Deployable Pipe-Z

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This paper presents a concept of deployable Pipe-Z (dPZ): a modular structural system which takes advantage of the robustness of rigid-panel mechanism and allows to create free-form links which are also reconfigurable and deployable. The concept presented can be applied for building habitats and infrastructures for human exploration of oceans and outer space. dPZ structures can adapt to changing requirements e.g. mission objectives, crew condition and technological developments. Furthermore, such lightweight and adaptable structural concept can assist in sustainable exploration development. After brief introduction, the concept of Pipe-Z (PZ) is presented. Next, the reconfigurability of PZ is explained and illustrated with continuous and collision-free transition from a PZ forming a Trefoil knot to a Figure-eight knot. The following sections introduce, explain and illustrate the folding mechanism of a single foldable Pipe-Z module (fPZM) and entire dPZ structure. The latter is illustrated with asynchronous (delayed) unfolding of a relatively complex Unknot. Several applications of PZ are suggested, namely for underwater and deep-space and surface habitats, for permanent, but in particular, temporary or emergency passages. As an example, a scenario of a failure of one of the modules of the International Space Station is presented where a rigid structure of 40 fPZMs bypasses the "dead link". A low-fidelity prototype of a 6-module octagonal dPZ is presented; several folding schemes including concentric toric rings are demonstrated. Practical issues of pressurization and packing are briefly discussed.

Keywords: ocean & space outpost; banana-split; deployable structure; rigid-panel folding; free-form.

1. Introduction

Deployable structures offer several advantages for building, not only for structures on Earth, but in particular for stations and habitats in space and undersea. Intelligent constructive and packaging concepts allow for maximum load capacity and minimization of material use coupled with an increase in operational and habitable volume [1].

The majority of concepts for such habitats in outer space struggle to accommodate rectangular floor plans, which are the most common for humans, into cylindrical or spherical launch vehicle. E.g. cylindrical pipes have been proposed for Mars habitat modules in [2]. Two schemes have been presented there: a "bologna-slice" configuration of transverse stack of circular floors in a cylinder (or a sphere), and a "banana-split" configuration of longitudinal stack of floors in a cylinder. The former system is proposed for larger-diameter habitats, the latter one – for both larger and smaller habitats.

Another popular concept are the inflatable structures, which offer many advantages over conventional structures for space applications [3]. Already in 1961, a tire manufacturer Goodyear has built a prototype for National Aeronautics and Space Administration (NASA) of a 9-meter-diameter ring as an inflatable space station. In theory it could host two people, but was never flown [4]. Thirty years later this idea was further developed into the "TransHab" project, which was intended as a replacement for the already existing rigid International Space Station (ISS) crew habitation module. It has also not been completed. However, in 2012, NASA awarded Bigelow Aerospace a contract to construct the Bigelow Expandable Activity Module as a commercial space station design. Further advances in materials engineering of inflatable technologies (e.g. implemented in space suits), led to increased interest in inflatable, flexible composite structures [3]. For a review of inflatable technologies for space applications with emphasis on free-form see [5].

Presented in this paper system based on Pipe-Z takes advantage of the robustness of rigid-panel mechanism and allows to create free-form tubular shapes which are also reconfigurable and deployable.

2. Pipe-Z

Pipe-Z (PZ) is a parametric design system introduced in [6] which is comprised of congruent elements - Pipe-Z modules, PZM for short. Despite this extreme modularity, it allows for creation of practically any three-dimensional link. Figure 1 demonstrates this design versatility with three prime mathematical knots.

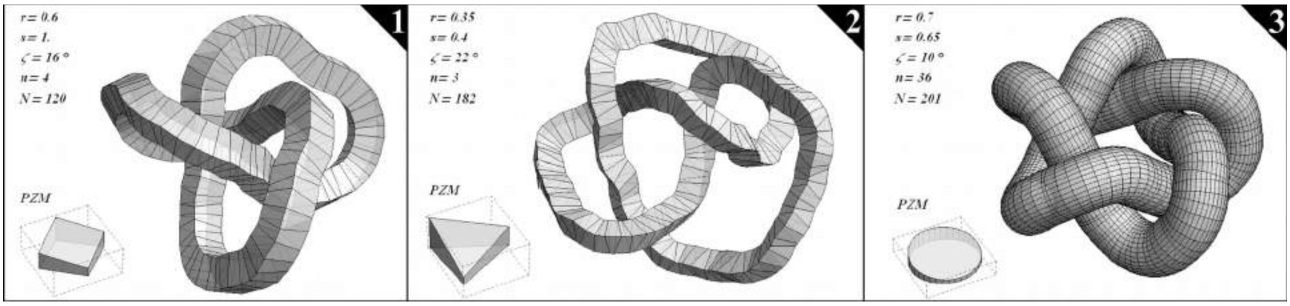

Figure 1: Various PZ knots assembled with different PZMs: 1) Trefoil (31), 2) Figure-eight (41), and 3) Cinquefoil (5_1). N and n are the total number of PZMs and number of sides of the PZM, respectively. The remaining parameters are explained further in text.

Each PZ structure is composed of one type of unit, called Pipe-Z modules (PZM), analog to congruent sectors of circular tori used to create pipe-connections where the central curve has a constant curvature [7]. The assembly of PZ is sequential. The top face (T) of the previous unit becomes the base (B) for the next one. The successive unit i is rotated by a twist angle $\varkappa_i$. In general, the twists can have real values ($\varkappa_i \in \mathbb{R}$). However, in the case of faceted PZMs, that is based on polygons of n sides, it is natural to consider only the twists which align the facets of consecutive units. Then the twist angles have only rational values, specifically multiples of $2\pi/n$, which are called dihedral angles and for an i^{th} unit are denoted as k_i ($k_i \in \mathbb{Q}$). Thus each unit has one degree of freedom (1DOF) – rotation about the normal to its base (see figure 2). Controlling only this parameter in assembly of a number of congruent units allows to create practically any passage in space. For further discussion on free-form vs. modularity see [8].

2.1 The PZ module

PZM is defined by the following parameters $r: (0, \infty)$, ϱ: $[0, \infty)$ and ζ: $(0,\infty)$, which denote: radius, corresponding radius and central angle, respectively. The notation conforms to [7]; $r, \varrho, \zeta \in \mathbb{R}$. PZMs are comprised of two faces T and B, corresponding to the top and the bottom of a unit. For practicality, T and B are assumed to be identical, and their relative position is controlled by ϱ and ζ. The faces of T and B can have shapes of circles or regular polygons of an arbitrary number of n sides, where $n > 2$ (see Figure 2).

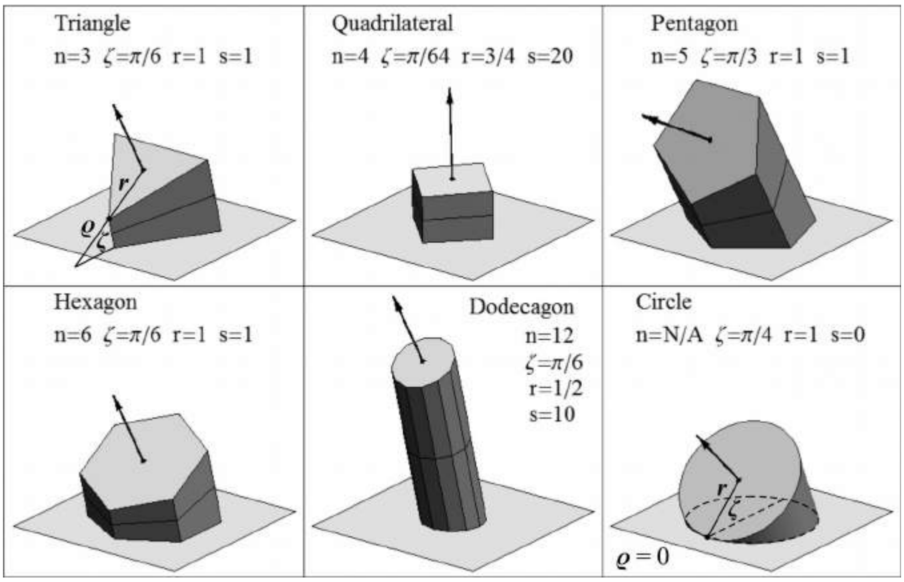

Figure 2. Examples of various PZMs. Black arrows indicate normal vectors of the subsequent unit. It is also convenient to introduce an additional parameter $s = \varrho/r$; s :[0,∞). Therefore, r is a global parameter relating the size of PZM to the size of the geometrical environment and s is the relative parameter defining the "slenderness" of PZMs. For further details on the geometry and other related issues including: the alignment of units along a guide path, optimization of PZ in respect to the adherence to the guide path, minimization of the number of units used, hybrid fabrication of physical replicas of the module, etc. see [9].

2.2 Reconfigurability of PZ

PZ structures allow for reconfiguration without the necessity of disassembly, that is solely by controlling the twist angles of the individual PZMs. Figure 3 shows a collision-free transition of a 125-unit PZ structure between two different prime knots. At first, a Trefoil (3_1) is formed, which after 23 time-steps transforms to a Figure Eight knot (4_1). At each step the twist angles are adjusted for several PZMs. Since the PZMs in this example are based on dodecagon the dihedral twists are multiples of π/6.

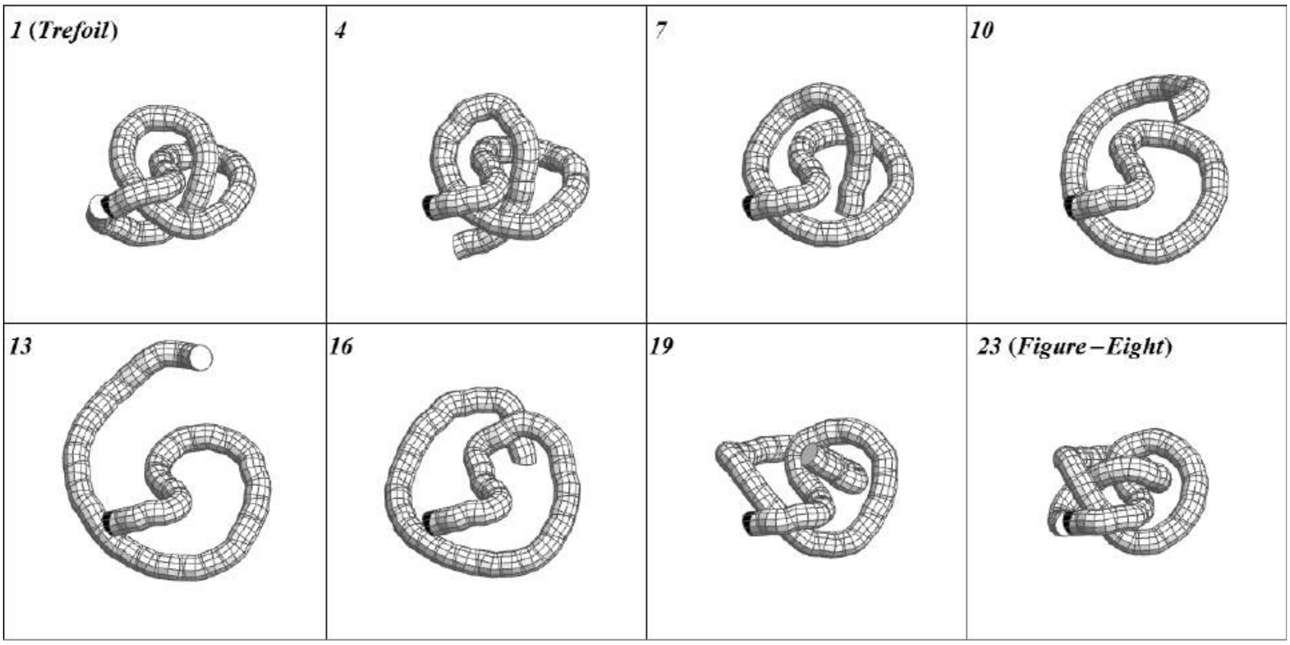

Figure 3. Selected steps of the 23-steps transformation of PZ from a Trefoil to a Figure-eight knot. The first PZM in the sequence is shown in black. The upper and lower rows show the "unknotting"

and “knotting”, respectively.

The history of alterations at each time-step can be represented by the matrix of changes (MOC) shown in Figure 4.

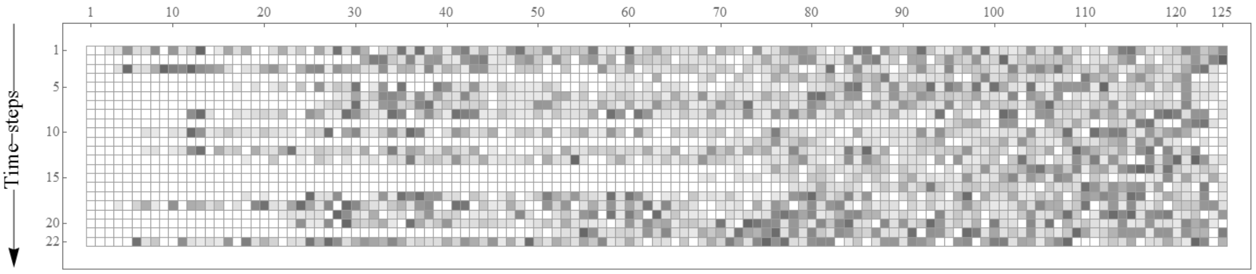

Figure 4. MOC for the transformation of a PZ from Trefoil to Figure-eight knot. Greater twists are indicated by darker grays. Each row corresponds to the sequence of 125 PZMs at the given time-step. The first unit of the PZ corresponds to the leftmost cell in MOC.

For further details on the concept of a Pipe-Z virtual manipulator see [10].

3. Foldable Pipe-Z

The entire PZ structure can be taken apart for stowage and transportation by separating the units. Its “bounding solid” can be also reduced by the reconfiguration described above. However, the most effective is the introduction of hinges to each PZM, so they become mechanisms which can be folded. Such deployable systems are called rigid-panel structures. The parts that make up the structural mechanisms are themselves the structural components that carry out the functions required for the deployment [11].

3.1 Foldable Pipe-Z module (fPZM)

A rational way to fold a PZM is to take advantage of its planar symmetry between faces *T* and *B*. The intersection of that symmetry plane and vertical trapezoidal sides form the axes of revolution for the fold. Thus the fold of the entire unit is a function of angle ψ between those halves of the side facets. For each facet ψ is the same. It seems particularity practical, since each panel or group of panels can be folded by synchronized actuators. Figure 5 shows a physical model of a foldable Pipe-Z module (fPZM) in the “outside-in” scheme, that is where the side elements are “folded out” in the stowed position. This model has been made of corrugated board to simulate the rigidity and somewhat realistic thickness of the elements.

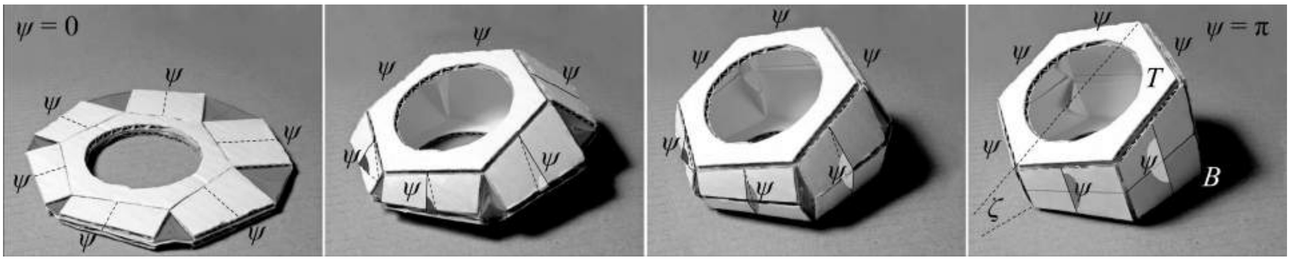

Figure 5. Four stages of unfolding of a physical model of fPZM. From the left: $\psi = 0$ at stowing configuration, two intermediate positions and $\psi = \pi$ for full deployment. At the deployed position the angle between faces B and T reaches ζ.

3.2 Preliminary geometrical analysis

fPZM is a rigid-panel structure of trapezoidal panels connected by cylindrical (revolute) hinges. Therefore it is crucial that none of the parts of fPZMs are distorted during the folding. The physical models including the one shown in Figure 5 indicated that fPZM is a sound mechanism. Figure 6 shows preliminary geometrical analysis which further support this statement.

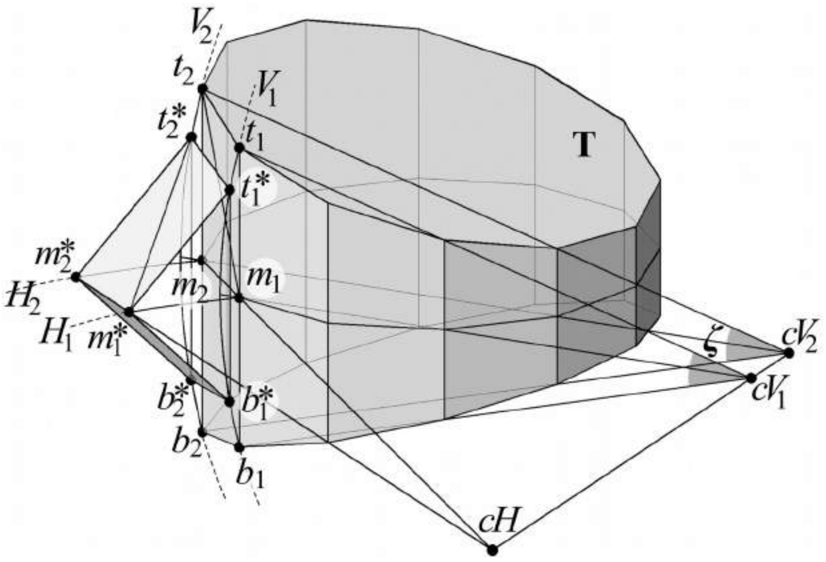

Figure 6. Line defined by points cH and cV_1 is the axis of the central angle ζ. Arc V_1 with center in cV_1 is the trajectory for points $t_1 \rightarrow t^*_1$ and $b_1 \rightarrow b^*_1$. Analogously, V_2 with center in cV_2 is the trajectory for points $t_2 \rightarrow t^*_2$ and $b_2 \rightarrow b^*_2$. These trajectories are perpendicular to the horizontal plane (m_1, cH, cV_1). Concentric arcs H_1 and H_2 with center in cH lying in the same horizontal plane are trajectories for points $m_1 \rightarrow m^*_1$ and $m_2 \rightarrow m^*_2$, respectively. The distances are preserved during this transformation, e.g.: $t_1\, t_2 = t^*_1\, t^*2$, $m_1\, m_2 = m^*_1\, m^*_2$, $b_1\, b_2 = b^*_1\, b^*_2$, $t_2\, m_1 = t^*_2\, m^*_1$, $t_1\, m_1 = t^*_1\, m^*_1$, etc.

Although the fold is a function of the side angles ψ, it is linked to the angle (ζ^*) between faces T and B of a fPZM. Obviously, for ψ equal to 0 and π, the values of this corresponding central angle are 0 and ζ, respectively. Angle ψ does not depend on the number of sides n. The trigonometrical relationships of a folded triangular fPZM (n=3) appear straightforward as shown in figure 7.

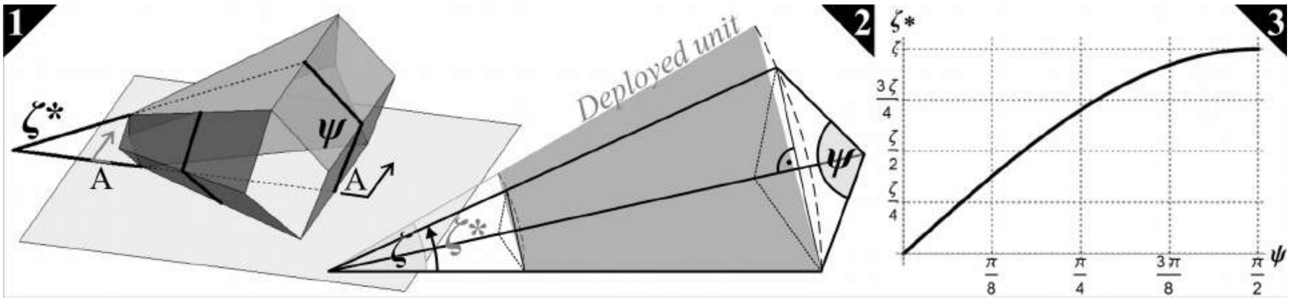

Figure 7. 1) An isometric view of a partially folded fPZM. 2) A section A-A with ψ, ζ and ζ* in the same plane. 3) Plot showing the relationship between angles ψ and ζ*.

Based on the relationships shown in Figure 7, the intermediate values of the central angle ζ^* for fPZM during folding can be calculated as follows:

$$\zeta * 2\arcsin\left(\sin\frac{\zeta}{2}\times\sin\frac{\psi}{2}\right) \tag{1}$$

Where $\sin(\zeta/2)$ is a constant parameter for a given PZM.

Such folding seems intuitive and practical, as the module is formed from rigid plates with revolute hinges only. This is expected to facilitate both the deployment/stowing and sealing/pressurization processes. The same idea of folding, among others, has been considered for a human lunar base in [12].

fPZM resembles one of the systems proposed there, namely “Ladybird IIa”. The folding mechanisms in both cases are practically the same. “Ladybird IIa” is based on an octagonal prism with congruent side panels, which, however, allow to form straight tubes only. That system has been suggested to “construct habitable space providing advanced shielding and as an additional shielding for existing habitats”. fPZM, however, is suitable for creating free-form shapes, in particular complex linkages, as illustrated in the following subsection.

3.3 Folding of a multi-module Pipe-Z

The process of deployment alike reconfiguration poses several technical and geometrical difficulties. One of the fundamental problem is the avoidance of collisions which are equivalent of self-intersections from the perspective of geometry. It becomes particularly challenging in cases of complex three-dimensional structures. Self-intersections in PZ can be avoided by adjusting the twist angles as shown in section 2.2 (“Reconfigurability of PZ”). In case of deployment, alternatively, the unfolding rate of fPZMs can be differentiated. In other words, the assigned value of ψ can vary. Additional function has been introduced, so the angle ψ depends on two parameters:

$$\psi(t,f)=\frac{\pi}{2}\begin{Bmatrix} 0 & f<\frac{t}{2} \\ 1 & f>\frac{t+1}{2} \\ 2f-t & else \end{Bmatrix} \tag{2}$$

where t and f are: the threshold and normalized unfolding rate, respectively. Parameter f changes from 0 to 1 uniformly for all fPZMs. Threshold t is assigned to fPZMs individually. Figure 8 visualizes the relationships among ψ, t, and f.

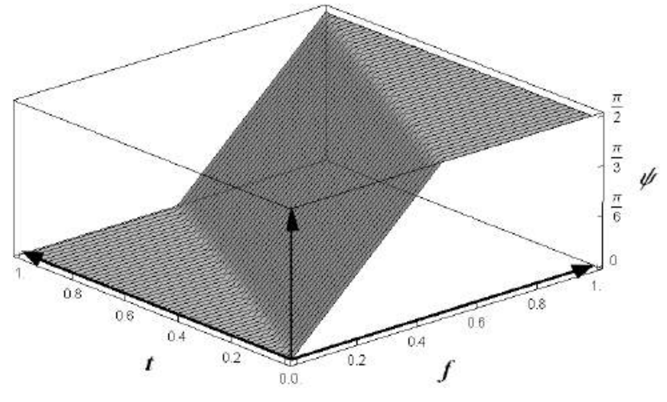

Figure 8. All units unfold at the same rate f. However, the threshold t can be assigned to the units so their actual unfolding angle ψ is different at the intermediate states. As a result, all the units perform full deployment, however at different pace.

Figure 9 shows the deployment of a relatively complex spatial PZ structure forming an Unknot. Unfolding of this structure with uniform angle ψ for each fPZM would cause collisions. Thus, the thresholds t for the units have been assigned similarly to the Figure 8, so the first and last units (along the t axis) in the sequence unfold at first and at last, respectively.

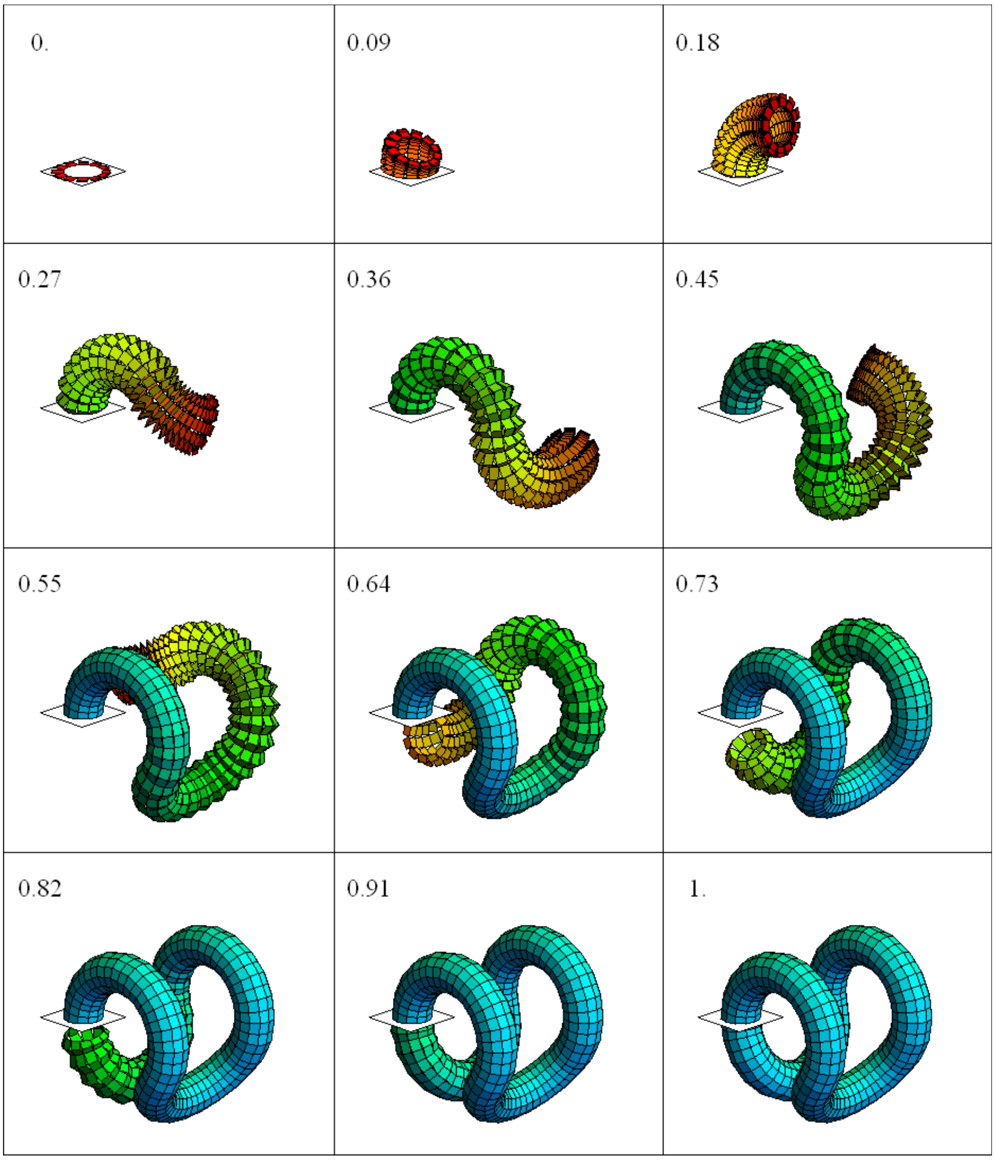

Figure 9. Asynchronous (delayed) deployment of an Unknot. The first unit is fixed to the white horizontal plate. Hue indicates the unfold angle ψ for the individual units. Red and cyan indicate fully stowed and deployed positions, respectively. For each state the unfolding rate f is shown in the top left corner.

4. Deployment of an emergency/auxiliary dPZ link

Let us consider a scenario where an additional link or passage of complex free-form shape needs to be (quickly) constructed. It can be unpressurized and serve as shielding/casing for installation ducts or emergency link in Earth atmosphere. It can also be pressurized to serve as an emergency link for suited shirt-sleeved personel of an undersea or outer space stations. For illustrative purposes of showing a challenging dPZ shape, a failure of the Zarya unit of the International Space Station (ISS) is considered (Figure 10).

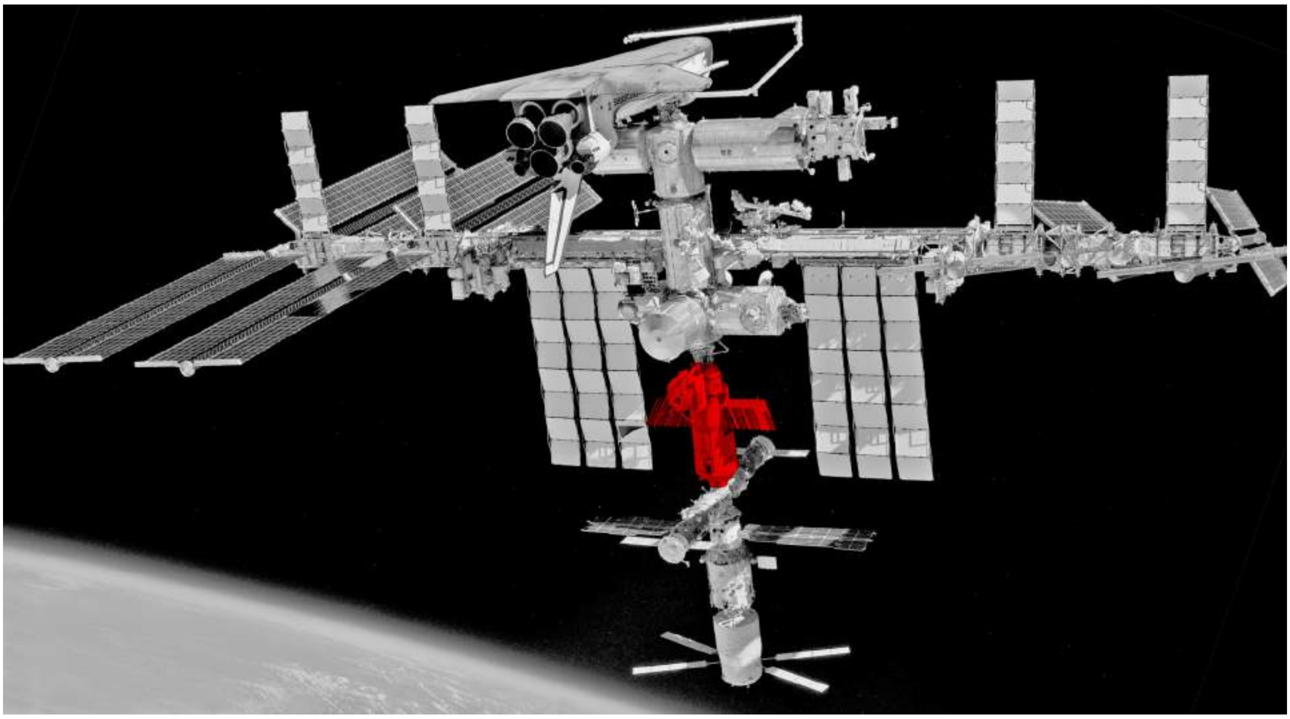

Figure 10. A possible scenario of a major failure of Zarya module (shown in red). (Photo: http://amsat-uk.org/tag/international-space-station/).

Figure 11 shows the deployment of a PZ bypass bridging back the ISS. In order to avoid the collisions during unfolding, the deployment is asynchronous (delayed) exactly alike the one shown in Figure 9.

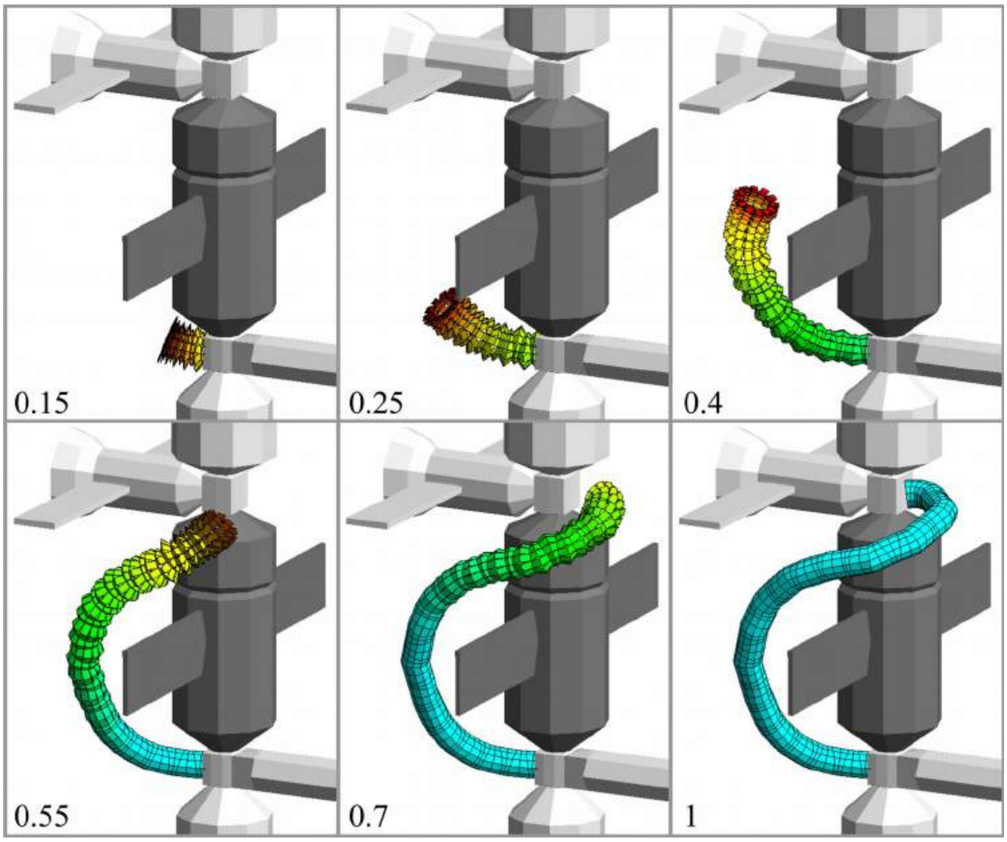

Figure 11. Selected steps of the continuous deployment of 40 fPZMs to bypass the "dead link" (shown in dark gray). Hue indicates the unfold angle ψ for the individual units. Red and cyan indicate fully stowed and deployed positions, respectively. For each state the unfolding rate f is shown in the

bottom left corner. The 3D model of ISS has been downloaded from the NASA 3D Resources [13].

5. Some practical considerations

Although conceptually pleasing, the actual feasibility of dPZ for particular applications depends on meeting the requirements of particular environment, as illustrated in Table 1.

Table 1. Requirements for deployable system

Application	Pressurization	Mass	Volume
Structures on Earth	✗	✗	✗
Underwater habitat	✓	✗	✗
Outer space habitat	✓	✓	✓
Structure in outer space (unmanned)	✗	✓	✓

5.1 Pressurization/sealing

The main problem in pressurization, is safe sealing of the joints. Particularly problematic are hinged joints. One of the possible solution could be based on the concept of the “foldable barrel” (FB) [15]. Although the geometry of PZ is sightly more complex than FB, the same principle can be applied, as shown in Figure 12.

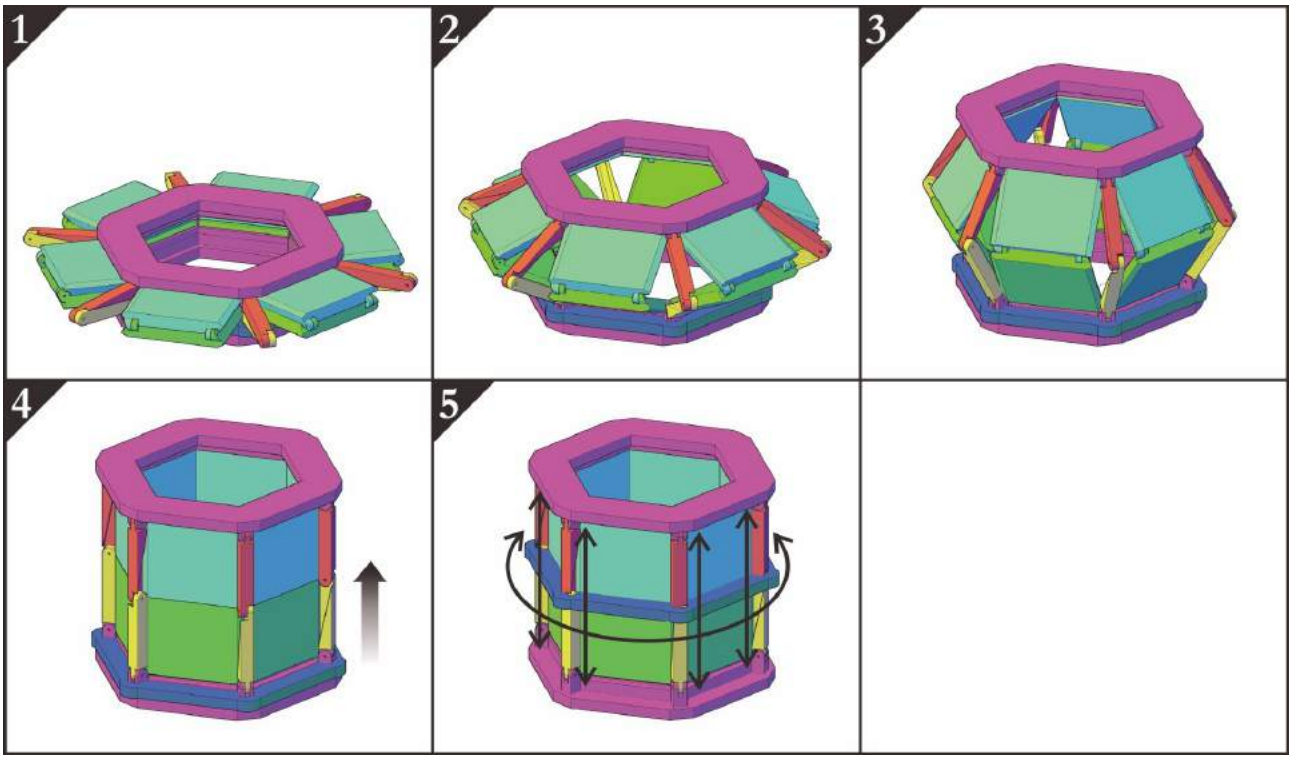

Figure 12. Deployment of a “foldable barrel” (FB). 1) Stowed position. 2-3) Intermediate positions. 4) Upright position. Arrow indicates the bracing ring to be raised. 5) Deployed and braced position. Arrows indicate tensional members.

In this case the stresses in the pressurized hinges in the deployed position are minimal. Such non-loadbearing hinges are relatively simple, and could be made of elastomer [14] which could also serve as a part of the sealing. Additionally, all edges of the shell plates are compressed, which is also advantageous for air-tightness. Figure 13 shows a possible solution based on "foldable barrel – hourglass" (FBH) [15]. There are fewer elements and the implementation for dPZ is straightforward.

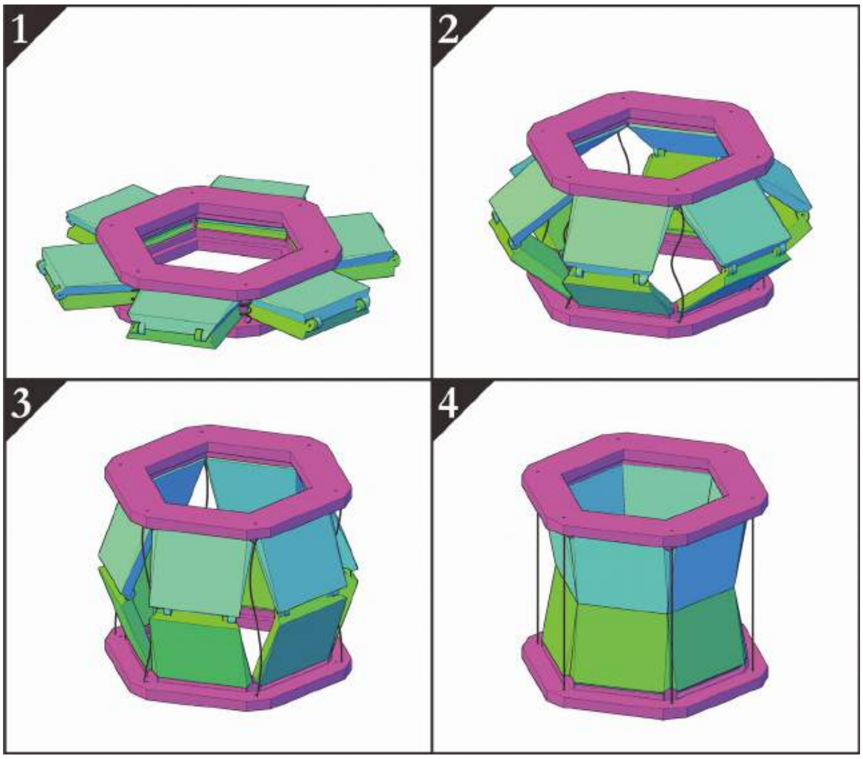

Figure 13. "Foldable barrel – hourglass" (FBH). 1) Stowed position. 2-3) Intermediate positions. 4) Deployed position. The compression members (cables) are shown in black.

As Figure 13 indicates, in principle, the hinges in the middle section of FBH bare tensional stress, however the linear connections are compressed. If the internal pressure is not higher than the external one, it is due to the tension in the cables. If the vessel is under-pressured, the cables are redundant, which makes this solution particularly suitable for underwater applications.

Although in principle the "outside-in" deployment is much more straightforward and intuitive, in case of super-pressured vessels it is not practical, as the linear connections are subject to tearing. Although in FBH (Figure 18), to some degree, the internal pressure could be compensated by increased tension in the cables, it is not efficient, and for substantial super-pressure – irrational.

In principle, the "inside-out" (IO) deployment mechanism, although much more complicated, is more suitable for super-pressured vessels. Figure 14 shows schematically the two-step deployment of an IO unit. At first, the initially folded side panels are being deployed forming a perforated shell. Next, these side panels unfold to cover the voids from the inside.

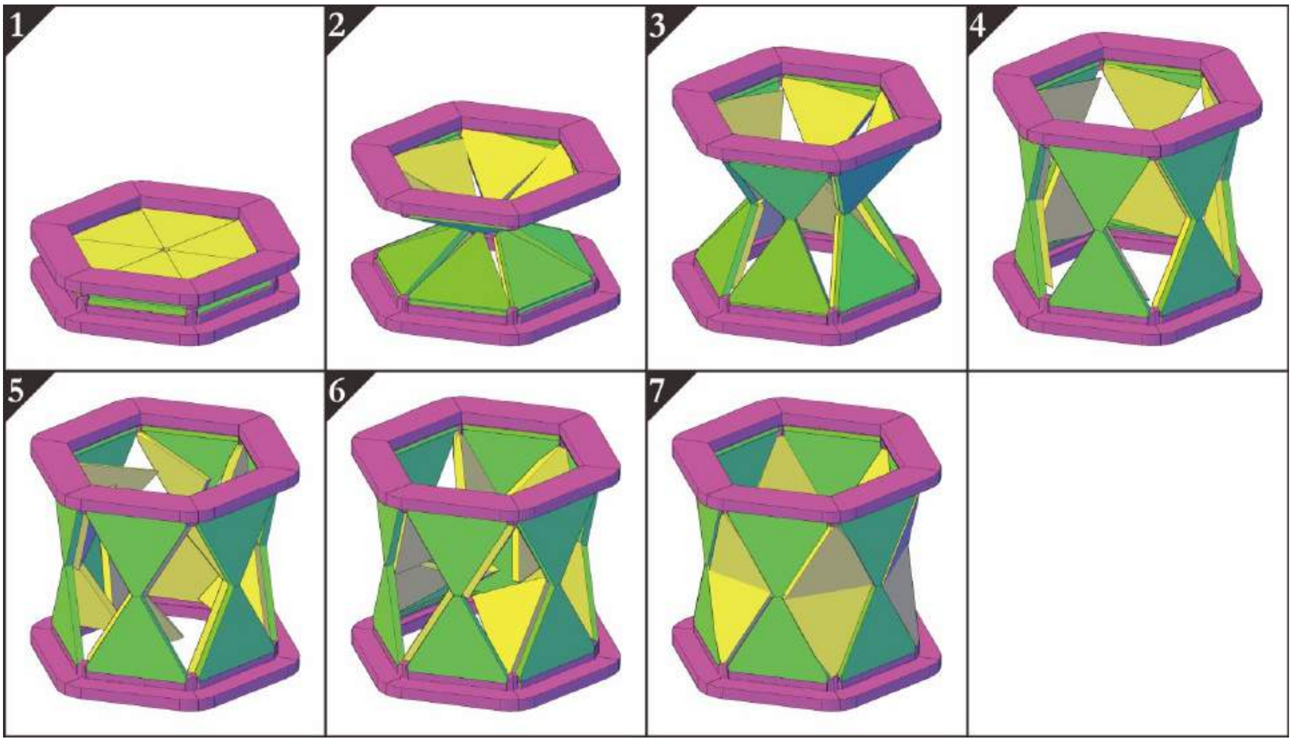

Figure 14. The two-step deployment of an "inside-out" unit. 1) The stowed position. 2-4) First step deployment of the side panels. 5-7) Secondary deployment covering the voids.

As Figure 14 indicates, the IO system is substantially more complicated, However, the linear connections are compressed, which is advantageous for super-pressurized vessels such as space stations or habitats. Another benefit is much better "packing" (see sub-section below).

Alternatively, the folding of dPZ can be based on collapsing rigid concentric toric rings (CTR). As shown in Figure 15, in this concept there are no hinges.

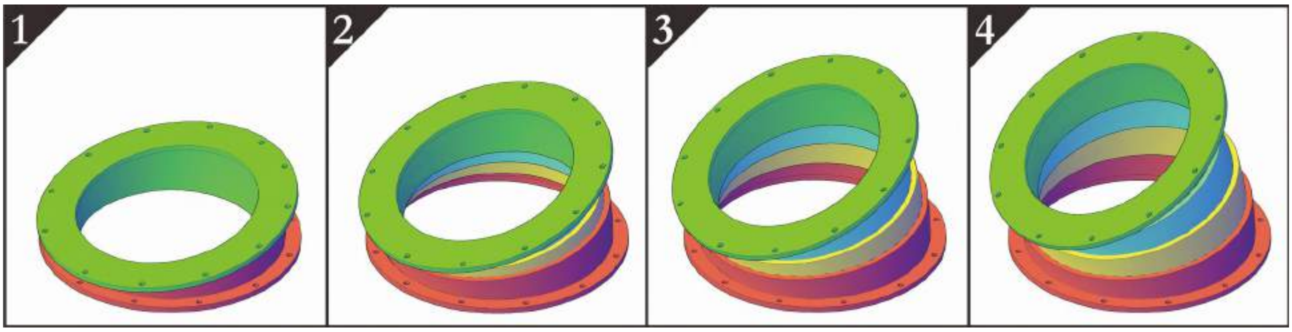

Figure 15. Deployment of a system based on concentric toric rings. 1) Stowed position. 2-3) Intermediate positions. 4) Deployed position.

As Figure 15 indicates, for CTR system reaching full rigidity, sliding mechanism, and sealing pose major challenges. The same scheme based on inflatable structure could avoid the last two problems rather easily, however achieving satisfactory overall rigidity of an elongated modular structure (without internal rigid reinforcements) seems very difficult, if possible at all. Nevertheless, the benefit of this system is that it is neutral to under- and super-pressure, and a structure composed of relatively few inflatable such units seems rather feasible.

5.2 Packing

Packing is particularly important for space applications, where configurations for launch are a vital consideration. The volume reduction ratio (VRR), that is the relationship of the bounding volumes of the module in stowed (VB_s) and deployed (VB_d) states. VRR for FB (Figure 12), FBH (Figure 13), FB-IO (Figure 14) and CTR (Figure 15) are: 0.69, 0.557, 0.226 and 0.33. Not surprisingly, the "inside-out" system has the best packing characteristic. Second best is the toric ring system, and the worst – the most straightforward, that is "outside-in" folding systems.

6. Low-fidelity prototype

A low-fidelity 6-unit octagonal dPZ has been made of paper, similarly to the physical model of a hexagonal fPZM shown in Figure 5. Also here, for enhanced realism, the panels have been made of thick corrugated cardboard. For easier identification the fPZMs have been fabricated in contrasting colors. The units are connect by internal tubular elements forming revolute joints (1DOF: rotation of the units in respect of each other), as shown in Figure 16.

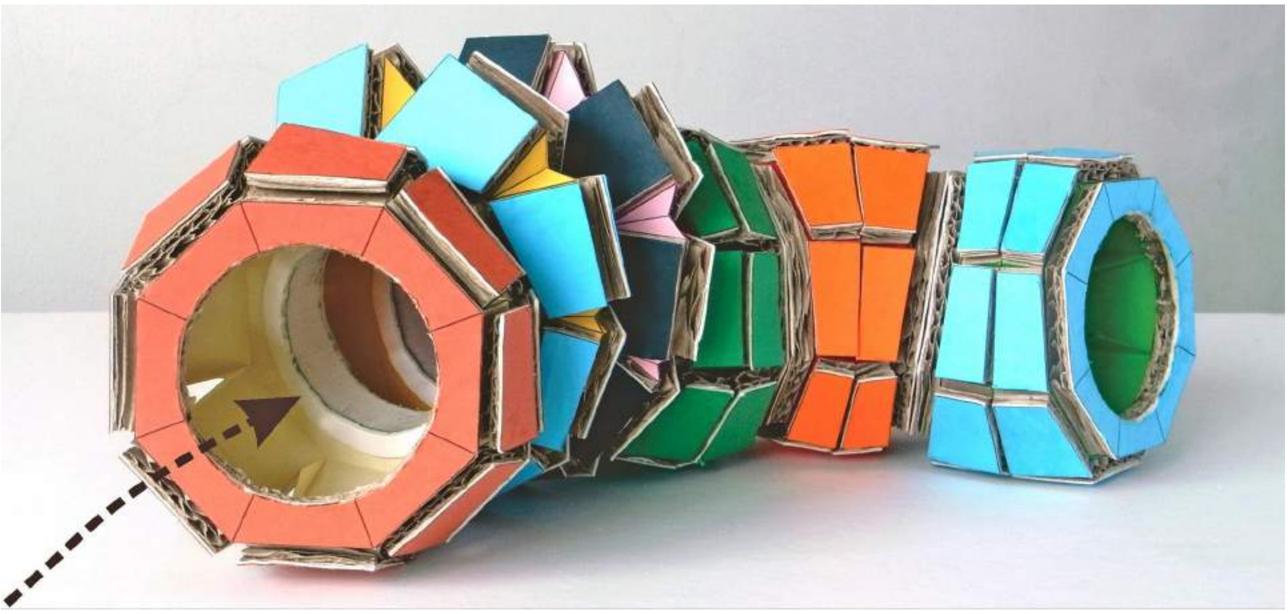

Figure 16. Partially deployed low-fidelity model of a fPZ. Dashed arrow indicates one of the internal connectors between fPZMs, which have 1DOF and allow for a relative contiuous rotation between every pair of units.

Each fPZM has two discrete states, stowed and erected, and the transition is done manually. Erected units are stiffened by external band clamps made of white rubber bands, as shown in Figure 17.

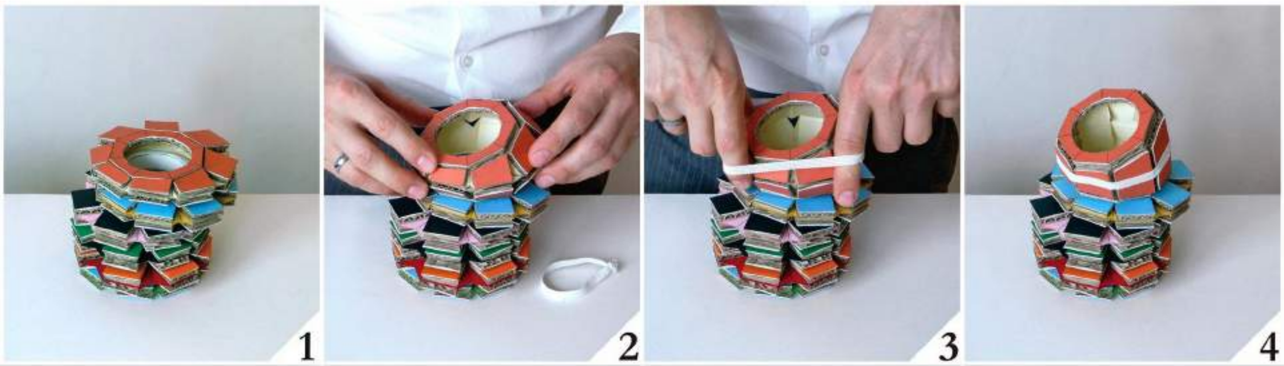

Figure 17. Deployment of the first fPZM of the low-fidelity prototype of dPZ. 1) Stowed position; 2) Manual unfolding; 3) Placing a rubber band; 4) Deployed and stable position.

Figures 18, 19 & 20 show the deployment of a half-toric, cylindrical and helical dPZ, respectively.

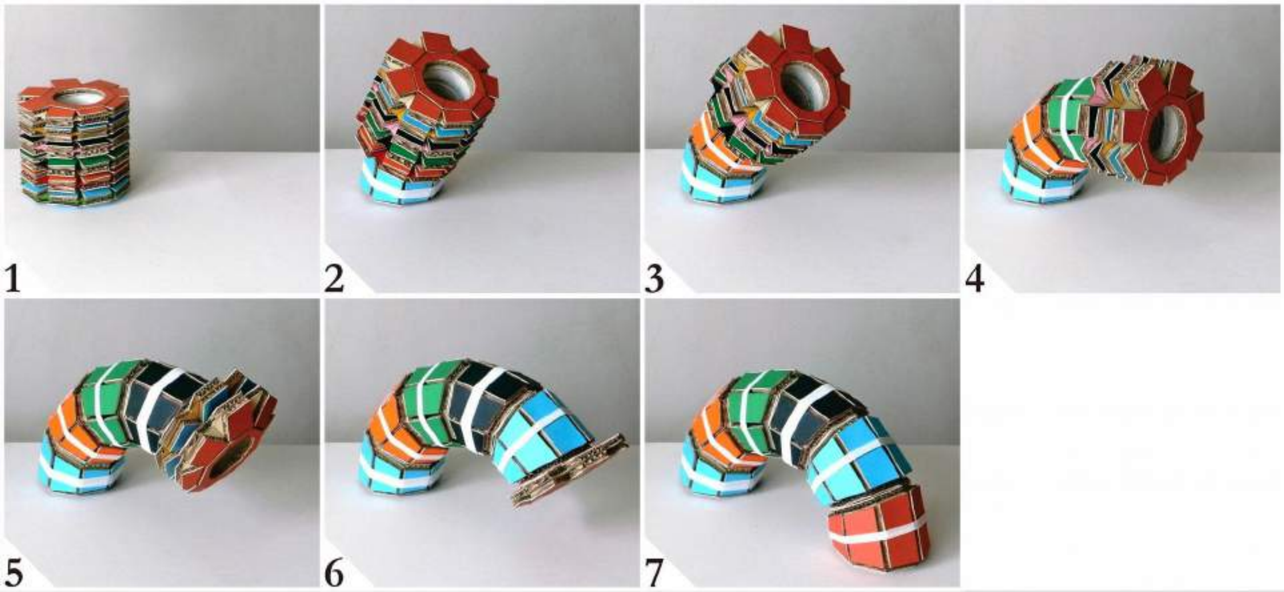

Figure 18. A sequential deployment of a half-torus comprised of 6 octagonal fPZMs. The deployed units gain rigidity from the compression bands shown in white.

Figure 19. 7 steps of deployment of a dPZ forming a cylindrical pipe.

Figure 20. Deployment of a helical dPZ.

6. Conclusions

This paper introduces the concept of deployabe Pipe-Z (dPZ). The major benefit of the novel approach presented here is the modularity of the system – entire structures are built of congruent units – foldable Pipe-Z modules (fPZMs). Although there are major technological challenges on the way to the real applications – it is encouraging that these problems can be narrowed down to a single module (fPZM). Moreover:

1. Existing systems for outposts, in particular undersea and space stations & habitats are usually either:
    - very "inflexible" in terms of form
    - require substantial labor on site
    - are free-form but seem not robust (see examples in [5]).

   PZ situates somewhere among those systems providing free-form, however, rigid structures.
2. The modularity of PZ facilities the maintenance and possible repairs or replacements.
3. "Design flexibility" of PZ both in terms of shapes and reconfigurability can contribute to diversification of the space habitats, which has been identified as a major factor for human well-being of astronauts [16], and in particular, space tourists [17].

Although deployable Pipe-Z (dPZ) still faces major practical issues, it seems that the concept can find applications in undersea or deep-space habitats and permanent, but in particular, temporary or emergency links for surface habitats. The "banana-split" configuration of dPZ seems the most practical. Specifically, dPZ may find applications in:

1. Surface habitats: with relatively small diameter, longitudinal, free-form PZ structures conform to the natural topography of the landing site, which provides good structural stability. It is particularly practical for long links. According to Ref [2]: "long modules with horizontal layouts present special landing problems for planetary surface applications". PZ structure can be transported and landed in stowed configuration and unfolded into an elongated and possibly complicated tube.
2. The conceptual simplicity of PZ makes it suitable also for self-assembly, or robot-assisted assembly. Thus the landing base can be installed before the arrival of the colony [18].
3. Retrofitting of existing undersea, orbital or surface systems with additional linkages or passages.
4. E.g. the polar regions of Mars are of particular scientific interest (artifacts of life forms and climatic history) [19]. However, the outposts in permafrost areas will be extremely difficult to build and maintain. PZ structures could also serve as pipelines or unpressurized casing for installation ducts to such areas.

The challenges for the future research:

1. Proper structural design. In a case of pressurized structures the essential and relevant rigidization comes from the internal pressure. The most efficient shapes for such a load are sphere and cylinder. It is conceivable to form the side panels (facets) of dPZ, so instead of being flat, as presented here, they can have certain curvature which would lead to more advantageous, that is cylindrical shape. This would probably decrease the packing compactness. Moreover, the middle sections of each fPZM can be reinforced by external tension members analogously to the rubber bands in low-fidelity prototype presented in Section 4. The final shape, however, is to be determined by complex multi-disciplinary optimization, considering not only structural issues but also deployability and usability, which are highly dependent on the environment where such a system is to be utilized.
2. Further particular issues such as wall thicknesses, hinges, folding mechanism, actuators, pressurization, etc.
3. Design of fPZMs in compliance with existing or recently proposed systems for internal habitat module layouts such as Random Access Frames [20].
4. Incorporation of the in-situ resource utilization (ISRU).
   According to NASA, "ISRU will enable the affordable establishment of extraterrestrial exploration and operations by minimizing the materials carried from Earth". Several systems (also modular) for surface habitats utilizing local materials have been already considered [5][21] [22] [23].

5. Pressurization of a partially deployed PZ: at the present stage a dPZ structure is pressurized after full deployment. However, it is desirable to design fPZM so the structure can be hermetic also at any intermediate position, which could be more practical.

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