70th International Astronautical Congress (IAC), Washington D.C., United States, 21-25 October 2019.

IAC-19,B3,8-GTS.2,4,x48931

DMF: Deployable Modular Frame for Inflatable Space Habitats

Vittorio Netti[1, *]

[1] *University of Houston*, vnetti@uh.edu
[*] Corresponding author

Abstract

Inflatable Space Modules for space exploration are now a reality. In 2016, Bigelow Aerospace tested the first inflatable module Bigelow Expandable Activity Module (BEAM) on the International Space Station (ISS), achieving success. This technology has higher volume limits than other launchers, substantially changing the previous concepts of construction and life in space. Nevertheless, inflatable modules technology lacks a reliable and functional platform to efficiently use all this space. Due to its limited dimension, the International Standard Payload Rack (ISPR), currently used on ISS, is not suitable for this purpose. The project aims at developing a new standard for payload rack in the inflatable space modules: the Deployable Modular Frame (DMF). The DMF expands itself radially from the center of the module, starting from four structural pylons. It creates a solid infrastructure allowing for the configuration of a variety of spaces, including storage space, laboratories, workstations and living quarters. The DMF consists of two main parts: the Deployable Frame (DF) and the Modular Rack (MR). Once the frame is deployed, it provides four linear slots suitable to install the modular racks. The rack is the basic element that allows for the storage of equipment inside the frame. Once they are installed, the racks can slide on the frame's rails, dynamically changing the space inside the module. This system, inspired by the Random Access Frame Random Access Frame (RAF) designed by A. Scott Howe for the Jet Propulsion Laboratory (JPL), achieves a high deployability through the use of constant force springs, deploying a radial rail system which reduces the work load of the astronauts on the rack. This asset reverses the internal configuration proposed by the Bigelow Aerospace. The frame includes a stereo-vision camera system to verify the correct deployment of the inflatable modules and the frame itself. The stereo-vision system checks whether the correct shape is constantly maintained.

Keywords: Inflatable, modular, ISPR, Space Operations.

Acronyms

BEAM Bigelow Expandable Activity Module
CTB Cargo Transfer Bag
DF Deployable Frame
DLR German Aerospace Agency
DMF Deployable Modular Frame
DREX Deployable Reflector EXperiment
ECLSS Environmental Control and Life Support System
ESA European Space Agency
FDM Fused Deposition Modeling
ISPR International Standard Payload Rack
ISS International Space Station
JPL Jet Propulsion Laboratory
LED Light Emitting Diode
MR Modular Rack
NASA National Aeronautics and Space Administration
RAF Random Access Frame
SNSB Swedish National Space Board

1. Introduction

Inflatable technologies for Space applications are not a new asset, but recent R&D provided by the private sector (e.g. Bigelow Aerospace ltd, Sierra Nevada Corp.) has demonstrated that these structures are a viable solution. Inflatable structures have larger diameter limits than commercial rocket fairings, thereby allowing current launchers to bring structures of much larger volume into

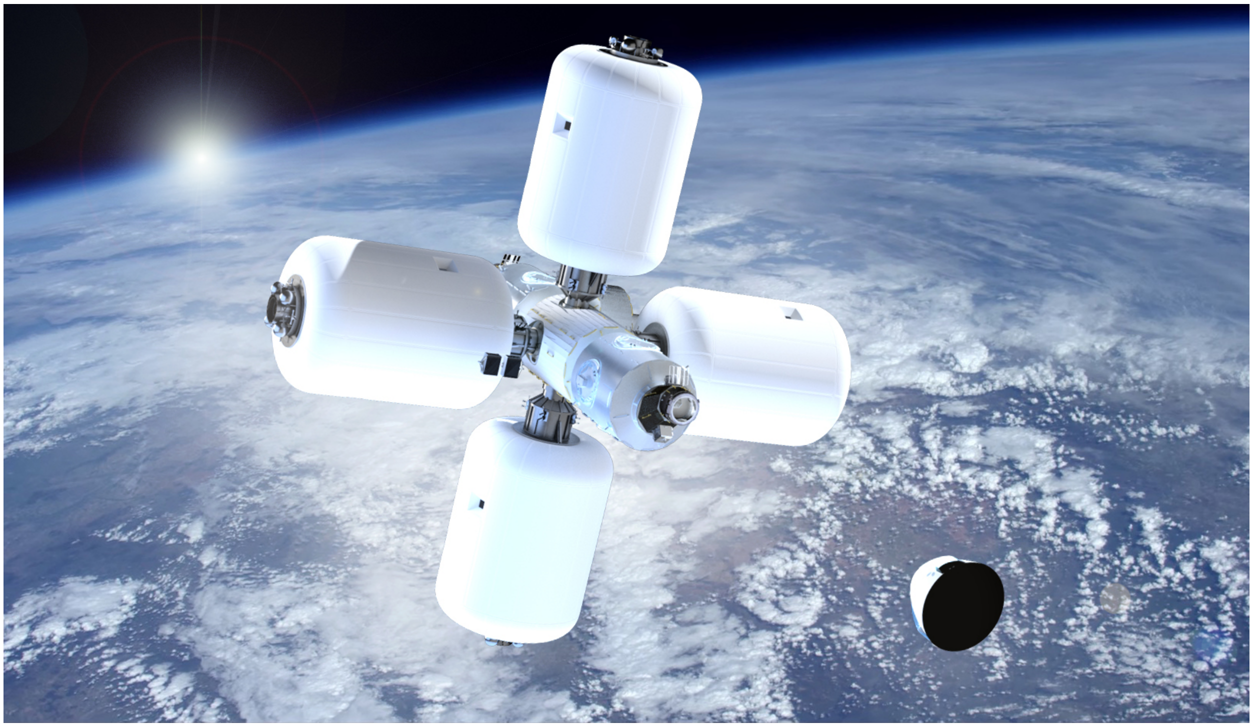


Figure 1: Concept for an inflatable space station

orbit. They represent a change of paradigm in manned space exploration and a flight-proven technology for the next generation of orbital, deep space and planetary habitats.

However, the adoption of this new architecture for space modules brings with it a set of challenges in human integration design. The main challenge is represented by the outfit of equipment and instrumentation inside a soft-based architecture. Until now, for this purpose we relied on modular racks such as the ISPR, still used on the ISS and derived from the Space Shuttle program. However, without a rigid infrastructure with which to outfit the racks, inflatable modules need a new standard infrastructure that allows for the efficient use of the space post inflation.

Proposed architectures for commercial modules such as the Bigelow B2100 or the Sierra Nevada make use of non-standardized assemblies, that require a lot of effort from astronauts to perform their functions. The aim of this paper is to explore a possible configuration to outfit standard racks inside an inflatable module. This standard will be used to configure laboratories, storage space, living quarters and other instrumentation in a modular and scalable architecture specifically designed for inflatable modules.

1.1 Relevant technologies

The DMF system uses a mix of tested and reliable technology to offer a solution to a common problem associated with inflatable space habitats. Every system component has a strong background in space applications. The three main related technology are described below.

1.1.1 Inflatable modules

National Aeronautics and Space Administration (NASA) first began studying the possibilities of inflatable structures around 1960, when researchers at NASA's Langley Research Center in Virginia drew up plans for a ring-shaped 24-feet large inflatable space station, based on the Von Braun visions. In 1965, the agency developed concepts for inflatable moon habitats, and in 1967 it

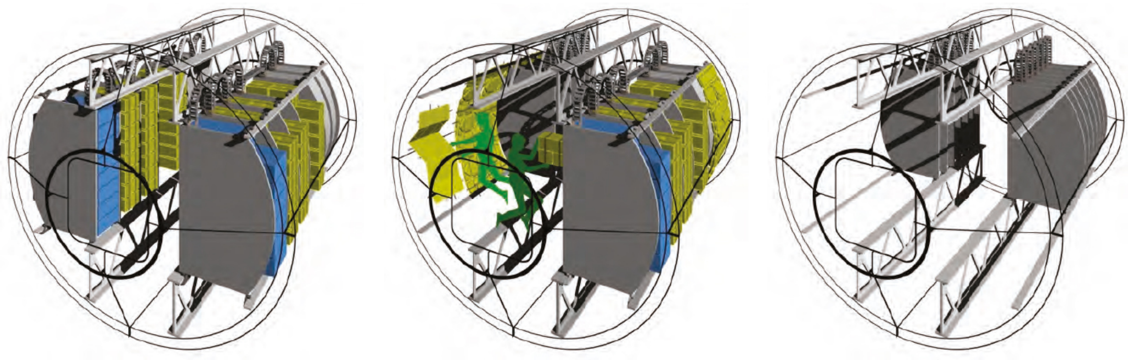


Figure 2: A scheme of the RAF II module structure

studied the idea of an air-filled space station nicknamed Moby Dick due to its large dimensions.

In 1997, NASA's Johnson Space Center developed the Transhab. A multi-purpose inflatable Space module, that used a water-filled section as a radiation shielding layer. The prototype was built and tested extensively before the project was cancelled in 2000. [1]

Just some year later, Bigelow Aerospace purchased the rights to the patents that NASA had filed for the technology. The project involved a new iteration of the Transab design, in order to bring the first inflatable space habitat to the ISS.

After 15 years of research and deployment, on April 8th of 2016, the BEAM reached its destination, and it underwent two years of extensive testing, revealing that the inflatable technology could play a significant role in future human spaceflight and low-Earth-orbit commercial venture. [2] Inflatable habitats in space have advantages over conventional metal structures:

1. Weight: BEAM, designed to expand to 16 cubic meters, weighs only 3,000 pounds at launch. Its density (mass divided by volume)—is 88 kilograms per cubic meter. By comparison, the density of the Destiny module is 137 kilo grams per cubic meter. The ISS's Tranquility module has a density of 194 kilograms per cubic meter.
2. Dimensions: folded into its launch configuration, BEAM takes up a space five feet by seven feet.
3. Manufacturing cost: 17.8 million—as one of its key advantages over older technologies.
4. Radiation shielding: the BEAM module has proven to be more effective in crew protection against cosmic radiation then the traditional aluminium modules.
5. Impact resistance: hyper-velocity impact testing shows that inflatable modules offer a better protection against micro meteoroids then actual ISS modules.

The commercial successor of the BEAM module, the B330, provides 330 square meters and can accommodate six astronauts.

inflatables modules typologies: Over the years, space agencies such as NASA and European Space Agency (ESA) as well as many private companies, proposed different architectures for inflatable modules, both for space and planetary applications. While such architectures are common for earth applications, where logistic and assembly are not an issue, in space these structures have to deal with a new order of challenges, such as micrometeoroids, regolith, dust, sandstorms and cosmic radiations. In order to maintain structural rigidity, many of these proposed architectures wrap the inflatable body around fixed structures, such as beams or pilons. Every access to the module is cartherized by an airlock, even when the access is not directly in contact with the external environment; this solution is a safety requirement of each module for space applications, to ensure the possibility of sealing a compartment that is suffering from decompression or contamination, preventing further damage to the rest of the structure. Sometimes these modules include windows integrated within the inflatable structure. Until now we observed a particular trend in distinguishing typologically different design solutions between planetary and microgravity-based designs of the inflatable modules, as well as their proposed internal configurations. Contrary to rigid models, it an efficient standard for internal and external architecture for inflatable models has been difficult to define, likely due to the lack of flight proven inflatables. Different providers have proposed a variety of design solutions, but extensive testing in a microgravity environment will be required to validate a limited number of validated solutions.

1.1.2 Random Access Frame

In 2014, Senior System Engineer A. Scott Howe and Space Architect Raul Polit-Casillas developed the RAF project at the NASA JPL, in order to define a new standard intended to substitute the old ISPR derived from the Space Shuttle Program. The ISPR, made to easily swap large hardware units, was designed around the Space Shuttle vessel and its dimensions. Now, the system has proven to be outdated, and in need of replacements for the future missions. The RAF concept was developed with this purpose in mind, allowing for denser packing of modules, better access to items, and more flexible of volumes. [3] The RAF shares the same system of movable library shelving as the ISPR, only accessing one corridor at a time. The single corridor system allows for tighter packing of hardware storage and logistics elements.

As the floor area on earth, work surface area is the most important habitat characteristic in zero-gravity conditions. This means that there is no more ceiling, nor walls, but every surface can become a workspace. The RAF system, includes a foldout tertiary structure that allows dedicated work surfaces to be exposed on demand. Every component of the RAF concept is designed to be a kit-of-parts for assembly, dis-assembly and reconfiguration. Every frame can be reconfigured for different functions later on. The newest in-space manufacturing techniques will make it possible to substitute the original metal frames with lighter ones once the zero-gravity condition is reached. A single unit of the RAF II concept has been built in 2014 at CalPoly Pomona University, and have been tested in the Neutral Buoyancy Pool of University of Maryland [4]. The study of A.Scott Howe and Raul Polit-Casillas demonstrated how a dynamic configuration architecture, similar to the ones that we experience in many work and private spaces, can provide a more flexible and efficient infrastructure for long duration space travels.

1.1.3 Spring Driven Deployable structures

Deployable structures are a common asset for space applications and were developed to store equipment with extensive surfaces, such as solar panels or heat radiators. The optimization of deployment for complex surfaces is a current challenge for space agencies as NASA. [5]

During 2017, a team of university Students from Unipd, developed the Deployable Reflector EXperiment (DREX) project within ESA, German Aerospace Agency (DLR) and Swedish National Space Board (SNSB) within the REXUS BEXUS Programme. DREX aim was to develop a Spring Driven Expandable Reflector for orbital and suborbital environment. [6]

The DREX project serves as a reference for passive, spring-driven structure deployment systems. Unlike the motor-driven that is commonly used on spacecrafts, spring-driven deployment relies on pre-compressed springs to accomplish the final shape of the structure,thereby reducing the likelihood of failure of powered and mechanical components.

The project presents a new design for a parabolic reflector, able to extend its surface through a spring-driven, radial opening, umbrella-like mechanism. The deployment of the dish is initiated by the release of a retention system that holds the arms in position. This new concept has been selected by SNSB/DLR/ESA to be tested in stratospheric environment on its REXUS/BEXUS project. On October 17, 2017, DREX flew from the SSC launch base and reached expected altitude. The Deployment subsystem of the antenna is composed of six folding arms, connected by four joints to the central core. The Actuation subsystem initiates the expansion phases, freeing the arms that are able to rotate, dragging and unfolding the membrane. The foldable arms are linked to the vertices of the central hexagon frame by hinges, featuring preloaded springs for the deployment Actuation. After the actuation mechanism starts the deployments, the pre-charged springs impress a constant force on the hinges, allowing the arms to deploy. The deployment speed is controlled by rotary dampers placed on the hinges, that impress the force against the springs to maintain a constant rate of movement and ensure a smooth deployment. Two stereo vision systems have been used to acquire precise data about the membrane final shape.

Spring-driven deployment is more power efficient and less subject to failure than other methods of achieving a motor-free synchronized deployment in a space environment. Thanks to the significantly lower static forces to which space structures are subject, the system used by DREX is easily scalable to much bigger structures.

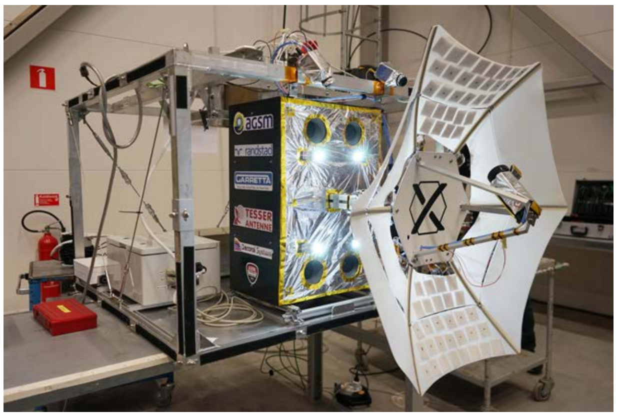


Figure 3: the DREX test unit at ESRANGE

2. Concept

The DMF exploits one of the most common configurations for inflatable modules, using the existing structural beams that provide structural rigidity between the two main airlocks. DMF adds a deployable sub-structure in which it is possible to safely outfit the equipment and instrumentation. DMF share the same flexibility of a standard rack module such as the ISPR, enabling the development of standardized equipment shared between inflatables of different sizes and configurations. The internal outfit of the equipment still relies on the work of astronauts, but the pre-deployed infrastructure mitigates the general effort needed for in-space assembly. The racks are set perpendicular to the corridor, dividing the dynamic space from the working surfaces. After the assembly phase, the system provides a dynamic asset to configure the internal space at will, sliding the outfitted racks onto the deployed rails. This feature, shared with the mobile shelving systems from contemporary libraries, allows for a working surface 4 times bigger than those of traditional architecture. Although the racks cannot all be accessed at the same time, multiple experiments and equipment can run simultaneously, even in a compressed configuration, since all the submodules stay connected to the external interfaces (placed in the pylons). The Bigelow Aerospace B330 has been chosen as testbed for the proposed technology. In order to demonstrate the system capabilities, the B330 design provided in this paper can be different from the last one proposed by Bigelow Aerospace, based on the last public design iterations.

2.1 mechanical subsystems

The DMF module is composed by two subsystems: the DF and the MR. The two systems are complementary and, with minor adjustments, can be adapted to different inflatable module configurations. While the dynamic phase of the DF takes place only in the deployment phase of the system, the MR maintains its dynamic capabilities during its entire lifetime. The function of the DF is to provide the infrastructure for the MR, and the only effort needed to keep it in working condition is to verify that the deployed shape is maintained. The MR is the substructural unit which allows for the outfitting of equipment. Each rack is standardized and is made of structural profiles and joints. A minimum of 2 racks is needed to assemble a submodule, in which install the equipment. The dynamic component of MR is composed by five four-wheeled, greaseless sliders, that allow each rack to slide onto the DF rails.

2.2 Deployable frame

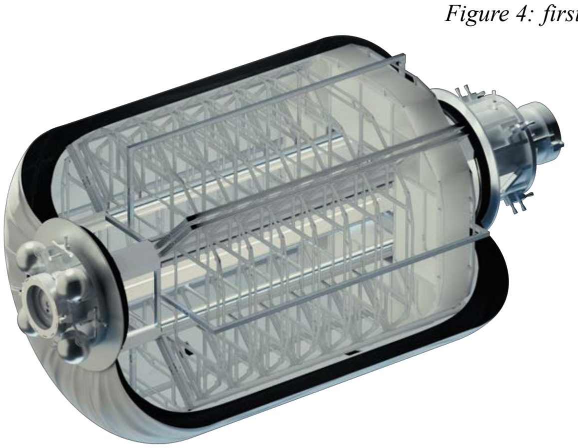
The DF is made of 3 main parts: The Four pylons, the twelve rails and the twenty four spring driven joints. The four central pylons represent the main structural force of the modules: they prevent the horizontal collapse of the module and absorb the most of the static loads. The Environmental Control and Life Support Systems (ECLSSs) run through the pylons, transporting fresh air, water and power inside the modules.

Each pylon provides one white Light Emitting Diode (LED) direct light for daily operation and two blue LEDs indirect lights for higher visual comfort levels during nighttime operations. Two deployable rails are stowed from each pylon during the deflated phase of the module. Each rail is a Bosh Rexroth 100x100 profiles 8m long. After the module inflation, a laser measurement system assures that the module expansion has been correctly execute, and that there is enough space for the rails to deploy inside the module. After the confirmation measurement, the rails start to deploy radially using spring driven joints.

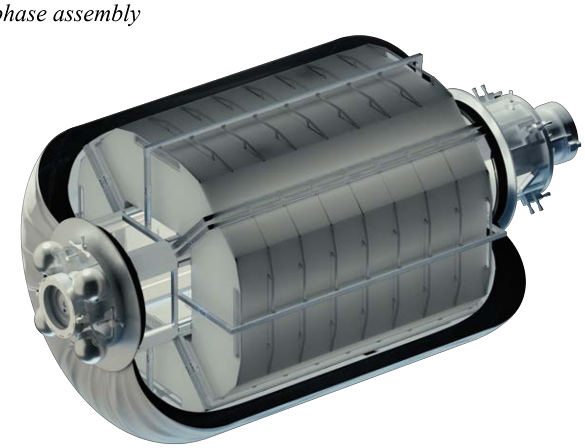
(a) DMF in stowed configuration.

(b) DF deployment

Figure 4: first phase assembly



(a) MR configuration.



(b) Rack enclosures outfitting.

Figure 5: Second phase assembly.

There are six joints for rail, three for each side. There are two kind of joints: single and double joints. A single joint can achieve a rotation of 90 degrees, whereas a double joint can achieve a 180 degree rotation. Each joint uses a precharged constant force spring where its rotation is restrained by a mechanical lock that is activated by an electrical switch. After the spring is released, the rails start to expand and an electromagnetic damper slows the rotation of the joints enough to control the strength of the springs until the end of the deployment. Once the deployment is complete, the joints are locked in position, and the laser measure system gauges the distances between the pylons and the deploys rails, assuring complete deployment.

2.3 Modular rack

The MR is assembled from commercial, off-the-shelves, structural profiles (40x40mm and 40x80mm), joined on each side by a bolted plate on the profiles. Each rack comes assembled, and can slide on the rails using to five sliders with 4 wheels each. Each slider includes a manual block system to fix the rack on the rails once the final position is set. A single rack can be interfaced with more of it to create more complex structures.

The equipment stored in the sub-modules are powered through the main pylons, and can still slide on the frame without being disconnected them from the power source.

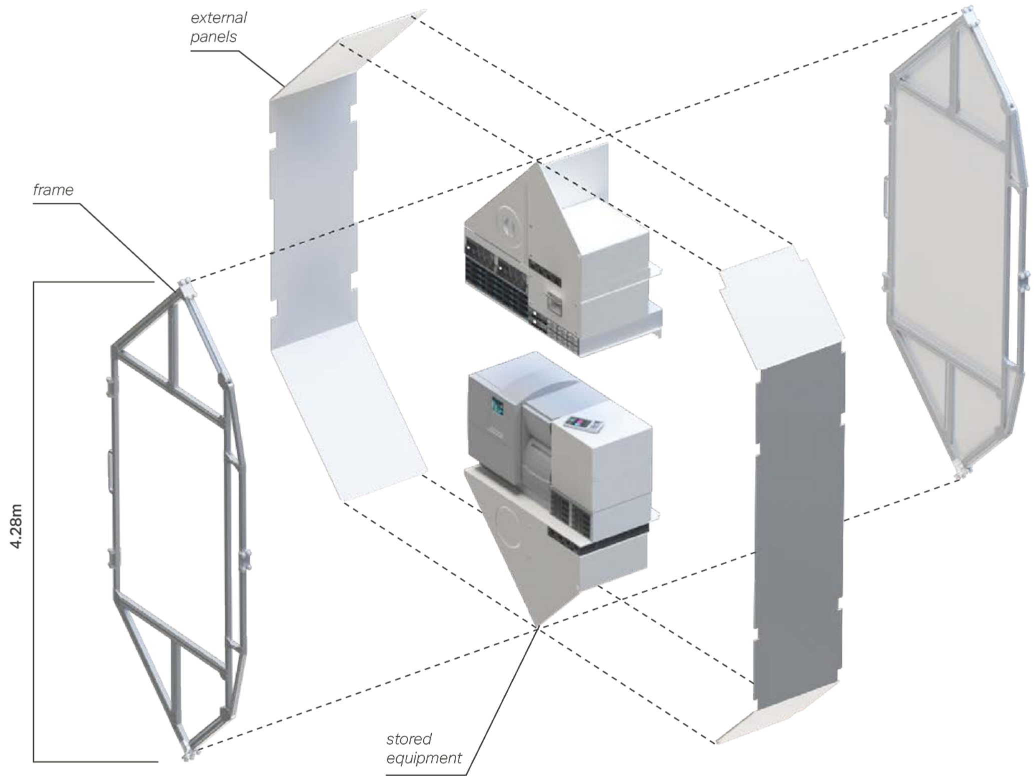


Figure 6: exploded view of a submodule

The maximum distance to create a connection between two racks is settled at 1.1m due to the dimensions of the panels. The sub-module allows for the maximal distance to be set to 8 frames in a b330 module, resulting in a single-structure module with a maximum length of 7.58m. Since the static loads on the frame are lower in space than on earth, and do not need to bear launch forces, the racks can be manufactured directly on board, utilizing manufacturing techniques such as 3d printing, resulting in a much lighter total weight of the structure.

2.3.1 Submodules

The submodule is the basic unit of the DMF system. Each submodule has functions comparable to an ISPR module but with 3 times the available surface. As stated above, a submodule is composed by two MR and a set of polimeric enclosure panels to join the two racks. While one single module can provide the working surfaces to operate experiments and scientific equipment, more submodules can be joined to outfit closed subspaces inside the module, such as crew quarters, greenhouses or environmental controlled spaces. The submodules are connected through flexible cabling with the interfaces placed in the structural pylons, that provides power, controlled atmosphere, water and data. Thanks to this feature, the module can be compressed onto the DF rails without interrupting any functions. All the components and the equipment needed to outfit the submodules can be stored in the central hallway during the launch phase.

2.4 ConOPS

The module is first launched and then docked to an existing space vessel. The module connects to the vessel ECLSS systems, is powered, and then begins to inflate.

After inflation is complete, a total of twelve rails will deploy: eight rails will deploy radially starting from the four structural pylons and the remaining four rails will deploy from the connecting beams. The deployment utilizes pre-loaded, constant force springs placed in every joint of the frame, which are held in place by a retention system until the deployment phase.

Every joint includes a two-way safety system in order to ensure that the 90° synchronised movement needed to accomplish the deployment was effectively achieved. The primary safety system is intrinsic and is composed of a metal plate attached to one face of each joint; when this metal plate comes in contact with the opposite face, the loops is closed and deployment is confirmed.

The secondary safety system is human operated: once the frame deployment is complete, a crew member pushes a metal pin through two complementary holes inside the joint in order to strengthen the connection between the two components of the joint.

Once the frame is secured, the racks, which are stored in the middle of the hallway until the frame is in the stowed position, can be moved into place manually. That operation requires each astronaut to place each rack onto the frame and release the safety lock on each slider. There are five sliders in each frame. Once all the locks are released, the racks can slide on the rails smoothly. The internal configuration can be set up by moving the frames on the rails, before or after setting up the equipment. After the internal configuration is setup, the panels, which are stored in the hallway together with the racks when the frame is in stowed position, can be mounted.

The panels are mounted with a set of pressure pins that can be placed in position by simply pressing them though the holes in the panels and directly into the guides on the profiles.

Once the panels are in place, personal and scientific equipment can be stored inside the racks. The racks can still slide on the rails at any moment in order to dynamically change the internal space and to compress the equipment that is not needed at that time. The rack system allows for a variety of configurations, best-suited for the specific mission requirements. For example, it is possible to build a full cargo module with a total volume of 179mc or a fully-equipped laboratory to perform on-board analysis.

The DMF aim to enstablish a new standard for space application that will substitute the existing ISPR The proposed internal configuration for the b330 made by the Bigelow Aerospace leaves the majority of the space achieved through the inflatable module technology unused, thus failing to utilize the advantages of this platform. Instead, with the DMF system it is possible to: 1. configure the space to offer more livable space for the astronauts. 2. use a maximum of 95% of the available volume for storage spaces, equipment and other functions. 3. configure the space to accommodate both livable space and equipment in order to achieve the most efficient and flexible internal configuration.

2.4.1 Launch configuration

During the launch phase the DF is compressed in its stowed configuration and the joints with the pre-charged constant force springs are constrained in position until the deployment phase. The MR racks and all the equipment are stored in the hallway and restrained to the four structural pylons. The internal disposition of the equipment is valued every time in order to deal with changes in weight and to not interfere with the center of mass of the module. Further considerations include the necessity to design a restraint grid for the stored equipment and the iteration of a load distribution model to support the launch feasibility with different launchers. Also the design of the restraint system for the pre-loaded springs during launch is a main requirement.

2.4.2 DMF assembly

After the deployment phase and the outfitting of the MR, the astronauts will proceed to integrate the equipment with the racks and place the submodule enclosures. First, astronauts will verify that the shape has been correctly achieved and the conditions of the environment are stable. Next, they will enter the module and proceed to release the cargo restraints. The racks are manually mounted on the rails and then slid onto the rails to reach the final configuration of the module. In order to mount the rails on the module, at least two crew members are needed to fit

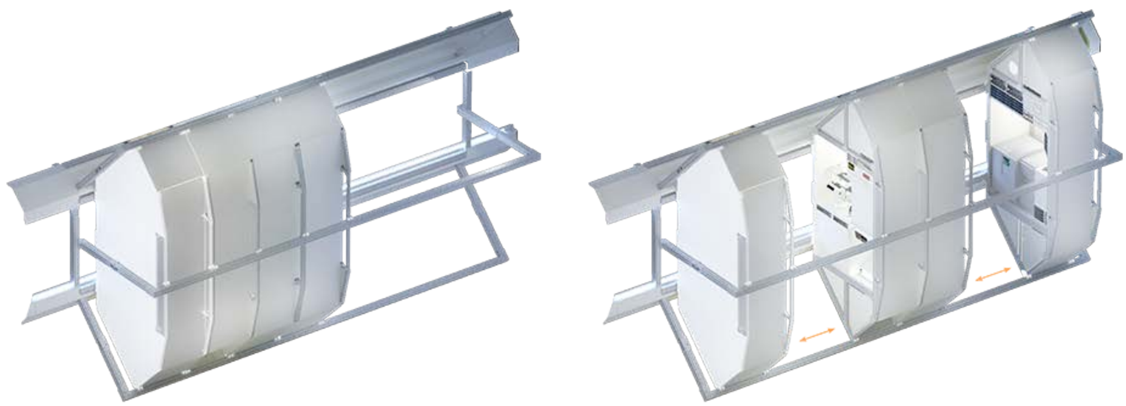


Figure 7: Dynamic reconfiguration of the internal space through DMF

the MR correctly. The second step involves outfitting of the equipment onto the racks. The outfitted equipment is connected to the power and data source placed in the four pylons. Finally, the astronauts will cover the racks with the enclosure panels.

In-Space manufacturing: After that the module experienced the Max Q during the launch, the microgravity environment make possible to produce the racks in space through Fused Deposition Modeling (FDM) printing. Once in a microgravity environment, the racks can be produced via FDM printing. The lack of load forces make unnecessary the excellent mechanical properties of the structural profiles. In this way it's possible to reduce greatly the mass of the module at launch with a tradeoff in therm of rise of complexity and time of assembly.

Shape verification subsystem: There are two possible technologies that can be used to integrate a shape verification subsystem in the DF. The purpose of the system is to use the distance between the deployed rails and the soft shell to produce data that is useful for ensuring that the correct shape of the external soft shell is constantly maintained. This system is useful for recording the performance of the shell during its lifetime, recording the micrometeoroid impact response of the external layers, and acting as a depressurization event detector. In order to achieve this purpose, there are two viable technologies that could be potentially used:

- Using the sterovision technology, two cameras are installed on each rail. On the internal soft shell there are markers printed on each variation of 5 degrees. The stereovision software will be used to create a real-time 3D model of the internal shape.
- Installing a fixed Lidar measuring system in each of the DF. Each laser will measure constantly the variation of distance between the rails and the external shells. More misuration sensor will be installed, more accurate will be the shape reconstruction.

3. Applications

One of the most important features of the DMF system is its flexibility. The system can be used for a large variety of mission-specific environments and can still be reconfigured during the mission adapt to changes in mission specifics. In contrast with the ISPR, it is possible to disassemble the racks and pass them through the airlocks in order to outfit another module with the same system. The DMF system can easily be adapted for ground modules too: by leaving one of the four rack spaces empty, the hallway of the module can achieve standing height.

3.1 Orbital and deep space applications

3.1.1 Layouts

Below are three different configurations that can be achieved by the DMF system:

- laboratory module: includes analysis systems, a mi-

crobial incubator, a biology lab, a storage compartment and a toilet
- Habitative module: include 4 private rooms, a toilet, a bathroom, a kitchen and a common area
- Cargo module: include 16 storage compartment racks and 2 Cargo Transfer Bags (CTBs) compartment

Laboratory:
Module properties:
- Total Volume: 330mc
- Sub-modules: 12
- Space use: 46,26%
- Equipment volume: 136mc
- Cargo volume: 9.72mc
- crew: 8

(refer to figure 8)

Habitat:
Module properties:
- Total Volume: 330mc
- Sub-modules: 6
- Space use: 38,88%
- Equipment volume: 112mc
- Cargo volume: 9.7mc
- crew: 4

(refer to figure 9)

Cargo:
Module properties:
- Total Volume: 330mc
- Sub-modules: 16 (448 hard box, 60 CTBs)
- Space use: 56,26%
- Cargo volume: 179mc

(refer to figure 10)

3.2 Planetary applications

The standardization of internal outfitting proposed by the DMF is a valuable asset for planetary applications too. If the module is placed horizontally, it will be possible to change the use intended use for the superior and inferior submodules, that will be used just for cargo and storage purpose (e.g. consumable goods or water tanks). If the module is placed vertically, the DMF is used to outfit the different floors of the structure, Some submodules should keep their dynamic space reconfiguration capability to exchange material and equipment through different floors. The MR will be reconfigured to outfit equipment placed horizontally.

4. Conclusions

The DMF System uses solids and existing technology to create a new standard system of inflatable space habitats in hopes of substituting a system inherited by a space platform that that no longer exists. The primary aim of the DMF System is to maximize functional flexibility without give up to the mission specific configuration standards. Working on a single platform system reduces the economic impact of mission planning and optimizes efficient use of the space.

Cost and mass reduction, modularity and standardization are the key concepts behind the design of the DMF which inspire the new generation of modular assets for deep space exploration.

4.1 Future work

This paper describes the components and the operations related to the DMF module. Further developments and technologies could be implemented in order to improve the general design, reduce the assembly efforts and assess the feasibility of the systems. The main directions of the DMF development are identified in:

Automation in assembly: Study on implementation of automated assets to perform autonomous assembly operations, such as robotic arms to reduce the efforts of the astronauts during the assembly.

Escape system: Feasibility study for the design of a pressurized submodule as a safety measure in case of a depressurization event.

Structure Optimization: Optimization and simulation of drag forces acting on the system during deployment and reconfiguration, in order to iterate the design of the main structural components.

Component design optimization: Characterization of the sub-components of the system, such as the rotatory dampers, the power/data interfaces and the submodules enclosures. Testing of different FDM printing techniques and architectures.

Acknowledgements

The author of this research would like to thank Bigelow Aerospace ltd. which work inspired this paper, Prof. O.

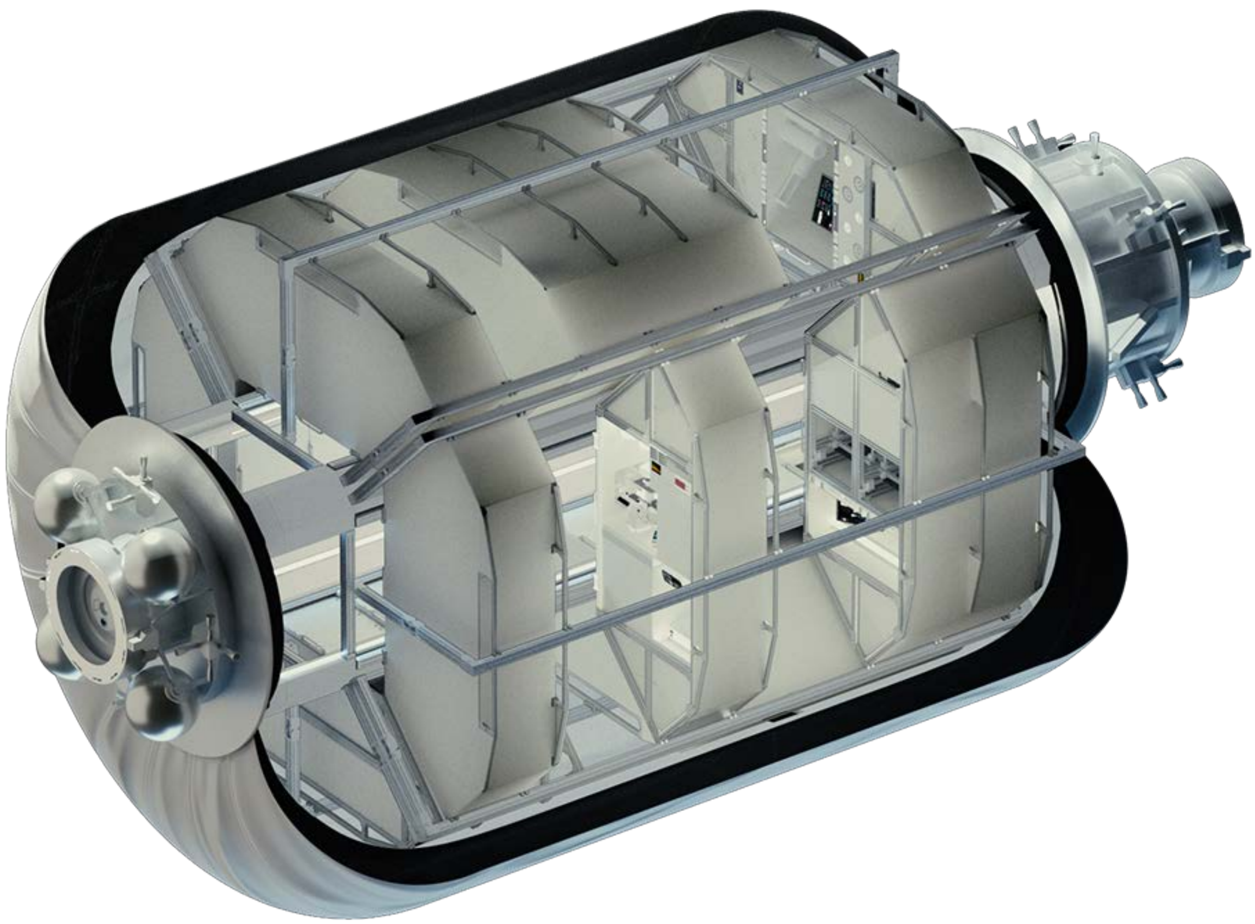


Figure 8: Laboratory configuration

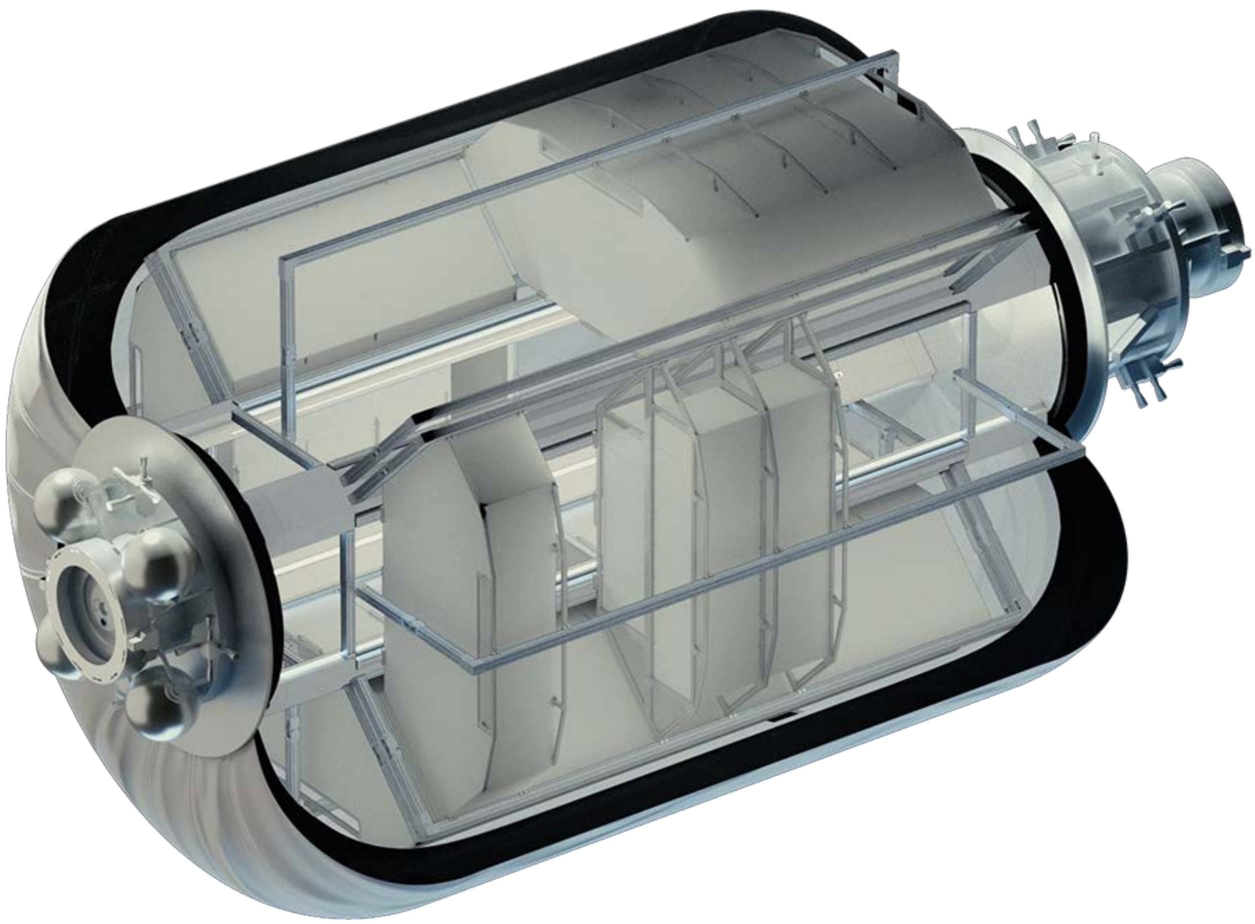


Figure 9: habitat configuration

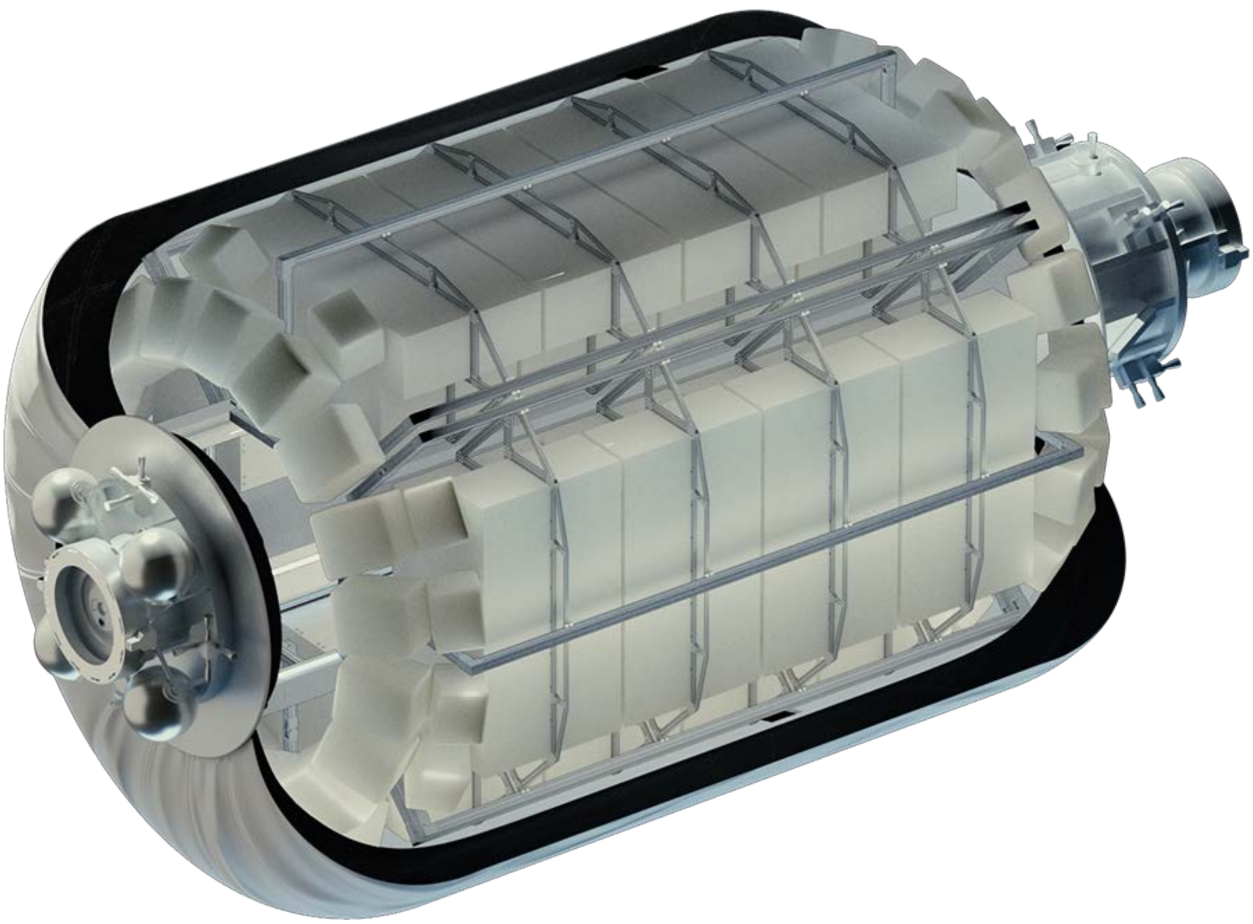


Figure 10: cargo configuration

Bannova from SICSA, A. Scott Howe and Prof. Mirko Zaccariotto from UniPD for the project reviews

References

[1] K. J. Kennedy and C. M. Adams, "ISS TransHab: An inflatable habitat," in *Space 2000*, 2000, pp. 89–100, ISBN: 0784404798. DOI: 10.1061/40479(204)8.

[2] E. Seedhouse and E. Seedhouse, "Bigelow Expandable Activity Module," in *Bigelow Aerospace*, Springer International Publishing, 2015, pp. 87–98. DOI: 10.1007/978-3-319-05197-0{_}5.

[3] A. S. Howe and R. Polit-Casillas, "Random Access Frames (RAF): Alternative to Rack and Standoff for Deep Space Habitat Outfitting," Tech. Rep., 2014.

[4] A. S. Howe, R. Polit-Casillas, D. L. Akin, K. Mcbryan, and C. Carlsen, "Random Access Frame (RAF) System Neutral Buoyancy Evaluations," Tech. Rep., 2015.

[5] W. M. Sokolowski and S. C. Tan, "Advanced self-deployable structures for space applications," *Journal of Spacecraft and Rockets*, vol. 44, no. 4, pp. 750–754, Jul. 2007, ISSN: 00224650. DOI: 10.2514/1.22854.

[6] G. Tesser, V. Netti, C. Ambrosini, A. Bellina, L. Bogo, S. Di Marco, F. Marconi, and D. Soso, "DREX: A SPRING DRIVEN DEPLOYABLE REFLECTOR ON BEXUS24," Tech. Rep.