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The Future Unfolds - Simplifying Polyhedral Space Habitat Module Deployment Using a Contiguous Unfolding Method

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Abstract

The concept of polyhedral space habitat modules has been proposed as an improvement over cylindrical modules for decades and has increased in popularity in recent years. Polyhedral modules have the potential to enable the construction of large-scale habitat construction. However, the efficient deployment of polyhedral space habitat modules presents significant challenges. There are two established methods for the deployment of polyhedral habitats: quasi-stochastic assembly and origami-like deployment. Each of these methods have unique drawbacks including risk of loss, complex control mechanisms, excessive deployment hardware, panel thickness limitations, deployment ratio limitations, shape limitations. While overcoming these challenges is critical in ensuring the practicality of polyhedral module deployment, the specific method used to solve these challenges will have a significant impact on the cost and feasibility of the entire system. The ideal method for polyhedral habitat deployment should be simple, inexpensive, and reliable. This paper proposes a straightforward method for the deployment of polyhedral space habitat modules, utilizing a contiguous unfolding technique for flat-packed panels. Diverging from established methods, this method employs a linear process wherein flat-packed panels are rotated about their edges through mechanical means to form their final three-dimensional shape. The goal of this research was to verify the feasibility of this contiguous unfolding technique using digital simulations. A principal finding of this research is the successful, collision-free demonstration of the unfolding process for panels with non-trivial thickness. This verification promises a simple, inexpensive, and reliable deployment method which overcomes the limitations inherent in the established methods. Future research should focus on increasing the technology readiness level of this deployment method through either parabolic flight or on-orbit experimentation. This contiguous unfolding deployment method represents a fresh perspective in the growing field of polyhedral space habitat module construction and contributes to more efficient and feasible solutions for large-scale habitat construction.

Keywords: (space habitat, deployable structure, module, polyhedron, folding)

Acronyms/Abbreviations

TRL	Technology Readiness Level
SMA	Shape memory alloy
NiTi	Nickel-Titanium

1. Introduction

The development of space habitats is a critical step in humanity's expansion beyond Earth. At this point in the development of the space frontier, mass-to-orbit capacity is limited, and considerations of cost effectiveness and return on investment remain high priorities for space missions. For this reason, cylindrical modules have been the de-facto choice for space habitation due to their structural simplicity and well-understood development processes. However, cylindrical modules are extremely limited in size by the interior dimension of the rocket fairings they are stowed in (being largely cylindrical themselves).

Deployable habitats (those that have a small overall volume during transport and can deploy into a larger volume when needed) offer an alternative to the traditional cylinder, boasting interior volumes and dimensions that can far surpass those of traditional cylinders. Despite the promise of deployable structures, they present several engineering challenges. The transition from a compact, stowed configuration to a fully deployed three-dimensional habitat requires precise control, reliable mechanisms, and a deployment profile that minimizes the risk of failure. Some examples of proposed deployment methods are the various origami-inspired deployment methods and quasi-stochastic assembly, and while these methods offer unique benefits, they are each hampered by practical limitations such as complexity, added mass, and risk of failure.

To progress the field, it is essential to develop a deployment method that is not only technically feasible, but also cost effective, reliable, and versatile. This paper introduces a novel deployment method* for polyhedral space habitat modules that addresses many of the limitations inherent in the aforementioned methods. By

* This deployment method was introduced by this author in a previous research paper involving multi-criteria analysis of various polyhedral habitat module forms [5], though a similar method was briefly mentioned earlier in a dissertation by Ekblaw [8]. In the text of the dissertation, the author did not consider this method to have potential as a primary deployment method due to the perceived lack of reconfigurability.

employing a contiguous unfolding technique, flat-packed panels can form the final polyhedral shape in a simple, straightforward process. Through digital simulations, this paper demonstrates that this technique can be collision-free and capable of utilizing panels with non-trivial thickness.

2. Theoretical Framework

Successfully folding a number of faces into a three-dimensional polyhedron requires certain conditions to be met. One of these conditions is that the structure must be contiguous in a meaningful way. In other words, all components must always be in contact (either directly or by extension) with the rest of the components. This is to avoid the possibility of one or more components being lost to space. A contiguous structure also precludes the necessity of a large net for component containment [1].

Another condition is that the panels cannot collide/intersect during the unfolding process. This second condition becomes more of a consideration and concern when the faces are thicker and more rigid, unlike origami-like deployment [2, 3], as they cannot occupy the same volume at any point in the unfolding process. For example, while a thin sheet of paper may be folded many times over and retain its flat appearance due to its two-dimensional approximation, this is not possible with thick, rigid, panels.

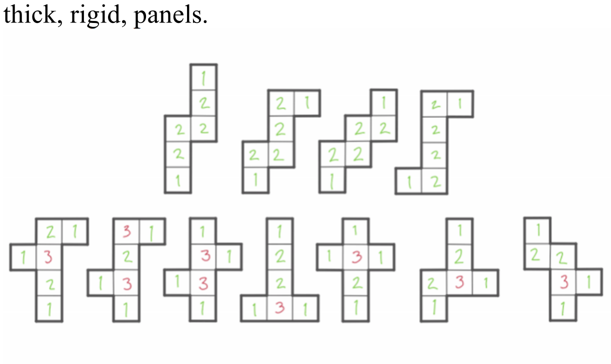

Fig. 1. Face nets of a cube, linear nets shown above.

When considering the folding of faces into polyhedral shapes, it is helpful to begin by first assessing the unfolding of polyhedra into flat faces. For any polyhedral shape, a net can be created by unfolding the faces of the shape until only a flat network of faces remains. A given polyhedron can have numerous permutations of nets, and these nets may fall into certain categories having useful properties. One of these categories is the linear net, wherein each face is connected to no more than two other faces (see Fig. 1). The linear net is useful in that it allows the faces to be folded on top of one another in an alternating, accordion pattern, like folding a narrow strip of paper back and forth. The unfolding of these panels would occur at alternating convex and reflex angles (see Fig. 2). This accordion fold permits a highly compact stowage volume while maintaining contiguous connection between the panels. The alternating unfolding of a linear net is the core principle of the contiguous unfolding method.

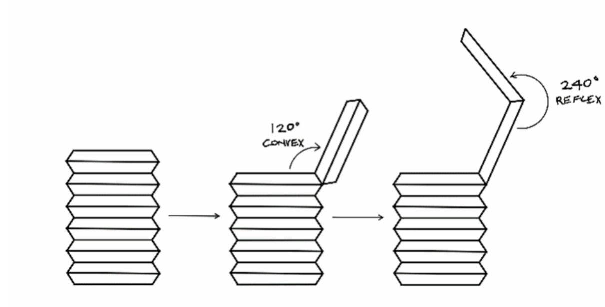

Fig. 2. Stacking of a notional linear net (rhombic dodecahedron depicted), indicating alternating convex and reflex actuation joints.

Any polyhedron can be represented by a graph where each node of the graph represents a face of the polyhedron. A linear net can be represented on this graph as a "path" through this network of nodes (see Fig. 3). To get an idea of how many paths exist for a given polyhedron, the paths can be counted, provided that:

1. A single node is designated as the starting node
2. All nodes are visited only once
3. Isomorphic paths are not counted more than once

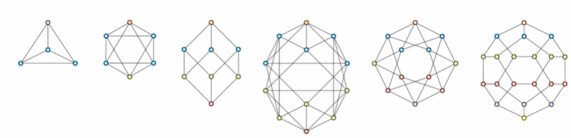

Fig. 3. Face graphs for common polyhedra, indicating the face nodes colored by tier. From left to right: tetrahedron, cube, octahedron, dodecahedron, rhombic dodecahedron, and icosahedron. Tier 0: orange, Tier 1: blue, Tier 2: green, Tier 3: red, Tier 4: violet, Tier 5: yellow.

Additionally, a path can be called "closed" if the ending node is adjacent to the starting node*.

To determine if two paths are isomorphic, the graph can be represented such that the starting node is placed at the top, the connected nodes are placed in the next tier, the new nodes connected to those are placed in the tier below that, and so on until all nodes are tagged with a tier identifier, as depicted in Fig. 3. Any path stemming from the starting node can then be represented by a list of tier identifiers (ex: [0,1,3,2,1,3,4,3,1,2,3,1], see Fig. 4). In this way, any two paths that share the same list of tier identifiers can be considered isomorphic and thereby redundant.

* Closed paths can be advantageous for the purposes of utility loops; electricity, data, and coolant are some examples of utilities that could benefit from being in closed loops.

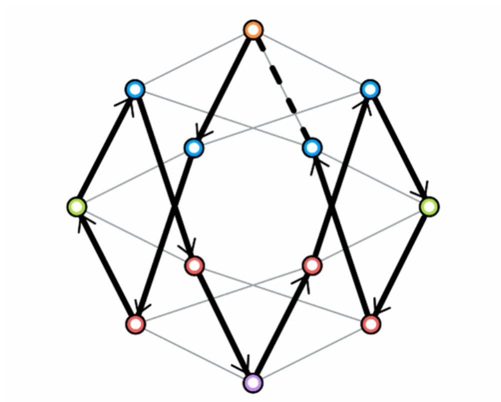

Fig. 4. Path represented on face graph of a rhombic dodecahedron. The permutation [0,1,3,2,1,3,4,3,1,2,3,1] is shown, representing a closed path.

The following table shows the number of unique paths and unique closed paths of linear networks for some common polyhedra. It should be noted that the validity of each unique path and unique closed path is contingent on whether the path can be deployed without self-collision, see section 3.2.

Table 1. Linear network paths for common polyhedra

Polyhedron	Number of Faces	Connections per Face	Unique Paths	Unique Closed Paths
Tetrahedron	4	3	1	1
Cube	6	4	4	3
Octahedron	8	3	3	2
Dodecahedron	12	5	270	110
Rhombic Dodecahedron	12	4	130	48
Icosahedron	20	3	26	10

Table 1 shows that the number of unique paths and unique closed paths is positively correlated with the number of faces and the connections per face, but connections per face has a stronger impact on the number of paths. The dodecahedron, having a high face count and the highest number of connections per face, is the polyhedron with the most unique paths and unique closed paths, followed by the rhombic dodecahedron. A higher number of paths simply illustrates the versatility of the polyhedron with regard to deployment options. Having numerous deployment paths increases the deployment options, potentially reducing collision risk.

3. Actuation and Deployment Sequence

3.1 Actuation

The panel deployment need only occur once - when the module is deployed - so a reversible solution or one that is able to actuate multiple times at the expense of mass and complexity is not necessary. For such a singular, reliable method of mechanical actuation, a shape memory alloy (SMA) actuator seems to be uniquely suited to the purpose.

3.1.1 Technology

Nikel-Titanium (NiTi) alloy has been extensively tested and used in industrial and commercial applications (including for/by NASA [4]) to great success. Made from commonly occurring materials, NiTi alloy is a simple alloy. It is lauded for its tuneable mechanical properties of superelasticity and shape memory. It is the property of shape memory that makes it ideal for the purpose of actuation.

The shape memory of NiTi alloy occurs at a specific temperature (tuneable by nickel-titanium proportion) and has the effect of returning the metal to the trained shape even after relatively large (up to 6-8%) pseudo-plastic deformation. In the use case of actuation, NiTi alloy can be used to change shape (ie: perform mechanical work) when it reaches a certain critical temperature. Since NiTi alloy is electrically conductive, this temperature can be reached via electrical resistance heating. As a measure of mass to strength ratio, NiTi alloy performs well compared to other actuators such as electrical motors or electromagnets. After successful deployment, the NiTi alloy actuators can be removed as they are no longer needed to perform work.

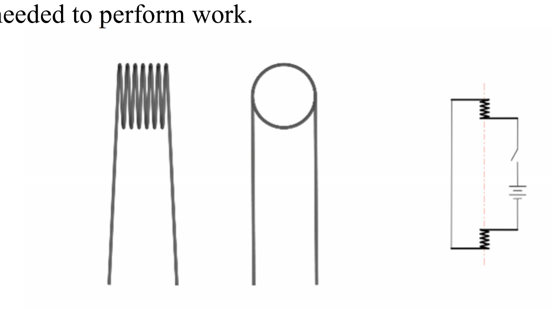

Fig. 5. NiTi torsion spring (left and center); circuit configuration (right).

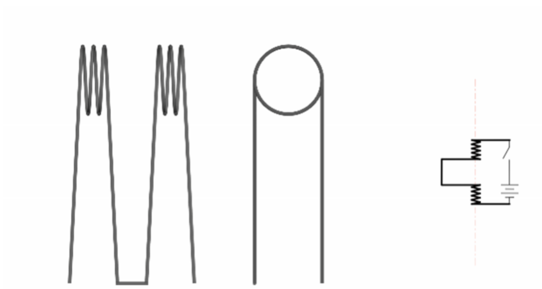

Fig. 6. Custom NiTi torsion spring (left and center); circuit configuration (right).

3.1.2 Form

The purpose of the actuator is to rotate the panels about their edges with respect to other panels, so the action is a rotational action. For this purpose, torsion springs fabricated using NiTi alloy would suit this range of movement while limiting the plastic deformation to within the 6-8% range. The springs can be fabricated such that their arms have a pre-critical-temperature position that secures the panels in the stowed configuration and a post-critical-temperature position set to the deployed rotation which also allows the springs to be removed. During actuation, a current is passed through the spring, heating the spring up to or past the critical temperature, wherein the spring rotates, turning the panels into position. Once the panels are in position, a secondary locking mechanism can engage to secure the panels and ensure an airtight seal. Each actuation mechanism would need the resistance heating circuit to start and end in the same panel for circuit control purposes; this can be accomplished using two actuation springs connected in series via a stationary rail (see Fig. 5), or a single actuation spring shaped such that the ends of the spring are located within the same panel (see Fig. 6). Once the module is fully deployed, the NiTi torsion springs can be removed entirely from the joints for future use or disposal. Whether the springs are trained as one-way or two-way springs depends on the chosen deployment profile.

3.2 Deployment Profile

3.2.1 Sequence

For any given folded net of panels, there exist many options for how to go about unfolding the panels into their final polyhedral shape. Beyond the folding order of the net, there is the question of which joints to unfold at which stages of deployment. Broadly speaking, there are four distinct profiles for the unfolding deployment of polyhedral module panels: simultaneous, individual, staged, and progressive (see Fig. 7).

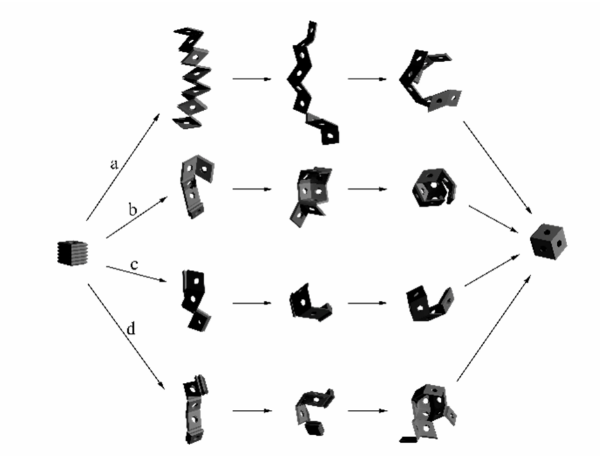

Fig. 7. Examples of deployment profiles:
a) simultaneous, b) individual, c) staged, d) progressive

Simultaneous

A simultaneous deployment sequence is one in which all panels are actuated at the same instant. This results in all the panels rotating about each other's edges until they lock into their final position and the desired shape is achieved (see Fig. 8). While the control profile is simple, it results in a complex dynamic of panels exerting torques on each other in numerous planes, the force and direction of which are in constant flux. For simulations of this deployment profile, the assumptions about the actuator's torque strength, panel mass, and timing are all key. If any one of these values are misaligned from the real-life case, the module could unfold in a way that risks self-collision and/or inadequate joint-locking prior to completion.

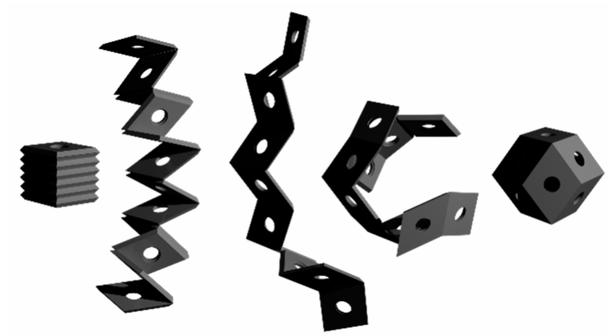

Fig. 8. Simultaneous deployment

Individual

A deployment sequence is individual when each panel is actuated in turn and no other panel can be actuated until the previous panel has locked into place (see Fig. 9). A benefit of this profile is that the deployment process can easily be simulated beforehand and self-collision risk can be all but eliminated, barring actuation failures. Each step of the deployment process is predictable and is not sensitive to small differences from the simulation. The deployment can be easily paused or delayed at any point during the deployment process if sensor readings are anomalous, or simply if more time is required for a given actuator to complete its deployment.

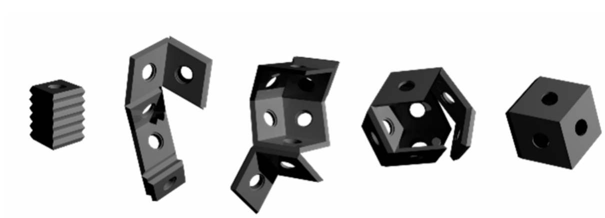

Fig. 9. Individual deployment

Staged

A staged deployment profile is a hybrid of the simultaneous and individual profiles, wherein small groups of panels are actuated simultaneously, resulting in two or more stages in the deployment process (see Fig. 10). A staged profile can be faster than an individual profile while mitigating much of the dynamic risk involved in a simultaneous profile. This is because the panels can be grouped in such a way as to avoid self-collision with reasonable assurance.

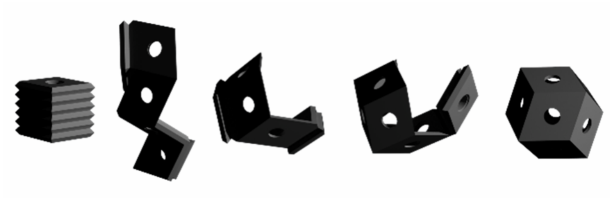

Fig. 10. Staged deployment

Progressive

A progressive deployment sequence combines elements of both the simultaneous and staged sequences. Like the simultaneous sequence, at least one panel is always moving during deployment, but, similar to the staged sequence, the panels are activated at different times (see Fig. 11). The progressive deployment sequence resembles a staged deployment that overlaps instead of being sequential. This is likely the most complex and dynamic deployment profile to design in that the actuation timing can be defined on a rolling basis rather than a sequential basis. Like the simultaneous deployment, the torque strength, panel mass, and timing can greatly affect the end result.

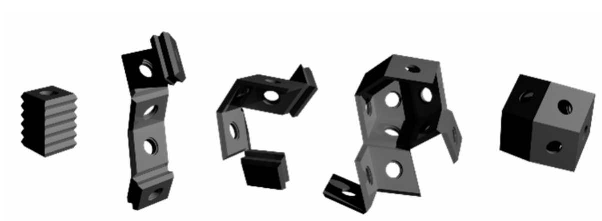

Fig. 11. Progressive deployment

Given that the deployment durations in question are not a critical factor during on-orbit assembly, an individual deployment profile is recommended in most circumstances as it carries the least risk in deployment issues and requires the same actuation control technology without the need for flawless and carefully coordinated timing.

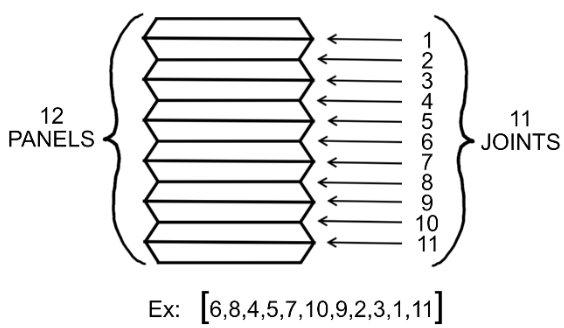

Fig. 12. Panel joint enumeration and sequence notation

3.2.2 Permutations

Depending on the shape under consideration, the number of joint actuation permutations can be quite numerous (assuming an individual deployment profile). For a polyhedron of a given number of faces, there are one fewer number of joints that will be actuated during deployment (for example, a cube having (6) faces will have (5) joints actuate during deployment). A deployment sequence consists of an ordered list of these joints (see Fig. 12), where the actuation order of each joint is given by its position in the list. The number of permutations for such a sequence of joints can be found using the permutation formula (see Equation 1).

$$P(n,r) = \frac{n!}{(n-r)!} \qquad (1)$$

To get the total number of individual deployment profile options, the number of permutations must be multiplied by the number of unique paths (see Table 2). Many of these permutations would inevitably result in collisions of the panels. In fact, collisions can even occur on the first or second actuation, depending on the polyhedron. For this reason, careful selection of a deployment sequence is of paramount consideration.

Table 2. Polyhedron deployment permutations

Polyhedron	Unique Deployment Permutations	Unique Closed Paths	Total
Tetrahedron	6	1	6
Cube	120	3	360
Octahedron	5,040	2	10,080
Dodecahedron	$3.9916 \cdot 10^{7}$	110	$4.3908 \cdot 10^{9}$
Rhombic Dodecahedron	$3.9916 \cdot 10^{7}$	48	$1.9160 \cdot 10^{9}$
Icosahedron	$1.2165 \cdot 10^{17}$	10	$1.2164 \cdot 10^{18}$

4. Model Validation and Comparative Analysis

To validate the concept of this novel unfolding process, digital model simulations were conducted along with a qualitative, comparative analysis.

4.1 Digital Simulation

A successful collision-free unfolding process can be modelled without the need for practical demonstration by simulating the movements of the panels. The rhombic dodecahedron was selected for the purposes of this model validation, primarily because this polyhedron was found to be the most well-suited shape for the purposes of space habitat modules [5] (see Fig. 7 –11).

4.1.1 Method

The (12) panel faces of the simulated rhombic dodecahedron were modelled using Autodesk 3DS Max software. These panel faces were then arranged in the stowed configuration, and their axes of rotation were located in accordance with the selected deployment profile. The panel hierarchy was set such that the centroid of the model was the primary "parent", the two center-most panels were "children" to the centroid, and each panel working outwards was the child to the panel that came before it. In this way, each panel is able to rotate with respect to their parent rather than the global coordinate system. Rather than simulating a single deployment profile, all four deployment profiles were simulated: simultaneous, individual, staged, and progressive. The model was animated using keyframes, wherein each panel would start rotating at a certain keyframe and end rotating at a certain later keyframe. For simplicity, the rate of rotation was kept constant for each panel without regard to acceleration or any differences that might be observed amongst the panels in a practical setting (due to inertia, the different positions of the panels, or any differences in leverage during deployment).

4.1.2 Results

In the simulations conducted, all four deployment profiles have demonstrated collision-free unfolding deployment. On their own, these results validate the concept and support the further investigation of unfolding deployment.

4.2 Comparison with Established Methods

There are two established methods in the literature for the assembly of polyhedra from individual faces: quasi-stochastic assembly and origami-like deployment. Each of these methods have been described in the literature and each attempt to solve the challenge of launching large habitable volumes in space-efficient packages. The ultimate goal of these deployment methods is to maximize quantitative and qualitative benefits while minimizing risk and expense.

4.2.1 Quasi-Stochastic Assembly

Conceived of by Dr. Ekblaw, quasi-stochastic assembly is a panel deployment method characterized by the use of electromagnets to attract and connect a number of free-floating panels in an automated and unsupervised manner. Experiments using small-scale hardware indicate the potential success of using magnets to successfully connect panels in a weightless environment, though the same experiments also note the various failure modes of such a system along with experimental examples of said failure modes [6]. One limitation of this method is that the magnetic field attractive force scales with the inverse cube of the distance*. In other words, the required magnetic force is extremely sensitive to distance. Once scaled up to full-size, the same set-up would not be as effective at attracting other panels, now at a further distance†. In concert with the experimental difficulty at small scales, quasi-stochastic assembly may require considerable mass for strong electromagnets and may not achieve initial success at full scale considering the identified failure modes. Quasi-stochastic assembly involves the complex interactions between magnetic forces in a nearly random initial condition, which assumes complexity without the assurance of knowing how the deployment process will result. Proponents state that if initial success is not achieved with quasi-stochastic assembly, then further attempts may be carried out with no drawbacks [1], however it is not clear that the safety of the hardware can be reasonably assured if the components are allowed to be repeatedly and erroneously collided with each other. On a positive note, as the panels can be thick and the joints robust, quasi-stochastic assembly is not by its own merit necessarily vulnerable to radiation exposure or air leakage.

4.2.2 Origami-like Deployment

Origami-like deployment for non-pressurized structures has achieved a high TRL for its use in devices such as solar panel arrays and has even been proposed for coronagraph shades and pressurized orbital, lunar, and Martian structures [7]. There is, however, a limit to the exterior panel thickness of the structure before the pre-deployed configuration becomes untenable for use. While a thin membrane may enable homogenous, air-tight structures, their limitation in thickness does not allow for substantial radiation shielding material to be integral to the structure. Research on thick-panel origami-like deployment has emerged that acknowledges the aforementioned limitations and attempts to prove that these limitations can be overcome [3]. While the method proposed for thick-panel origami-like deployment appears to successfully demonstrate deployment, this has only been demonstrated for a flat plane rather than an enclosed volume. Additionally, the thick-panel deployment method proposes no solution for limiting air leakage through the necessarily large gaps between the faces at the pivot points. The high number of moving parts and complex actuation interactions further complicates the successful deployment of origami-like deployment and contributes to a higher risk of failure.

Table 3 provides a broad, relative (non-quantitative) comparison of these methods alongside the proposed contiguous unfolding method accross a handful of challenge metrics for any potential deployable structure intended for human habitation. The more checks a deployment method has conveys the relative susceptibility of that metric to the indicated challenge metric.

Each deployment technique varies in their relative susceptibility to the challenge metrics; a method might be susceptible to some metrics but not others. For example, the quasi-stochastic assembly method permits robust

* Depending on the actual distance between dipole magnets, the force will transition between the inverse square of the distance and the inverse cube of the distance, though at the scales in question the latter would be the dominant condition until the magnets are nearly touching [9].

† A larger scale can also be disadvantageous for magnetic attraction because the panels' mass increases with the square of the distance, so the attractive force of the on-board magnets must be exponentially greater at full-scale when compared to the scale models evaluated.

radiation shielding, however the other metrics remain a challenge. The thin and thick origami-like deployment methods are similar in their readiness to meet these challenges, though they are each reciprocal in their ability to address radiation and air leakage. By contrast, the contiguous unfolding method seems to be near uniformly well-positioned to address each of the challenge metrics.

Table 3. Susceptibility to deployment challenge metrics

	Deployment Hardware	Complexity	Risk of Failure	Radiation Vulnerabilit	Air Leakage	**Total**
Quasi-Stochastic Assembly	✓✓✓	✓✓✓	✓✓✓	✓	✓✓	12✓
Thin Origami-like Deployment	✓	✓✓	✓✓	✓✓✓	✓	9✓
Thick Origami-like Deployment	✓	✓✓✓	✓✓	✓	✓✓✓	10✓
Contiguous Unfolding	✓	✓	✓	✓	✓✓	6✓

5. Conclusions

Results from the digital simulations demonstrate that the contiguous unfolding method for linear polyhedral nets can successfully deploy a polyhedral module in a negligible duration using any of the four deployment profiles. By individually actuating the module face panels, the deployment can occur without substantial risk of complications or collisions. For any valid linear net there are likely multiple individual deployment profiles that can achieve a successful deployment, whether by changing the network path, the deployment profile or the sequence permutation.

The recommended actuation method (NiTi torsion springs) is a lightweight and established technology, requiring little in the way of future development and need not be integral to the module face panels.

When the deployment methods mentioned are qualitatively compared on their ability to address a number of deployment challenge metrics, the contiguous unfolding method seems better-positioned to address these challenges than the established methods.

Future work on contiguous unfolding deployment should demonstrate the unfolding of a test model in a weightless environment such as a parabolic or on-orbit flight experimentation. The successful demonstration of this method would further validate the feasibility of contiguous unfolding for space-based applications.

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