nature materials* 2, no. 4 (2003): 241.

[26] Haghighat, Bahar, Emmanuel Droz, and Alcherio Martinoli. "Lily: A miniature floating robotic platform for programmable stochastic self-assembly." In *Robotics and Automation (ICRA), 2015 IEEE International Conference on*, pp. 1941-1948. IEEE, 2015.

[27] Gilpin, Kyle, Ara Knaian, and Daniela Rus. "Robot pebbles: One centimeter modules for programmable matter through self-disassembly." In *Robotics and Automation (ICRA), 2010 IEEE International Conference on*, pp. 2485-2492. IEEE, 2010.

[28] Rubenstein, Michael, Alejandro Cornejo, and Radhika Nagpal. "Programmable self-assembly in a thousand-robot swarm." *Science* 345, no. 6198 (2014): 795-799.

[29] Kong, Edmund Mun Choong. "Spacecraft formation flight exploiting potential fields." PhD diss., Massachusetts Institute of Technology, 2002.

[30] Gettliffe, Gwendolyn Vines. "Stability analysis of electromagnetically supported large space structures." PhD diss., Massachusetts Institute of Technology, 2015.

[31] Bekey, Ivan. *Advanced space system concepts and technologies: 2010-2030+*. p.32, AIAA, 2003.

[32] Minovitch, Michael A. *Inflatable core orbital construction method and space station*. U.S. Patent 4,730,797, issued March 15, 1988.

[33] Cheung, Kenneth C and Neil Gershenfeld, “Reversibly assembled cellular composite materials,” *Science* 341, no. 6151 (2013): 1219-1221.

[34] Langford, Will, Amanda Ghassaei, Ben Jenett, and Neil Gershenfeld. "Hierarchical assembly of a self-replicating spacecraft." In *Aerospace Conference, 2017 IEEE*, pp. 1-10. IEEE, 2017.

[35] “Bigelow Expandable Activities Module (BEAM),” Bigelow Aerospace and NASA, [Online] Accessed 10 October 2018. Available: https://www.nasa.gov/content/ bigelow-expandable-activity-module.

[36] Sherwood, Brent. "Lunar architecture and urbanism." *SAE transactions* (2005): 354-361.

[37] Ekblaw, Ariel, Elisheva Shuter, and Joseph A. Paradiso. "Self-Assembling Space Architecture: tessellated shell structures for space habitats." In AIAA Scitech 2019 Forum, p. 0481. 2019.

[38] “NASA’s Lunar Outpost will Extend Human Presence in Deep Space.” NASA. [Online] Accessed 11 November 2018. Available: https://www.nasa.gov/feature/nasa-s-lunar-outpost-will-extend-human-presence-in-deep-space

[39] de Weck, Olivier, William Nadir, Justin Wong, Gergana Bounova, and Thomas Coffee. "Modular structures for manned space exploration: The truncated octahedron as a building block." In *1st Space Exploration Conference: Continuing the Voyage of Discovery*, p. 2764. 2005.

[40] Lin, Zhongjie. *Kenzo Tange and the Metabolist movement: urban utopias of modern Japan.* Routledge, 2010.

[41] Howe, A. Scott, Raul Polit-Casillas, David L. Akin, Katherine McBryan, and Christopher Carlsen. "Random Access Frame (RAF) System Neutral Buoyancy Evaluations." 45th *International Conference on Environmental Systems*, 2015.