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Exploring the Feasibility of Developing Expandable Station Modules for Generating Artificial Gravity Using Origami Principles

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Abstract

Microgravity is an ever-present challenge facing astronauts who spend any significant time in orbit due to its degenerative health effects on the human body. These health effects will be unacceptable for longer duration missions away from Earth, such as those to Mars, as the crew must maintain their physical capability to maximise the chances of mission success. This thesis explores the feasibility of a concept spacecraft module, making use of rigid-origami principles to produce an expandable structure, capable of being launched into orbit as a single object and requiring no further construction once launched. A module of this type would provide the crew with artificial gravity, particularly during non-work hours.

A wide variety of considerations have been made to investigate the feasibility of such a module. Analysis using paper models showed that the module proposed in this thesis can be expected to fit within the standard payload fairings of the available launch vehicles. A mass estimate, using the calculated surface area of the ring structure and material data, showed that the module will weigh far less than the maximum payload weight of the proposed launch vehicles, providing the opportunity to also carry the necessary compressed air and internal furnishings on the same launch vehicle. GRANTA EduPack material property charts were used to determine that the best material for the rigid panels will likely fall into either the metals or polymers classifications.

The findings of this thesis show that the proposed concept, while requiring further work to fully develop, is no longer held back by technological limitations as it was in the 20th century and can therefore be considered a feasible enhancement of space exploration. Furthermore, it may be critical to the success of future space exploration missions due to the increasingly long mission durations and the resulting effects of prolonged exposure to microgravity.

Declarations and Statements

Statement 1

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed:[redacted]candidate)

Date: 22/11/2024

Statement 2

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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Statement 3

I hereby give consent for my thesis, if accepted, to be available for electronic sharing.

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The University's ethical procedures have been followed and, where appropriate, ethical approval has been granted.

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Authorship Statement

The following people and institutions contributed to the publication of work undertaken as part of this thesis:

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Thesis/Paper – **“Exploring the Feasibility of Developing Expandable Station Modules for Generating Artificial Gravity Using Origami Principles”**

Candidate/Author is the sole contributor to this thesis/paper.

Signed: [redacted] (candidate)

Date: 22/11/2024

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Definitions of Abbreviations

Abbreviation	Definition
ISS	International Space Station
LEO	Low Earth Orbit
SMS	Space Motion Sickness
RPM	Revolutions Per Minute
SAHC	Short-Arm Human Centrifuge
3D	Three Dimensional
USA	United States of America
NASA	National Aeronautics and Space Administration
BEAM	Bigelow Expandable Activity Module
SLS	Space Launch System
UHMWPE	Ultra-High Molecular Weight Polyethylene
GFRP	Glass Fibre Reinforced Polymer
CFRP	Carbon Fibre Reinforced Polymer
FEA	Finite Element Analysis
TRL	Technology Readiness Levels
IOAG	Interagency Operations Advisory Group
ESA	European Space Agency

1 - Introduction

1.1 - Background

As humanity looks, once again, towards the stars with grand ideas of distant colonies and long-term habitation, the various issues associated with microgravity present a limiting factor to our progress. This is because future missions, such as those to the Martian surface, will require crew members to be at maximum physical capability in order to complete their mission successfully, which long term exposure to microgravity is not conducive to. Currently, on board the International Space Station (ISS), astronauts are required to use specialist exercise equipment, on a daily basis, to limit the negative physiological effects on the body due to microgravity [1]; while this solution is adequate for the small crew size and relatively short mission durations on board the station, it would be unsuitable for the larger spacecraft and crews that the next generation of space exploration will call for.

1.2 - Problem Statement

It is this problem that must be overcome before humanity can make realistic attempts to form permanent colonies in space and scientists have been attempting to find solutions to it since the early 20th century, long before we sent the first men to space. The idea of using rotating habitats to produce artificial gravity dates to the work of Konstantin Tsiolkovsky in 1903, when he proposed the use of a rotating wheel station to simulate gravity. This work was then progressed by Herman Potocnik in 1929, in a book titled ‘The Problem of Space Travel: The Rocket Motor’ [2], in which he discussed a wide range of topics related to space travel including rocket technology, orbital mechanics, space station design, the effects of microgravity on humans and potential solutions to this problem. This work has proven to be highly influential in the field of space science, with much of what he discussed still being foundational principles in spacecraft design. The concept of a rotating artificial gravity station was later popularised and brought into common knowledge by Wernher Von Braun in 1956 with his design for a space station utilising this principle.

Since then, the concept has been generally accepted among professionals in the field as a suitable solution, assuming the structure can be built, and has been repeatedly used within science fiction. The common problem with the previous concepts for such structures is that, due to the limitations of the available technology at the time, they would be prohibitively expensive with many potential points of mission failure.

1.3 - Aims and Objectives

An expanding ring module, making use of origami principles as well as modern materials and manufacturing techniques, could significantly reduce the final weight and cost of the system as it could be constructed on Earth before being launched as a single object using modern heavy-payload rocket systems. It is this concept that will be explored within this research and the feasibility of such a system will be analysed with reference to current and near-future technology. The process of developing this concept will make use of theoretical research, calculations, as well as physical prototyping.

The aim of this research is to answer a series of questions that form the foundation of the overall feasibility of the concept and provide a basic structure on which further research and development can be performed. This research seeks to explore the use of expanding habitation modules as an alternative to the standalone stations explored in previous works. These underlying questions can be summarised by the following three questions:

1) Firstly, what are the physical requirements for an artificial gravity module to operate and provide inhabitants with simulated gravity?

2) Secondly, can origami principles and folding patterns be used to produce semi-rigid expanding space habitation modules when combined with modern materials?

3) Finally, is it feasible to launch a self-contained artificial gravity module into orbit, as a single object, with current or near-future technology?

The first of these core questions is critical to the purposes of this research as it will determine whether a relatively small diameter module is suitable for providing astronauts with artificial gravity, compared with the significantly larger structures proposed previously. Exploring this design consideration, while critical to the success of the technology moving forward, is quite straightforward due to the depth of knowledge and understanding of the underlying physics. Computer-based analysis, using graphs produced in Python and online tools such as SpinCalc [3] to compare a range of configurations of module radius and spin rate, will be important to determining an optimal radius and rotation speed for this purpose. The findings of previous studies exploring how humans respond to the speed of rotating environments will be used to find a balance between inhabitant comfort and minimising the overall size and weight of the launch payload.

The second question must be answered as the module compressibility is a fundamental principle that sets this research apart from previous concepts. Physical prototyping using paper models will be essential in exploring the use of origami principles for this purpose. This research will also involve considerations towards how the structure would be constructed and deployed.

Finally, answering the third question will rely on research into, and analysis of, specific launch vehicles, available currently or in the near future, that could be used to deliver the payload to spacecraft in orbit. The suitability of the launch systems for this use will rely on the maximum payload dimensions and mass that can be launched with each system. If no existing solution is available, an analysis of the launch vehicle requirements and some alternative launch methods will be explored.

2 - Literature Review

2.1 - Microgravity and its Effects on Human Health

Microgravity can be explained by separating the word into ‘micro’ and ‘gravity’ and defining it as is done within the metric prefix system, where ‘micro’ represents a 10^{-6} multiplier to any given variable (for example one microgram is 10^{-6} grams) and considering ‘gravity’ to represent Earth’s gravity (1g). By this definition, only truly weightless environments such as low Earth orbit (LEO) and interplanetary space can be defined as a microgravity environment. For the purposes of this research, microgravity will be defined as per this mathematical definition and used in reference to weightless environments such as that of LEO or interplanetary travel. Other cases such as those of the Moon or Mars, where the gravity falls between that of microgravity and Earth, will be defined using the term ‘partial gravity.’

Microgravity can, either directly or in conjunction with other effects, cause a number of negative side effects within the human body as a result of the body’s adaptation to a 0g environment. These conditions range from simple ‘Space Motion Sickness’ (SMS) that most people adjust to after a few days to degenerative “bone demineralisation, muscle atrophy, cardiovascular deconditioning, altered sensory-motor control, and central nervous system reorganisations” [4]. These effects, of course, stem from the fact that life on Earth developed under Earth’s gravity, noted as 1g and being equal to an acceleration of approximately 9.81 m/s^2, and for this reason the proper function of the human body relies on this consistent gravity, which leads to negative effects when this gravity is removed. The length of exposure to microgravity influences how the body responds and as such, the required complexity of the employed countermeasures is dependent on mission duration. For short exposures, such as space tourism flights to the edge of space, the exposure to microgravity is so brief that no countermeasures are required however for longer spaceflights, due to the degenerative nature of the health effects of microgravity, more comprehensive countermeasures must be used. The previously mentioned article published in Extreme Physiology and Medicine [1] classified a six-month mission aboard the ISS as a “long-duration mission” as well as providing brief descriptions of the various pieces of exercise equipment both currently and previously used on board the ISS in order to combat the effects of microgravity. This definition of mission length coincides with definitions commonly used among other publications, where ‘short’ duration missions are often less than two to three weeks in length and ‘long’ duration missions are anything over three months.

While these exercise machines do reduce the negative effects to a degree, astronauts are still affected significantly over standard mission durations and as such, this solution would not be adequate for longer missions, such as those to Mars, where the crew would not have the luxury of dedicated physiotherapy and medical teams after landing on the surface.

A paper by Goswami et al [5] explores how the human body adapts to altered levels of gravity in a review of previous literature and studies. The body of evidence regarding the effects of microgravity on male physiology are substantial, due to over 20 years of data collected during missions to low Earth orbit, however the data regarding female physiology is much more limited and further study will be required to determine any differences in how female physiology is affected; there is evidence from Earth-based analogues to suggest that the bodies of males and females respond differently to the same environmental conditions and this may need to be accounted for in spacecraft design. Studies of subjects in parabolic flight where humans are repeatedly exposed to short bouts of partial gravity revealed that “the threshold for the perception of verticality by humans is between 0.16g and 0.38g.” These results are corroborated by studies conducted on board the Space Shuttle, where the threshold of perceived verticality among the crew in orbit was found to be 0.22g. Other research was conducted to find the limit where subjects were able to complete basic tasks and found that “postural readjustments, object handling, and mechanical tasks such as bolt tightening did not pose significant problems at gravity levels higher than 0.2g.” The results of these studies may explain some of the issues the crew of the apollo missions experienced on the lunar surface, particularly in regard to balance, and may be evidence to support the claim that they could perceive verticality but lacked much of the ability to complete precise movements. It is important to note that the cumbersome nature of the suits worn by astronauts, particularly the large life support system, may have also contributed to their mobility issues. It can therefore be concluded that an artificial gravity module should be designed to provide a minimum level of gravity of 0.2g.

The ethical considerations of providing or denying artificial gravity should also be discussed in relation to future missions, in particular whether it is ethical to deny astronauts artificial gravity for extended periods if there is the capability of providing it. Goswami et al recommend that it become an ethical requirement to "provide functional gravity as part of a spacecraft life support system to keep crew healthy and safe" [5] and that space agencies should prioritise the safety and good health of the crew over "mission costs, complexity, and logistical challenges." Particularly in the case of manned Mars missions, the cost associated with providing artificial gravity to the crew would likely be relatively small compared to the total cost of the mission and would almost certainly improve the likelihood of mission success. This fact would be especially true using a system like the one proposed by this thesis, that could drastically reduce the costs associated with launching and constructing the structure.

The gold standard for combatting the harmful consequences of microgravity exposure is full-station artificial gravity, where astronauts would live in space as they do on Earth, however in the near future it is likely far more reasonable to aim for the addition of habitation/recreational modules with artificial gravity where crew members would stay while sleeping or during down-time. This alone would reduce their overall exposure to microgravity across the duration of the mission by more than 30% which could have profound effects on preserving the crew's long-term health and physical capability. In order to properly test the effectiveness of varying degrees of microgravity on a wide range of factors including the effects of partial gravity on human physiology, plant growth, etc, a module capable of a range of rotation speeds would provide an ideal testing platform; this should be taken into consideration in designing a module as proposed by this research.

2.2 - Producing Artificial Gravity by Rotation

The use of a rotating body to generate artificial gravity was first proposed in 1903 by Konstantin Tsiolkovski and the idea was later developed by Herman Potocnik and Wernher Von Braun. Artificial gravity by rotation works using the principles of circular motion and Newton's third law, where centripetal acceleration, given in equation 4, is responsible for keeping an object in circular motion and acts in a direction towards the centre of rotation. In accordance with Newton's third law there is a corresponding acceleration equal in magnitude and opposite in direction to the centripetal acceleration, often referred to as centrifugal acceleration. In this research, this centrifugal acceleration will be referred to as the 'perceived gravity' and represents the artificial gravity that acts on an object held within the ring module. Due to the direction of this acceleration, the orientation of the liveable space within the ring module is such that local vertical always lies towards the centre of rotation, as shown in Figure 1. In order to optimally negate the physiological effects of microgravity, it is reasonable to assume that a rotating habitation module should produce a perceived gravity of 1g, equal to the gravity on Earth's surface, however further study of astronauts in varying degrees of partial gravity may demonstrate that partial gravity is sufficient.

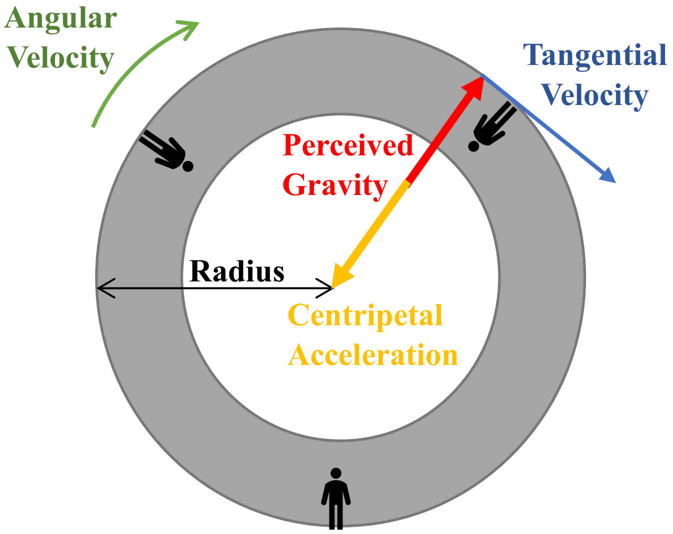


Figure 1: A diagram depicting the defining principles of artificial gravity production in a ring module by rotation.

Producing artificial gravity by rotation is reliant on the radius and rotation speed of the module, with a smaller rotation radius requiring a higher rotation speed for the same perceived gravity outcome. A negative result of producing artificial gravity with a small radius/high spin rate is the Coriolis force, an inertial force, dependent on the angular velocity of the rotating environment as well as the mass and linear velocity of an object, that causes the object in motion within a rotating field of reference to the appear to move in a curved trajectory. The apparent deflection of the object is referred to as the Coriolis effect. The Coriolis force acts in a direction that is perpendicular to both the angular velocity of the rotating frame of reference and to the linear velocity of the object relative to the rotating environment. The Coriolis effect is proportional to the rate of rotation of the reference environment and because of this, an ideal case for producing artificial gravity would make use of a very large, slowly rotating environments.

An article from Lackner and DiZio [6] notes that in order to minimise the cost of an artificial gravity vehicle, it is critical that the "smallest radius and highest rotation rate possible" is used. While this configuration is optimal for low cost, discomfort may be experienced by the inhabitants at high rotation rates due to Coriolis effects, defined by the author as "disorienting, nauseogenic cross-coupled semi-circular canal stimulation" during head movements. In layman's terms this means that fluid in the vestibular canals of the inner ear, which is responsible for our ability to determine physical orientation and balance, responds differently to head movements in a rotating environment than it would in a stationary environment due to Coriolis forces. This effect can cause discomfort however the source states that even at 10 RPM, considered excessively high by other sources, "movement endpoints and trajectories are initially deviated however subjects readily adapt with 10-20 additional movements." This finding suggests that modules can be designed to use higher rotation speeds, therefore allowing for smaller module diameters, through the use of prior training and acclimation procedures.

2.3 - Previous Concepts for Rotating Artificial Gravity Stations

Among the first concepts for a rotating ring station, designed to provide artificial gravity to the inhabitants, was a design outlined by Herman Potocnik in ‘The Problem of Space Travel: The Rocket Motor’ [2] in 1929. His design, depicted in Figure 2, was produced with a clear intention to provide a living space that would directly mimic life on earth, with all rooms being “furnished with modern-day comforts; even cold and warm water lines.” This proposed station would be approximately 30m in diameter and would complete a full rotation “in about 8 seconds”; this is equivalent to approximately 7.5 RPM and would generate a level of gravity almost identical to that of Earth. Potocnik notes that due to the nature of how the perceived gravity relates to the diameter and rotation speed of the station there would be a small difference in the perceived gravity between the head and feet of the inhabitants, leading to an approximate difference of 11%, however he states that this gradient should be “hardly noticeable.” The station was designed to be powered by a solar generator comparable in principle to standard steam turbine generators that are still in common use today that would use a parabolic mirror to produce steam; This generator would produce DC power that could then be stored in a battery array for later use.

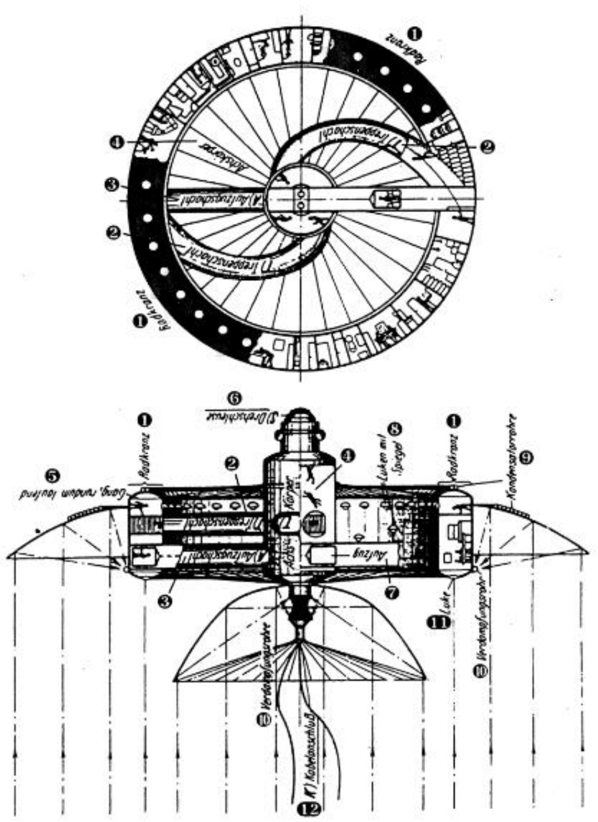


Figure 2: A diagram, taken from Herman Potocnik’s book titled ‘The Problem of Space Travel: The Rocket Motor’ [2], depicting his concept for a rotating ring station used to generate artificial gravity for the inhabitants. The key given below is also taken directly from the source to provide clarity.

Key:

1. Wheel rim, 2. Well of the staircase, 3. Elevator shaft, 4. Axial segment, 5. Circular corridor, 6. Turntable airlock, 7. Elevator, 8. Bull’s-eyes with mirrors, 9. Condenser pipes, 10. Evaporation tube, 11. Bull’s-eye (windows), 12. Cable connection

As mentioned previously, Wernher Von Braun produced a concept design for an artificial gravity orbital station, inspired by the work from Tsiolkovsky and Potocnik, and presented it to the public as well as government and military personnel in 1956. The station was designed in a toroidal shape, with two decks and a diameter of 200 ft (60.96 m) [7], intended to provide internal work and habitation space suitable for up to 50 inhabitants. The Von Braun station was described by Bekey and Herman [8] as a "springboard for exploration of the solar system." Von Braun noted the intended uses of such a station during the presentation of his design [7], suggesting a vast array of scientific and exploratory functions including laboratories, communications equipment, and Earth monitoring systems. Von Braun stated in his presentation [7] that the station would rotate at 3 RPM. Inputting the stated radius and rotation rate of the Von Braun station into SpinCalc [3] shows that the station would produce artificial gravity approximately 30% of Earth's gravity, slightly less than that of Mars. This may be sufficient for negating many of the negative effects of microgravity while also maintaining an ease of movement that is lost with weaker gravity such as that of the Moon, at approximately 17% of Earth's gravity, however further study would be required to determine the extent of the effects in this regard. Further study using an artificial gravity module as proposed in this thesis would provide data regarding how effective varying degrees of partial gravity are at negating the physiological effects of microgravity and determining whether supplementation with regular resistance training would be required to further reduce the health impacts to the inhabitants. Due to the much larger size of Von Braun's station, the gradient of perceived gravity between an inhabitant's head and feet, as noted by Potocnik [2], would be smaller than in Potocnik's design; this, combined with the slower rotation speed required, may lead to a more comfortable living environment for the inhabitants at the cost of operating within a lower level of gravity.

Von Braun's design was intended to be deployed using a series of inflatable sections that would be joined together and covered with protective panels once in orbit [7]. A central hub module would initially serve as temporary habitation for the crew constructing the station before being largely retired for use in docking and storage purposes. The station was intended to be powered by a nuclear reactor, located in the central hub in order to maintain a relatively safe distance between the inhabitants and the reactor at all times. While Von Braun's design was highly functional, the process of constructing it as originally designed requires many launches as well as relatively complex orbital construction; this leads to the proposal having many points of failure and these factors would greatly increase mission costs and are likely responsible for the design having not been implemented up to this point.

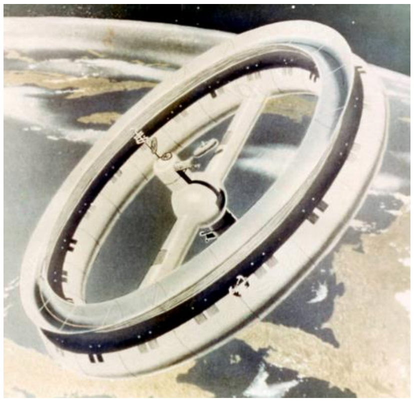


Figure 3: An artist's (Chelsey Bonestell) depiction of Wernher Von Braun's artificial gravity station from 1952. Images from: https://www.nasa.gov/centers/marshall/history/stations/images/early-wheel-station-concept

Another concept design that makes use of rotation to provide artificial gravity is the O'Neill Cylinder, a much larger station that was intended to more closely replicate the conditions of Earth for the purpose of permanent, multi-generational colonies living permanently in space. The station was designed by Gerard K. O'Neill in 1974 and outlined in an article for Physics Today [9], titled "The Colonisation of Space." The design, as depicted in the concept illustrations given in Figure 4, consists of a pair of cylinders that rotate in opposite directions, thus negating the gyroscopic forces generated by a single rotating body and allowing the station's orientation to remain fixed and more easily pointed at the sun. The proposed cylinders are 20 miles long and 4 miles in diameter, with three 'land' areas on the inside, separated by three large windows.

Due to the much larger diameter, the O'Neill cylinder rotates at a significantly slower rate than Potocnik or Von Braun's stations and, as a result, greatly reduces the Coriolis effects created and provides a much more natural feeling living environment; the larger station design also allows for the recreation of outdoor environments, as the image depicts in Figure 4. Outside the cylinders, a series of mirrored arrays reflect the sunlight through the windows, which can be opened and closed to simulate a day-night cycle for the inhabitants. These stations, with a land area across both cylinders totalling approximately 500 square miles, are large enough to house several million people comfortably. Due to the nature of the station the climate, gravity, and landscape of the internal space would be entirely controlled by the inhabitants, allowing for perfectly replicated environments to suit the requirements and desires of the inhabitants.

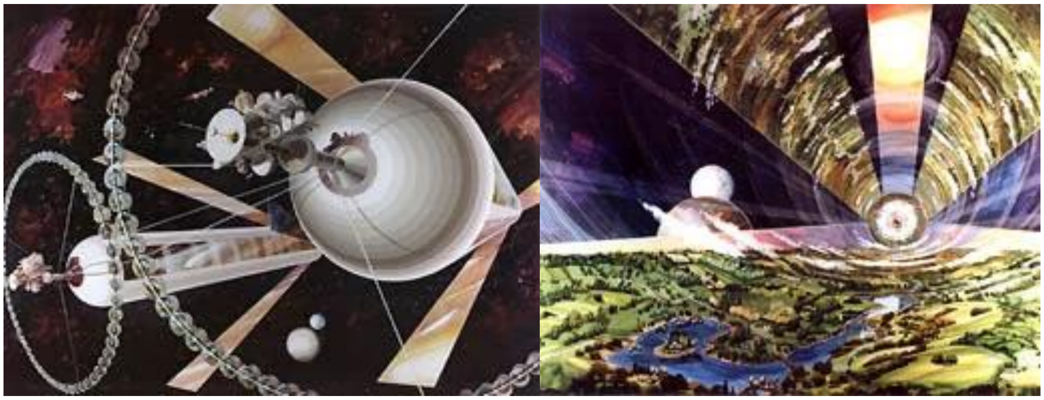


Figure 4: An artist's (Rick Guidice) depictions of the O'Neill Cylinder concept, from an internal and external perspective. Images from: https://space.nss.org/o-neill-cylinder-space-settlement/

Table 1 below shows a comparison of the module radius and required spin rate to achieve 1g in the artificial gravity concepts discussed to that proposed in this paper.

Creator of Concept	Module/Station Radius (m)	Required Spin Rate for 1g of Perceived Gravity (RPM)
Herman Potocnik	15	7.5
Wernher Von Braun	Approx. 30 (100ft)	5.5
Gerard O'Neill	100 - 3200	0.5 - 3
Jonathan Morgan (Candidate of this Thesis)	10	8-9

Table 1: A comparison of the radius and required spin rate for 1g for various artificial gravity station proposals.

3 - Methodology

3.1 - Determining Mission Requirements

When determining the mission requirements for a rotating habitation module, it is critical to consider not only physical limitations such as the module size and mass but also inhabitant comfort factors including the rotation rate and module diameter. All these factors are affected by the overall operational size of the module, with a larger diameter naturally leading to a larger size and mass but also resulting in a slower spin rate for a given perceived gravitational strength which generally produces a more comfortable living environment for the inhabitants. Equations 1-4 are critical for exploring the relationship between the module radius, spin rate, and perceived gravity and are the equations that form the basis of the SpinCalc tool [3].

Online tools, such as SpinCalc [3] can assist in quickly and intuitively experimenting with the balance between radius, spin rate, and the resulting gravitational strength, based on user inputs. SpinCalc also displays indicators regarding crew comfort for each variable based on data from a range of sources. For the purposes of this research, SpinCalc and its listed sources will be used to analyse the balance of module size and spin rate for a desired strength of perceived gravity. SpinCalc uses the following equations, along with two of the variables input by the user, in order to determine the relation between radius, spin rate, given as both angular and tangential velocity, and artificial gravity strength as centripetal acceleration:

$$Radius,\ R = \frac{V^2}{A} \qquad \textit{(eq.1)}$$

$$Angular\ Velocity\ [RPM],\ \Omega = \frac{V}{R} \qquad \text{(eq.}\textit{2)}$$

$$Tangential\ Velocity,\ V = \Omega \times R \qquad \text{(eq.}\textit{3)}$$

$$Centripetal\ Acceleration,\ A = \Omega^2 \times R \qquad \textit{(eq.4)}$$

While equation 2 uses Revolutions per Minute (RPM), the SI unit for rotation is Radians per Second (rad/s) which can be determined using the following conversion equation:

$$Radians\ per\ Second,\ rad/s = RPM \times \frac{2\pi}{60} \qquad \textit{(eq.5)}$$

These equations can be used to compare the relationships between the variables and to provide useful information that can inform decisions in pursuit of an optimised design. Figure 5 combines these equations to display the relationship between the module radius and the spin rate, normalised at a perceived gravity of 1g. The plot shows a decreasing rate of change in the required spin rate as the radius increases; this demonstrates that a smaller module radius does not necessarily result in a more uncomfortable crew environment compared to larger stations and as such, ring stations do not have to be as large as some of the designs proposed previously. A smaller module provides many benefits over large modules through their smaller mass, manufacturing costs, and ongoing operational/maintenance costs. Simple calculations show that compared to a centrifuge with a 2m radius, equivalent to the European Space Agency's 'Short-Arm Human Centrifuge' (SAHC) [5], the required spin rate to produce 1g of perceived gravity reduces by over 75% before the module radius exceeds 30m.

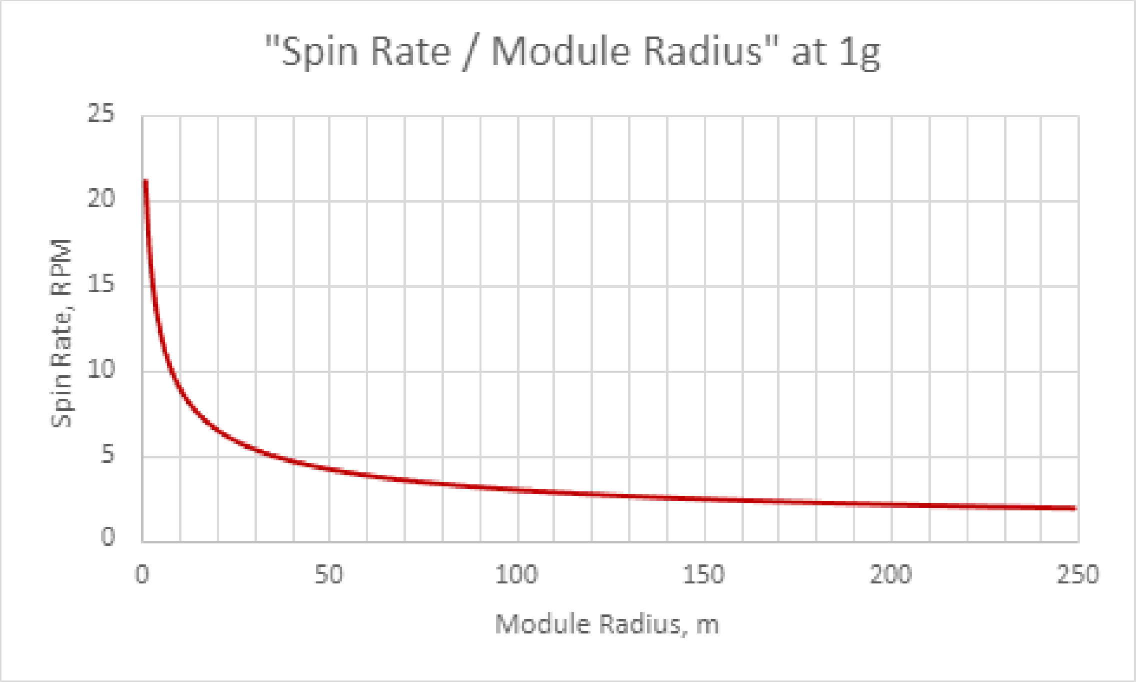


Figure 5: A plot showing the relationship between the module radius and spin rate of an artificial gravity module operating at 1g.

As the perceived gravity is dependent on the radius, a gradient in the level of gravity will form between the head and feet of inhabitants, expressed in figure 6 as a percentage of the perceived gravity at the feet that is lost at the head of the inhabitant; this could become a source of discomfort and difficulty in moving due to a feeling of disorientation if too large and as such, it should be minimised where possible. When plotting this gradient against the module radius as shown in figure 6, again using a perceived gravity of 1g at the inhabitant's feet to normalise the data, another negative exponential decline occurs. This gradient was calculated by determining the perceived gravity at the head and foot of a 1.8m tall astronaut, using the module radius for calculating the perceived gravity at the foot and by reducing the radius by 1.8m in the calculations for the perceived gravity at the head, and then determining what portion of the perceived gravity at the foot is lost at the head. In this case, the decline is even more sharp, with a reduction in gradient of 75% before the radius reaches 8m. This is consistent with Potocnik's view [2] that the gravity gradient would be barely noticeable and therefore should not present an issue in the design of artificial gravity habitats.

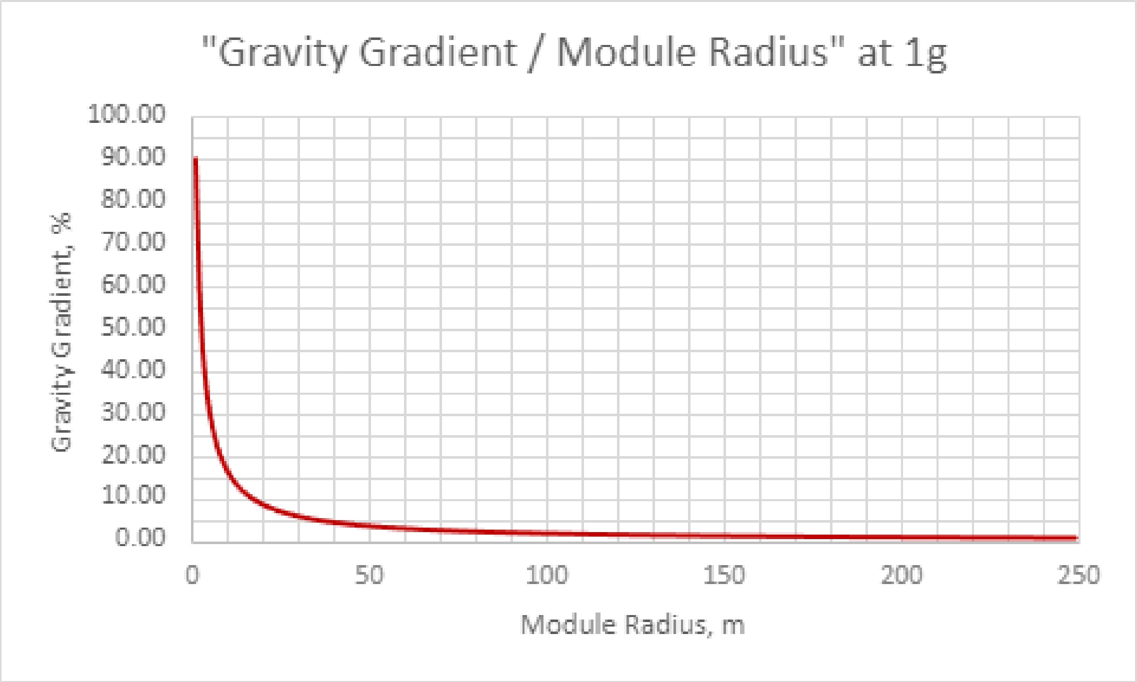


Figure 6: A plot showing the gravity gradient present between the head and feet of an inhabitant of an artificial gravity module operating at 1g.

The plot given in Figure 7 was produced using a Python script, supplied in the appendices, and displays the relationship between the module radius, perceived gravity, and the required spin rate. The plot uses module radius and the perceived gravity outcome as variables and then calculates the spin rate required for each combination of these variables using the equation given previously. The colour map runs between green, yellow, and red and is a visual analogue of crew comfort, based on the findings of the previous studies discussed earlier. Any region above 10 RPM exceeds the upper limits of what humans can adapt to and should therefore be excluded from consideration; the further into the green region the design configuration lies, representing a reduced spin rate for the given perceived gravity, the easier and more seamlessly an astronaut could be expected to adapt to the environment.

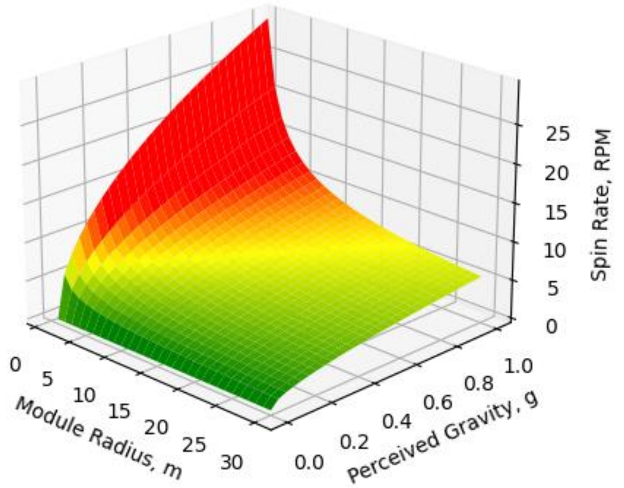
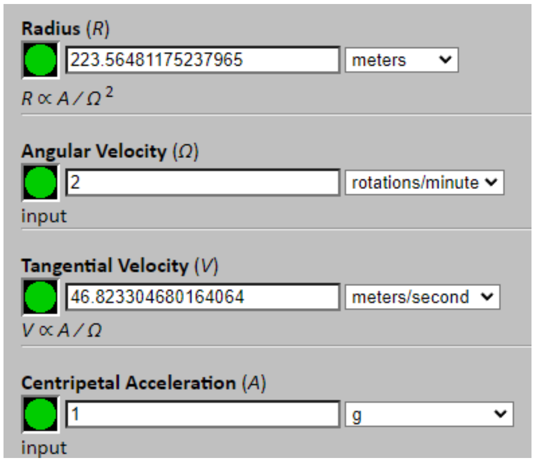


Figure 7: A 3D plot showing the relationship between module radius, desired perceived gravity, and the required spin rate. The colour spectrum applied to the plot provides insight into the comfort of the inhabitants.

The plot shows that at smaller levels of perceived gravity, such as around the 0.2g minimum concluded from the work of Goswami et al [5], even very small radii can be used comfortably however small diameter centrifuges would be very limited in terms of practical activity that can be completed while using it and for this reason, a larger radius is preferable for living or working spaces. Similarly, a very large radius can comfortably produce levels of perceived gravity all the way up and even exceeding 1g; however, this plot confirms that increasing the module radius has diminishing returns on improving crew comfort. It is reasonable to assume, based on previous studies, that astronauts would be capable of adjusting to rotating environments between 6-10 RPM with relative ease and as such, a module radius should be chosen such that at 1g, the spin rate lies within this region.

The plot demonstrates that a module radius of approximately 10-20m is suitable for this purpose; operating towards the low end of this range, and therefore near the upper limits of crew comfort, reduces the overall size of the module and aids in its feasibility due to reduced cost to manufacture and launch. For the purposes of this research, a module radius of 10m will be used as this demonstrates a habitat ring capable of providing astronauts with a wide range of gravity environments as determined by the mission whilst minimising the overall size. Reducing the module radius not only directly affects the stowed size of the module but also the total surface area of the module that must be manufactured, monitored, and maintained; keeping this at a minimum reduces the overall mission costs and increases the likelihood that the technology would be implemented.

While certainly not necessary as the required calculations are simple, online tools such as SpinCalc [3] can be used to quickly and intuitively experiment with and compare specific module configurations, using the previously given graphs as a guide, without the need for manual calculations. The output of this tool provides an easily visualised insight, using the coloured indicators to the left of each variable, into the relationship between the various physical parameters and the expected comfort levels of each configuration. Figure 8 displays an example of an ‘optimal’ design in terms of limiting Coriolis effects, minimising the rotation rate by use of a very large radius. Despite being an ‘ideal’ case for inhabitant comfort and providing a very large inhabitable space, therefore being a beneficial configuration for use in a station designed to support space-faring colonies such as the O’Neill cylinder concept [9], the large radius makes it an impractical choice for a single launch module as proposed in this study.



Radius (R)
🟩 223.56481175237965 meters
$R \propto A / \Omega^2$

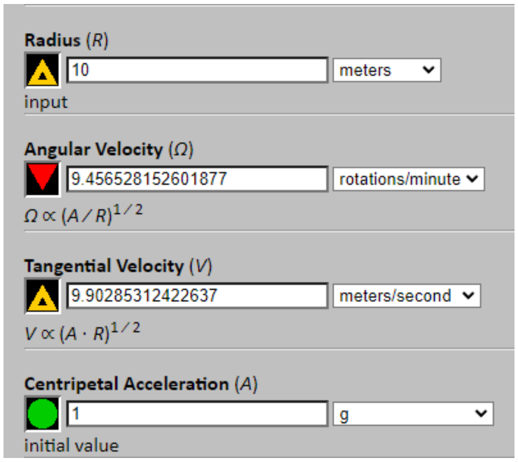
Angular Velocity (Ω)
🟩 2 rotations/minute
input

Tangential Velocity (V)
🟩 46.823304680164064 meters/second
$V \propto A / \Omega$

Centripetal Acceleration (A)
🟩 1 g
input

Figure 8: Parameters from SpinCalc, demonstrating an “ideal” case.

The previous experimentation made it possible to determine a configuration that appears to be suitable for the purpose; being a compromise between size and rotation rate as shown in figures 9 and 10. The configuration is capable of reproducing Earth gravity at a rotation rate that, while considered too high for immediate comfort, is within a range where adjustment was found to be possible by the study by Lackner and DiZio [6]. The same configuration, if used for reproducing Mars gravity (0.38g), operates at a reduced rotation rate that would be more immediately comfortable for the inhabitants. The ability for this configuration to operate up to full Earth gravity at the given radius allows the crew to gradually adjust to Mars gravity before reaching the planet, through a gradual reduction in rotation rate. Adjusting the perceived gravity in this way ensures the crew are physically able to maintain their effectiveness when they reach the surface which maximises the chances of mission success. As the level of artificial gravity is dependent on both the radius and speed of the rotating frame, a gradient will be formed between an inhabitant's head and feet. This is minimised at larger radii and may cause some discomfort if excessive. In the case shown in figure 9, the strength of gravity at head height would be approximately 0.85g for an astronaut 1.8m tall, thus producing a gradient of 15%; further study and experimentation would be required to determine the effects of this gradient on crew comfort. For comparison, the gradient experienced in the 'optimal' configuration, shown in figure 8, is less than 1%.



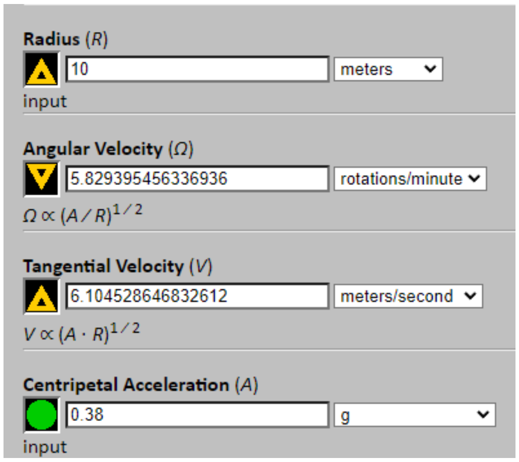
Radius (*R*)
▲ 10 meters
input

Angular Velocity (*Ω*)
▼ 9.456528152601877 rotations/minute
$\Omega \propto (A / R)^{1/2}$

Tangential Velocity (*V*)
▲ 9.90285312422637 meters/second
$V \propto (A \cdot R)^{1/2}$

Centripetal Acceleration (*A*)
● 1 g
initial value

Figure 9: Inputting the optimised design variables into SpinCalc demonstrates a balanced configuration, operating at full Earth gravity.



Radius (R)

10 meters

input

Angular Velocity (Ω)

5.829395456336936 rotations/minute

$\Omega \propto (A / R)^{1/2}$

Tangential Velocity (V)

6.104528646832612 meters/second

$V \propto (A \cdot R)^{1/2}$

Centripetal Acceleration (A)

0.38 g

input

Figure 10: The configuration from figure 9 is also suitable for operating at Mars gravity, providing a wide range of gravity conditions as required.

The creator of SpinCalc, Theodore W. Hall, includes the following statements on the website [3] that are critical considerations for the ongoing technological development of artificial gravity structures. Firstly, he states that “in orbital habitat design, the choice is not between artificial gravity and Earth gravity, but rather between artificial gravity and microgravity.” This statement serves to remind us that a non-ideal solution providing some gravity to the inhabitants may still be a superior option to the prolonged microgravity they would otherwise be exposed to. Furthermore, he notes that “it may not be necessary to provide immediate perfect comfort in artificial gravity, especially in small exploration-class vehicles with select crew.” This, similarly, reminds us that the use of these modules will likely be limited to individuals with specific experience and training for the environment and therefore does not need to provide a seamless transition, and that the use of dedicated adaptation procedures is an acceptable compromise given that the astronauts would undergo an adaptation period to orbital conditions either way.

3.2 - Statement of Mission Requirements

An artificial gravity module such as the one proposed by this research should be expected to generate between 0.38g and 1g, equivalent to the gravity of Mars and Earth respectively. For optimal crew comfort, the spin rate of the habitat should be minimised in order to reduce Coriolis effects, whilst balancing this against a reasonable module size. Reducing the spin rate requires a larger module diameter for the same level of perceived gravity, as noted in section 2.2, however maintaining the ability to launch the module as a single object is critical for minimising the overall costs associated with the system and therefore increasing the commercial viability of the technology. While it may not be critical that an artificial gravity module is launched as a single object, it is greatly preferable as doing so would minimise the cost and complexity of deploying the system when compared to launching the structure in sections and assembling them in orbit.

For the purposes of this study the following criteria and dimensions, shown in Table 2, will be used as a set of guidelines for determining the potential success or failure of the proposal. Keeping the deployed diameter small will greatly reduce the stowed size as a result and will therefore maximise the chances for success and feasibility of the system. Using the faring diameter for heavy-payload rocket systems, such as SpaceX's Starship or NASA's SLS, as a guide value for the maximum stowed diameter maximises the chances of launch capability on similar launch vehicles. The chosen spin rate relies on the findings of previous research, referenced by Theodore W. Hall via SpinCalc [3], and lies near the upper limits of what humans can adapt to; these higher spin rates allow for a smaller overall module size for the same perceived gravity. The variable nature of the perceived gravity is simply a derivative feature of the ring module, relating directly to the spin rate and deployed diameter of the module, however choosing 1g as the upper limit will ensure the inhabitants do not experience motion sickness due to the higher spin rate; this upper limit will also reduce the maximum strain requirements of the materials. These variables as shown should provide a good balance between the crew comfort, spin rate, and expected overall stowed size. The lower limit of the perceived gravity has been taken from the study by Goswami et al [5].

Design Variable	***Guide Value***
Deployed Diameter	20 m
Stowed Diameter (max.)	9 m
Rotation Rate	5.32 - 8.63 RPM
Perceived Gravity Level	0.2 - 1g

Table 2: A set of design variables as well as the relevant guide values for the purposes of this research and the resulting concept module.

Such a module, in order to maximise the range of operational uses and therefore the mission demand, should be capable of providing a variable level of artificial gravity to accommodate a wider range of crew needs. For example, the journey between Earth and Mars could provide a long enough period of time that with gradual reduction in rotation speed of the ring module, adaptation from Earth gravity to Mars gravity could be nearly imperceivable. A gradual adjustment in this way would reduce the harsh adjustment periods that would otherwise be required that could cause complications regarding the astronauts' ability to complete their mission. Alternatively, a constant gravitational strength lying within these limits could be used on board 'static' space stations such as the International Space Station, as per the specific requirements of the crew and any experiments being carried out.

3.3 - Concept Proposal

3.3.1 - Comparison of origami Folding Patterns

Origami originated in Asia over 1000 years ago [10] and is derivative of the Japanese words "ori" meaning "folding" and "kami" meaning "paper" [11]. It is an artform in which sheets of paper are folded in such ways as to produce 3D objects in a range of shapes. These folds are categorised broadly as either "mountain folds" or "valley folds" depending on whether the fold forms a peak or valley from the current perspective [10]. The use of origami principles and folding patterns can dramatically reduce the launch size of a given structure as well as protect structural elements from damage during launch. The use of deployable structures and origami-like principles is already common within spacecraft design, particularly in solar arrays and heat shields which are often created using a series of hinged panels. This kind of deployable structure, constructed using rigid panels, often runs into issues with flexibility and as a result, Tomohiro Tachi developed a method for solving these issues which he called "thick-panel origami" using tapered panels [11]. In this method, hinges are offset in such a way that the connecting line between hinges lies diagonally through the panel as opposed to along the surface, thus allowing panels to lie flat against each other when folded, as shown in figure 11. Using this method, we can much more effectively pack a structure into a smaller launch package.

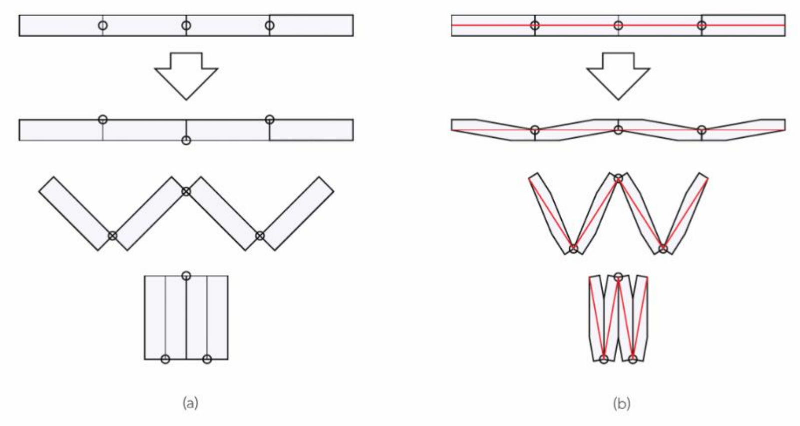


Figure 11: A diagram taken from 'Deployable Structures' [11] showing two methods for producing thick panel origami structures.

As materials engineering advances and the availability of smart materials increases, the potential for deployable structures that can avoid the use of hinges entirely also increases, for example by making use of shape memory materials to deploy the structure.

This could be useful in producing expanding space station modules, and similarly to improve more conventional station components such as solar arrays, to produce deployable structures with fewer potential points of mechanical failure due to the lack of hinges. Solar arrays using this technology could also make use of flexible solar cells to provide near 100% coverage area, thus increasing the overall efficiency of the array.

Deployable structures are generally classified as either “rigid component deployable structures” or “deformable component deployable structures” [11]. As the name suggests, rigid component deployable structures are made up of rigid parts, with deployment being fully controlled and stable at all stages. On the other hand, ‘deformable component deployable structures’ describes structures such as nets, fabrics, and inflatable structures; the deployment of these structures is largely uncontrolled can usually only be stable when used in conjunction with other structural components. Inflatable structures are versatile, durable, relatively lightweight compared to many rigid structures, and can usually be deployed more rapidly than a rigid component alternative. Some structures cannot be properly defined within these classifications and therefore alternative classifications can be used, namely “flexible deployable structures” and “combined deployable structures.” Flexible deployable structures consist of semi-rigid parts that are designed to have limited flexibility and allow for some deformation during deployment or use. Finally, a structure is classified as a “combined deployable structure” when it is constructed of a combination of rigid, deformable, and/or flexible parts to create a single mechanism.

Bigelow Aerospace, founded in 1999 by Robert T. Bigelow in Nevada, USA, specialises in the development of inflatable habitation modules for use in space exploration [12]. Mr Bigelow holds exclusive licensing rights to commercialise a technology for expandable space habitats that were developed, though ultimately abandoned, by NASA in the 1990’s. As of today, the company has successfully launched two subscale spacecraft, named Genesis I and II, into orbit as well as having ‘BEAM’, the Bigelow Expandable Activity Module, launched and docked to the ISS, where it is being tested for impact resistance, radiation shielding, and pressure stability. NASA’s Nathan Wells stated that the BEAM system has been cleared to remain on the ISS until 2028 due to it exceeding expectations [13]. This provides a perfect case study for the use of more expansive inflatable habitation structures in space exploration.

When searching for a suitable folding pattern for use in the concept design, there are a variety of considerations that must be made in order to make a final decision. Firstly, the complexity of the pattern is an important consideration as a simpler pattern would require fewer moving parts which, as a result, reduces the number of points of weakness and should provide a cheaper solution with better protective properties. Secondly, the compressibility of the pattern is critical as the stowed dimensions of the system rely on this variable and this factor will greatly affect the feasibility of the system due to launch vehicle payload restrictions. Finally, the deployment of the system should be considered because while a complex system may pack smaller, there is a higher chance of deployment issues due to the increased number of components.

In the search for an origami folding pattern suitable for this proposal, comparisons of paper models showed the 'Square Bellows' [14], as shown in figure 12, to be a promising example. It is a simple pattern made of relatively large panels. As the name suggests, the cross section of the pattern is approximately square which, while allowing for much easier implementation to mimic conventional Earth-like living spaces, may not be an ideal case for pressurisation due to the fact that round objects distribute stresses caused by pressurisation more effectively than objects with polygonal cross-sections; further study of this effect would be required to determine the extent of the consequences in this context. The 'Square Bellows' pattern could also be easily adapted to produce a wider space with a rectangular cross section, similar to the shape of Herman Potocnik's design [2]. As each side of the structure is simply constructed of alternately folded panels, the structure should exhibit a highly favourable compressibility ratio. Finding an optimal width for the panels within the origami structure will require a more in-depth study into a specific origami pattern used in the final structure. While it should be noted that wider panels will result in better compressibility than narrow panels, as there will be fewer folds per unit of length around the circumference of the structure, wider panels would also result in a larger amount of wasted surface area of the hull and therefore less usable space within the module due to the incomplete expansion of the inner surface. For this reason, it may be more beneficial to use narrower panels to maximise the usable space within the structure. Alternatively, it may be possible to modify the existing pattern to allow for full expansion of the inner surface, by making the inner panels narrower than the outer panels to account for the smaller circumference required, which would result in no wasted surface area; this must be explored in further research to ensure no adverse effects are created by doing this.

A test model, made by the candidate for the purposes of this research, was used to take rough measurements in order to estimate the compressibility of the folding pattern and therefore an estimated stowed size of the final structure. The outer face of the test piece measured approximately 20cm in length when expanded, and approximately 2cm when fully compressed. This suggests an approximate compression ratio of 10 for the Square Bellows pattern. Using this value and taking a module with each side of the square cross section measuring 3m, an estimated stowed size for the module can be calculated through a series of trivial calculations. Given that the circumference of a circle with a radius of 10m is approximately 62.8m, the circumference of the inner face of the ring structure when stowed can be estimated using the compressibility ratio to be 6.28m. From this, we can calculate the internal diameter of the ring in this position to be approximately 2m, and by adding 6m to this, to account for the width between the inner and outer circumferences of the habitable space, an estimated stowed diameter is found to be 8m. This estimation, whilst not necessarily accurate to the real module due to the potential for variation in compressibility based on the materials used, suggests that the proposed module will fit inside the standard fairings, and certainly within custom flared fairings, of the two launch vehicles considered later in the article, SpaceX's Super Heavy Booster and NASA's Space Launch System (SLS).

Figure 12: A paper model of the Square Bellows folding pattern, representing a section of the outer ring. Viewed from the side and from a perspective similar to that of an inhabitant.

Another potential option for a suitable folding pattern is the ‘Octagonal Bellows’ [15] which boasts a similar core deployment principle and compression ratio to the Square Bellows pattern, though with an octagonal cross section that may provide more favourable pressure distribution properties. An octagonal cross section was chosen for this comparison as it represents an approximate midpoint between polygonal cross sections ranging from 6 to 12 sides, where a larger numbers of sides would produce a more round cross section at the cost of a more complex pattern. This rounder cross section comes at the cost of a more complex pattern with smaller panels; this fact, while better distributing the number of vulnerable points between panels across the surface, also leads to less wasted material in the event a panel needs to be replaced. After producing a paper model, a few issues immediately present themselves when considering this pattern for use in this context. Firstly, the octagonal shape dictates that a separate floor would need to be installed within the ring, which would increase the system complexity, launch mass, and time taken to deploy the module in orbit; this floor is required as each edge of the octagon makes up approximately 30% of the available diameter and therefore creating a floor surface using one face of the outer skin, as is possible with the Square Bellows, would result in a very narrow walkway that would restrict the usability of the space. The separate floor provides approximately the same floor space as the Square Bellows pattern however to achieve the same artificial gravity conditions, the ring structure must be made to a larger diameter.

Despite the negative factors associated with it, a separate floor would provide space, separate from the inhabited section, where conduits for electricity, ventilation, heating, and water could be run and may also allow the floor to be dynamically isolated from the main structure to prevent the transmission of vibrations to other parts of the spacecraft. The process for determining the estimated stowed size of a module made using the Octagonal Bellows pattern is identical to the process used for the Square Bellows and while slightly larger in the stowed state due to the larger module diameter required, the difference is relatively small and thus would not disqualify it from being launched by the same launch vehicles as the Square Bellows.

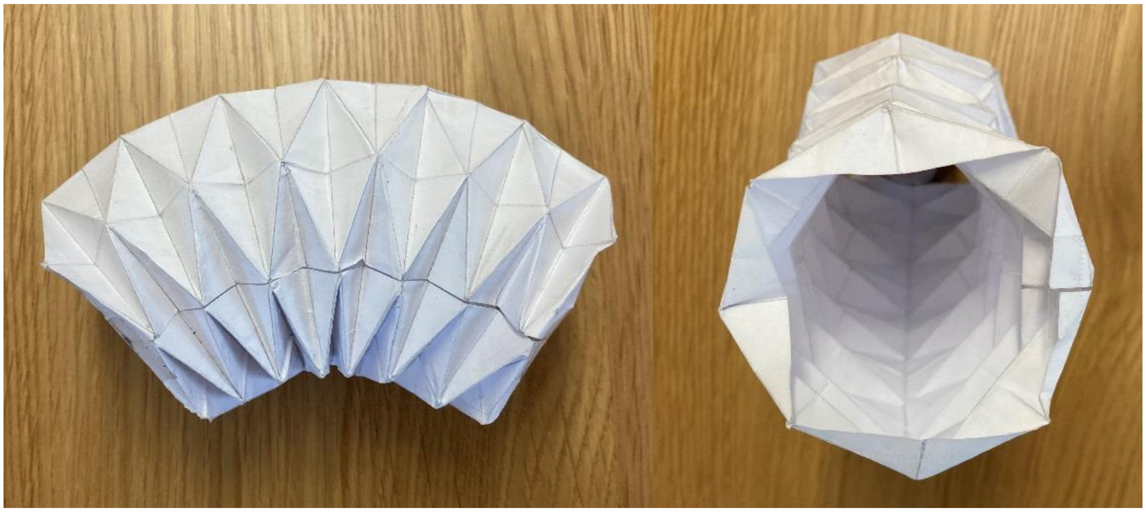


Figure 13: A paper model of the Octagonal Bellows folding pattern, representing a section of the outer ring. Viewed from the side and from a perspective similar to that of an inhabitant.

The larger required module diameter of the Octagonal Bellows to produce the same artificial gravity conditions, as well as the separate internal floor, naturally increases the total surface area, and therefore mass, of the system. The diagram given in Figure 14 demonstrates the difference in required surface area due to the larger module diameter, normalised for an equivalent cross-sectional area. These surface areas were calculated using the total expanded circumference of each pattern, multiplied by the width of each side of the cross-sectional shape, and then multiplied by the number of sides. In the case of the Octagonal Bellows, the separate internal floor requires a slightly larger maximum diameter for the module to place the internal floor at the same radius as the external face of the Square Bellows. The surface area of the separate internal floor is also included, which was calculated using the circumference of the module at the floor level as well as the width of the floor.

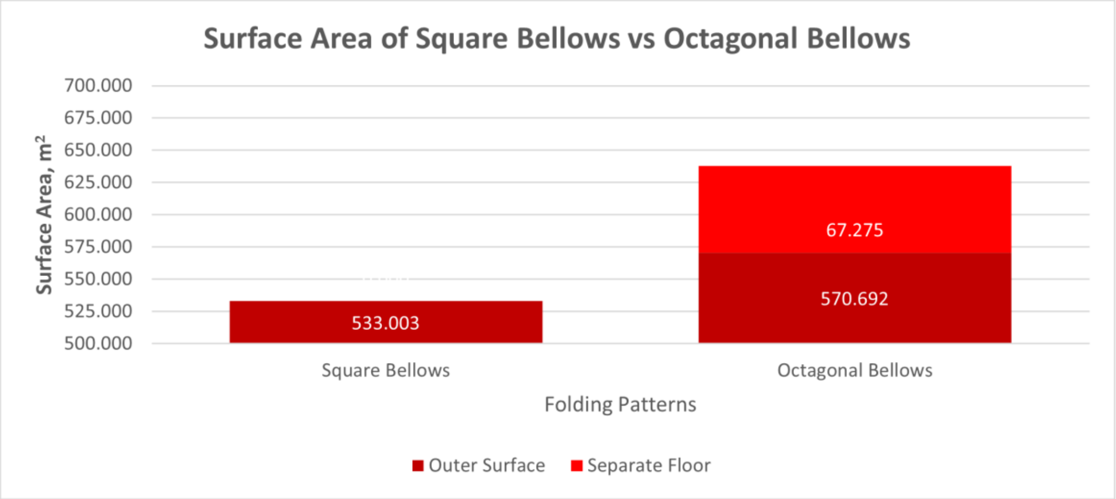


Figure 14: A chart showing the difference in required surface area between the Square Bellows and Octagonal Bellows for the same radius at floor level.

In order to allow the structures to expand fully and minimise the required surface area, both the Square Bellows and Octagonal Bellows patterns must be modified slightly by dividing certain panels to allow them to fold, marked by the green lines on the folding pattern diagrams in Figure 15. The difference between the two patterns is that, in the case of the Octagonal Bellows, the vertices between panels which may form stress concentration points are more evenly spread across the whole surface compared to the Square Bellows pattern where these joins are concentrated near the corners. This could aid in pressure distribution and reduce the likelihood of failure as the total number of vertices in each pattern are comparable. More in-depth analysis, using finite element analysis and high-fidelity models to analyse the stress distribution under operational conditions, would be required to determine the extent of this effect and the pressurisation characteristics of each structure.

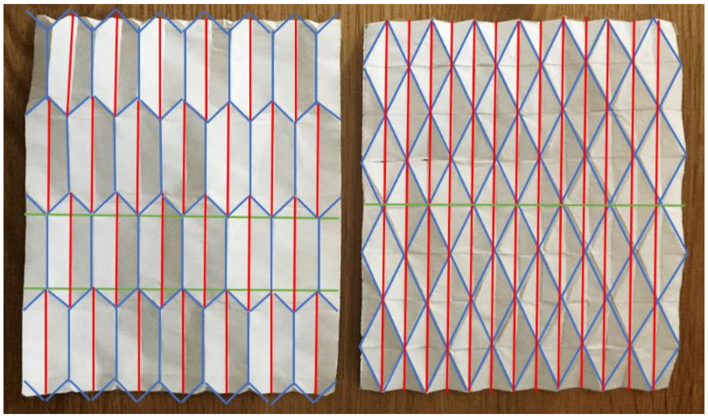


Figure 15: The Square Bellows (left) and Octagonal Bellows (right) patterns, overlaid to show mountain and valley folds.

Key:
Blue – Mountain Fold
Red – Valley Fold
Green – Non-conventional folds to allow for full expansion.

Of the two patterns analysed in this section the Square Bellows has shown to be the more favourable option as, along with the simplicity and compactness it provides, the significant reduction of total surface area and hence a reduction in total mass provides an extra benefit over the alternatives. Whilst there are many other bellows-type folding patterns that could be used for this purpose, with varying levels of complexity, depending on the polygon on which they are based, the two options compared in this research each demonstrate unique benefits for this purpose; the Octagonal Bellows, for example, can be expected to perform in a comparable way to more complex shapes like a decagonal bellows, however further increasing the complexity of the pattern will reduce the compressibility of the structure.

Further study of the pressurisation characteristics of origami bellows structures, under operational conditions, must be conducted in the future to ensure that a structure of this type is suitable for this use and will not cause dangerous stress concentrations between the panels; that said, I would not expect any significant issues that could not be accounted for by reinforcing the flexible hull wall at the higher-stress points but this must be confirmed.

Docking hatches and airlocks are common features onboard spacecraft and an origami structure would make these difficult to implement in the habitation ring. This issue can be overcome through the use of non-compressible sections in the ring where airlocks can be more easily installed; these sections would also provide perfect locations to attach the support struts that would act as access points to the habitation ring.

3.3.2 - Material Selection

Soft-wall Composite

Bigelow Aerospace's 'BEAM' uses a soft composite shell made from a combination of Vectran, a material similar to Kevlar though much stronger, for impact resistance as well as layers of polymer foam for radiation shielding [16]; a similar composite structure would be equally as applicable to an inflatable ring module such as the one proposed in this thesis. The company [12] claims that this composite allows for better impact resistance than traditional hard-shell modules due to the ability for the surface to deform temporarily and therefore dissipate the energy of the impact across the surface. Despite this benefit, the composite structure may be more susceptible to abrasive damage and could prove more difficult to maintain over longer time periods, likely requiring direct monitoring of any damage and then a full replacement of the module when the total damage severity passes a pre-defined safety threshold.

Armour Panels

For such a large structure, a method using only the soft-wall composite may prove to be both wasteful and costly due to the potential need to replace the whole structure in the event of damage and instead, easily replaceable semi-rigid armour panels fixed to the outside of the soft-wall composite would be a better option to increase the lifespan of the module. Such armour panels would achieve this by protecting the main wall structure from the abrasive or slicing effects of impacts while still allowing the module to flex and transfer energy across the surface. This configuration would therefore take advantage of many of the benefits of the inflatable soft-wall structures while also providing the opportunity to remove individual damaged panels for repair or replacement and thus reducing the future costs associated with the system.

For this purpose, the panels must be lightweight, capable of withstanding multiple impacts, and should be relatively cheap to manufacture in the required shape and size. The use of 3D printing technology onboard the spacecraft could provide an opportunity to recycle damaged panels for minimal ongoing costs and increased self-sufficiency. A low total mass is critical for this proposal due to the payload mass limitations of launch systems. Similarly, in order to reduce ongoing mission costs, the panels must be able to withstand multiple impacts from debris or micrometeoroids without failure. Finally, minimising manufacturing costs is important for the development and implementation of the design as a large surface area will need to be covered and high material costs could make this prohibitively expensive. When considering material options for the outer panels, it will be useful to make a comparison to modern ballistic armour as the requirements and functions of station module shielding is comparable. There are many materials used in ballistic armour that could be suitable for this use and these will be explored below.

Metallic

Using metallic panels is the most conventional, and mission-tested, option and would result in highly predictable properties, comparable to those found in current air and spacecraft hulls. This long history of use provides us with data that shows the high levels of reliability achieved when using metallic shielding. Due to the availability of the materials and widespread manufacturing facilities, the use of metallic plates is also a relatively cheap option and could lower the overall cost of the module substantially. Despite this benefit, the strength to weight ratio of metallic plates may be lower than some alternatives and would therefore take up more of the available payload mass of a launch rocket. Two metals commonly used in spacecraft hulls on board the ISS are aluminium and stainless steel; each have their own advantages and disadvantages and deciding between them is usually determined by the specific use-case.

An article from Kloeckner Metals, a metal distributor based in the USA, titled "When to Use Aluminium vs Stainless Steel" [17] provides an in-depth breakdown and comparison of the two metals and the cases where each would be a better option; the article breaks down the material properties, cost, environmental impact, and common uses of each metal as well as common alloy compositions. Given the already protective nature of the soft-wall composite, the lighter weight of aluminium may be a more desirable property than the increased strength of the stainless steel in this case.

Ceramic

Ceramic plates are more complex than metallic plates and use, as the name suggests, ceramic tiles supported by other materials, such as Kevlar, to stop projectiles [18]. The supporting materials help to prevent accidental breakage and maintain the integrity of the plate after impacts. Ceramic plates, while effective at stopping projectiles, are only suitable for a small number of impacts before they must be replaced; this is a considerable drawback for ceramics in this case as frequent resupply of replacement panels would substantially increase the ongoing maintenance costs of the system. Ceramic plates may be cheaper than other options, depending on the specific ceramic used, however the added weight, fragility, lack of flexibility, and increased potential for releasing debris when compared to the likes of polymers make ceramics a largely undesirable option for this use. It should be noted that technical ceramics differ from non-technical ceramics and that not all ceramics would be suitable for consideration for this use.

Polymer

Polymer plates, often made of polyethylene, are a lightweight option compared to metals or ceramics and can withstand more impacts, providing a longer effective lifecycle. Furthermore, polymer plates do not require supportive materials such as Kevlar, which is a contributing factor to them being lighter than other options, often being approximately 50% of the weight of the alternatives [18]. Polymer plates do not shatter after impacts and are instead deformed due to their ductility; this allows the plates to withstand a large number of impacts before needing to be replaced. Polymer plates also tend to “catch” projectiles and do not shatter so would not produce further debris as ceramics could.

The ability of polymer panels to flex would also be critical for the stowage and deployment of the structure. The benefits of polymer plates do come at a higher cost, relative to ceramic and metallic plates, however this is offset by the lower ongoing maintenance/replacement costs. The use of polymers also provides the potential for damaged panels to be recycled and remade into new panels through 3D printing technology, reducing the need for resupply launches to supply new armour panels.

In particular, ultra-high molecular weight polyethylene (UHMWPE) is a popular choice for polymer ballistic plates. Armour plates can be made in a wide variety of shapes and are produced by laminating many layers of a woven UHMWPE fabric under high temperature and pressure. In ballistics, these plates work by melting slightly at the point of impact and then re-solidifying around the projectile. In orbit, the projectiles are not likely to be hot enough to melt the polymer and therefore the plates would rely on plastic deformation to absorb any impacts, and fewer captured projectiles is likely. UHMWPE boasts a high impact resistance which makes it ideal for this purpose, the highest among any currently produced thermoplastic [19].

An important consideration when it comes to the use of polymers is their vulnerability to solar radiation which may reduce their effective lifespan to an extent where the use of polymers is no longer considered feasible. This must be determined by further study under operational conditions.

Composites

Composite panels, made from glass fibre, carbon fibre, or kevlar reinforced polymers, could provide a strong and lightweight alternative to other options; these materials, particularly in the case of glass fibre reinforced polymer (GFRP), may also provide cost benefits due to the widespread use and manufacture of glass-fibre structures. These kinds of simple composites, however, are often bulkier for a given level of impact resistance, requiring thicker panels compared to the alternatives.

Analysis using Material Property Charts

The graphs given in figures 16-20, taken from GRANTA EduPack [20], can be used to visually compare a variety of material properties for the material groups discussed above. The Y-axis on the charts represent the material groups and not a comparison of variables. In particular, critical properties such as density, price, fatigue strength (which shows the longevity of the material over many impact/stress cycles), and Young's modulus provide useful insight into the material options.

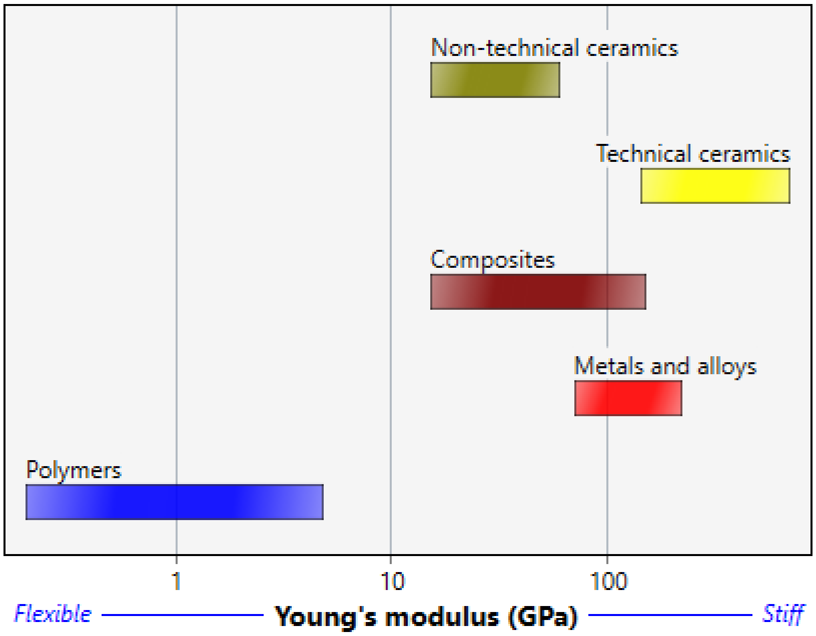


Figure 16: A chart, taken from GRANTA EduPack, comparing the Young's Modulus ranges of relevant materials classes.

The graph above shows the Young's Modulus which demonstrates the general flexibility of the panels which, to a certain degree, is necessary for the desired expansion characteristics of the module. The chart shows that ceramics are likely much too stiff for this purpose and as a result, using a metal, composite, or polymer panel is a better choice.

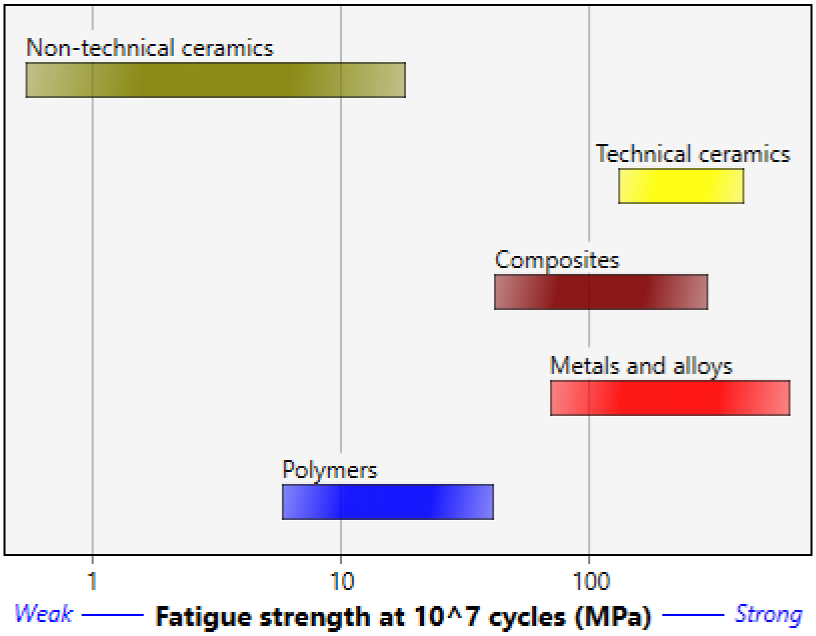


Figure 17: A chart, taken from GRANTA EduPack, comparing the Fatigue Strength ranges of relevant materials classes.

In terms of panel longevity, it is interesting to note that the polymer range is much lower which shows that polymer panels may need to be replaced more often than metals or composites; this is consistent with the previous analysis as the polymer panels would absorb impacts from debris through plastic deformation. This graph reinforces that ceramics need not be considered as the range of the technical ceramics fall entirely within those of metals and composites.

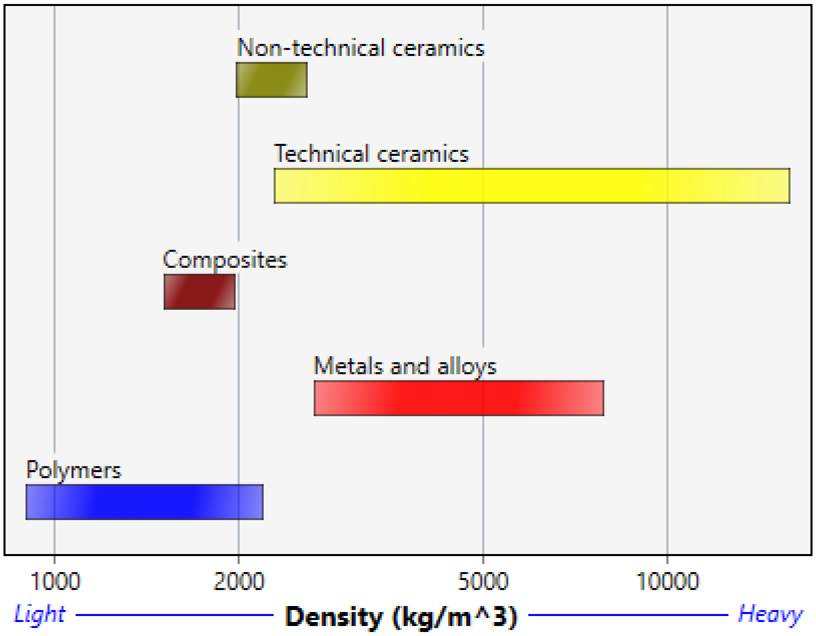


Figure 18: A chart, taken from GRANTA EduPack, comparing the density ranges of relevant materials classes.

The density of the materials is a critical consideration as a lighter structure will be much cheaper to launch and deploy and as such a lower density is preferred in this case; this is where the polymers display their most significant advantage, being substantially lighter than metals and only the heaviest section of their range being comparable to composites.

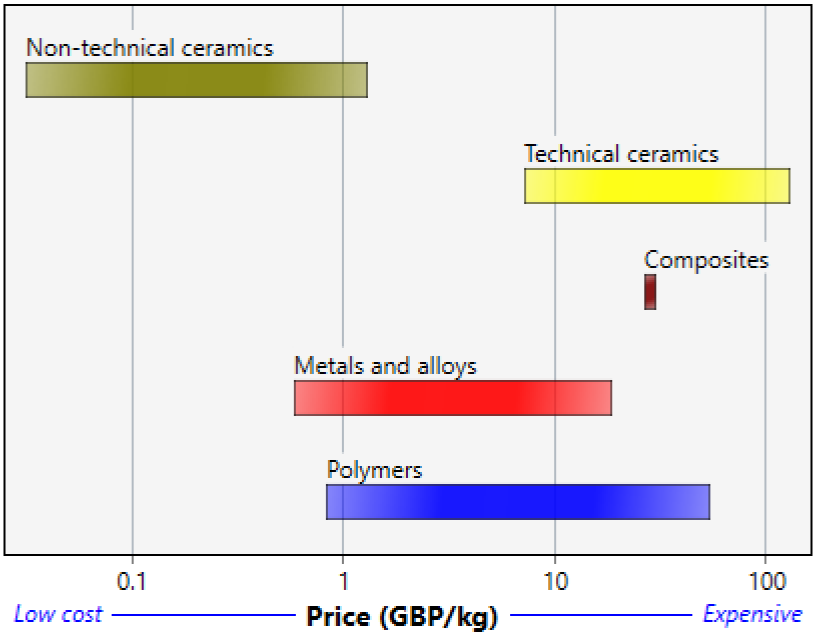


Figure 19: A chart, taken from GRANTA EduPack, comparing the price per kilogram ranges of relevant materials classes.

Cost is another critical factor in determining the best material option, as this factor will inevitably be a leading argument in whether such a module is adopted or not. Metals and polymers are the clear frontrunners in this case, with the two sharing much of the same price range. A lower cost not only provides benefits in the manufacture of the module but also in terms of ongoing maintenance costs.

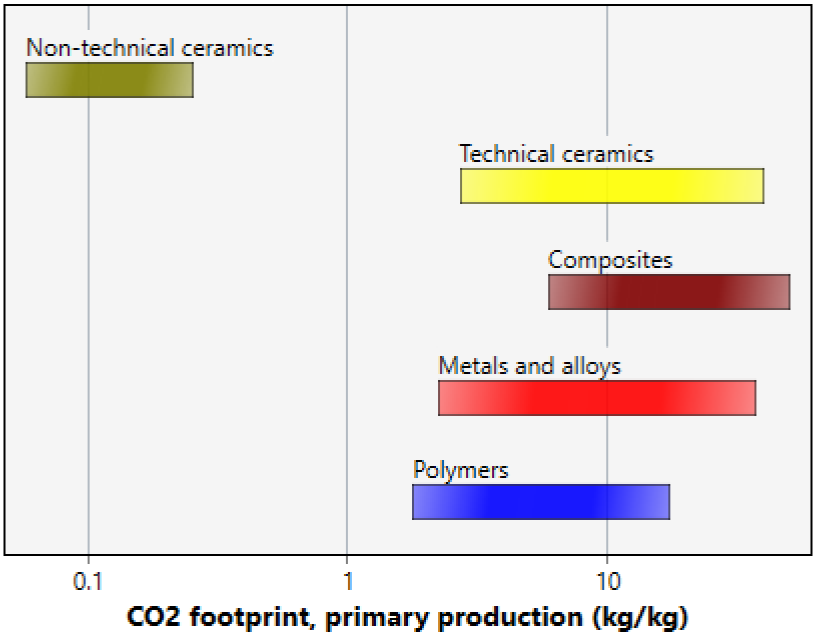
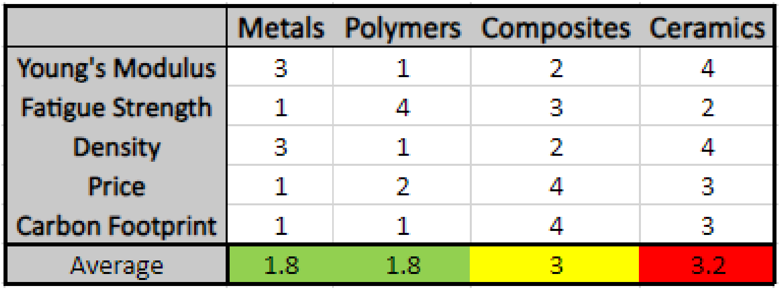


Figure 20: A chart, taken from GRANTA EduPack, comparing the carbon footprint associated with the manufacture of relevant materials classes.

Environmental impact is an increasingly critical consideration for any new technology and as such, this factor should be minimised in the material selection process. In this case, the metals and polymers again share much of the same range, with composites producing somewhat more emissions during manufacture.

These graphs can be used to form a preliminary conclusion using a decision matrix as shown in Table 3, by averaging the ranking of each material class in each category, based on the material property data given in the GRANTA EduPack graphs, where a low value demonstrates a more preferable material in each category. From this, it can be concluded that the best material for use in the module’s armour panelling should be either a metal or a polymer. In order to determine the best material more specifically from within these classes, a more detailed study comparing the properties and operational performance of specific materials should be conducted.



	Metals	Polymers	Composites	Ceramics
Young's Modulus	3	1	2	4
Fatigue Strength	1	4	3	2
Density	3	1	2	4
Price	1	2	4	3
Carbon Footprint	1	1	4	3
Average	1.8	1.8	3	3.2

Table 3: A table comparing the properties of material classes to determine an estimate for the best option for the armour panels.

4 - Discussion & Results

4.1 - System Operation & Visualisation

The manufacture and preparation of the module would be relatively simple as all of this work could be done on earth using largely conventional processes. This would drastically reduce the manufacturing costs and the likelihood of mission failures. Once constructed, the module should be put under a vacuum to ensure it doesn't prematurely expand during launch as the outside pressure decreases; this is critical as premature expansion could result in damage to the launch vehicle, the module, or both. The whole structure could then be loaded into the launch vehicle and prepared for launch, along with a compressed air tank necessary to inflate the module after installation.

The collapsible design allows for a faster deployment process as the whole module would be docked to an existing station or spacecraft and then inflated immediately using compressed air carried on board the launch vehicle. Furthermore, this design would not need a separate crew to oversee and complete the installation as would be required for an orbital construction. Prior to opening the module to the rest of the station, it should be left sealed temporarily to allow the module to be checked for leaks and other issues. Once these checks have been completed and the module is deemed safe, the crew could begin moving habitation or recreational equipment and facilities into the ring, freeing up space in the existing parts of the station for new experiments and equipment. During this period, it would be beneficial to keep the ring stationary, or at a very low level of perceived gravity, to make moving and constructing equipment or furnishings easier.

Finally, once everything has been moved into the ring, the rotation of the ring structure can be set in motion, either by an electrical gear and motor system or by simple thrusters, and the crew can begin using the living environment. Using an electric motor-driven system allows for fine control of the gravity level within the ring as well as computer-controlled changes in the rotation speed over time. A computer interface within the hub of the module would provide a convenient place to control the rotation speed and check the status of any monitoring equipment installed within the ring structure.

Following the deployment of the module, the crew can use the module for a variety of activities, particularly habitation, recreation, and other activities that are easier or more comfortable in the presence of gravity. This would allow the crew to have a significantly more natural living experience while in space, as all activities not requiring a zero-gravity environment, such as sleeping and eating, could all be done under artificial gravity.

An issue that any rotating module in orbit would face is that it would act as a reaction wheel, creating moment forces during acceleration or deceleration that would affect attitude control as a result. There are multiple solutions to this problem, with each having positives and negatives associated with them. Firstly, the most obvious solution is to have two rotating modules spinning in opposite directions as was used in the O'Neill Cylinder concept. This would counteract the rotational moments acting on the spacecraft; the drawback of this solution is the requirement for two full module systems which would double the cost and potentially lead to unnecessary or wasted space and would therefore be most suitable for larger stations. Secondly, a reaction wheel installed in the central hub could work to provide the opposing rotational moments in the same way a second module would, this would allow the module to be entirely self-contained. Finally, a station could use conventional attitude control thrusters to counteract the moments caused by the rotating module however this would be a costly approach and could drastically increase the fuel requirements on board and for this reason it is not recommended.

When designing the habitable space inside the ring, it may be useful to take inspiration from the carriages of modern sleeper trains as the long and narrow design will inevitably lead to similar design considerations and layouts. For example, crew cabins could be designed such that each member of the crew has their own small room, located along a hallway, and communal spaces such as kitchen/dining areas and general recreation areas would be relatively easy to create due to the open space available. Partitioning walls could be constructed as needed within the ring to separate different rooms where the crew would benefit from extra privacy or noise reduction, such as bathrooms, bedrooms, and exercise areas, however if an open plan design can be made to work, this is preferable due to the lower material requirement.

Rotating habitation modules such as these have a wide variety of uses for future missions in space, including variable gravity experiments and providing habitation to astronauts to prevent the negative effects of microgravity. In particular, such a module would be useful for missions to Mars, as the gravity within the ring could be gradually reduced over the course of the journey to allow the crew to adjust to Mars gravity gradually, improving their mission effectiveness when they reach the surface. According to an article from Space.com [21], a manned mission to orbit Phobos, a Martian moon, may be viable as early as 2033. The article refers to the presentation of results from a workshop organised by the Planetary Society to discuss the feasibility of a crewed mission to Martian orbit in 2033 and it was found that such a mission could fit within NASA's human space exploration budget. The Phobos orbital mission would last approximately 30 months with 9 months of travel each way and 12 months in orbit studying the Martian moons, Phobos and Deimos, and potentially remote operating rovers on the Martian surface. A mission of this duration, more than double the current record for longest continuous spaceflight, held by the Russian cosmonaut Valeri Polyakov at 437.7 days [22], could expose the crew to previously unseen degenerative physiological effects due to extended exposure to microgravity and as such, an artificial gravity solution could be considered critical for the health of the crew and therefore the success of the mission.

The use of origami principles to produce modular habitation may also prove to be a useful endeavour for surface missions to the Moon or Mars as it could provide options for quickly deployed surface modules for astronauts to operate from until more permanent solutions can be constructed. This solution would provide a larger space for a crew to use as required, compared to the habitable space within the lander, and could deliver a more comfortable stay for short-duration missions on the surface.

The visual shown in Figure 21 was created using Blender [23], a popular piece of software for 3D modelling, art, and animation, and is included here to give an idea of what the module concept proposed within this thesis might look like in operation. The model is a low-fidelity representation, intended only to aid in visualisation of the idea at this stage of the development, and much more detailed models produced using appropriate design software such as SolidWorks or Fusion360 would be necessary for more accurate visualisation and simulation of the system. Producing more detailed models, unfortunately including a more accurate representation of the origami structure despite my attempts to do so, was not possible within the timeframe of this research project. The models required to construct the station itself were produced especially for this visual by the candidate however the Earth orbit environment was produced by AL-Studios, a creator on the CGTrader platform [24].

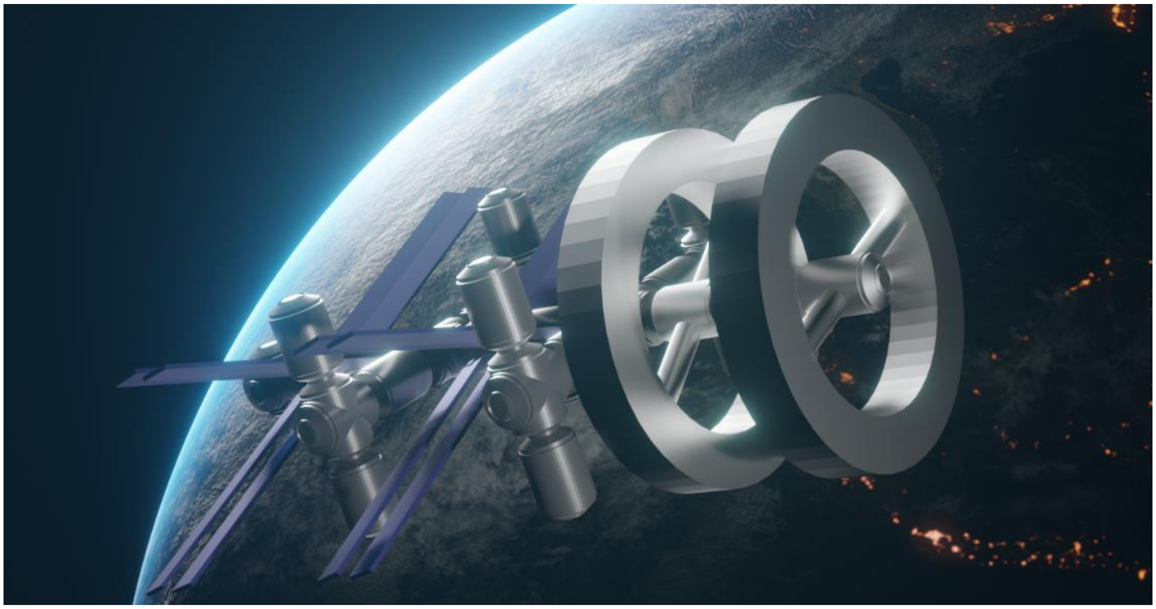


Figure 21: A digital visualisation of what a station employing a set of artificial gravity modules may look like. The image was created using Blender.

4.2 - Discussion of System Feasibility

4.2.1 - Using Origami Principles for Space Applications

The use of deployable structures is widespread in space technology in many forms. Solar arrays are a very common example, where fixed panels are joined with hinges and folded into significantly smaller packages for launch to orbit where they are extended for use. In more recent years, examples of inflatable space habitat structures, particularly those from Bigelow Aerospace, have provided an opportunity to explore different possibilities that were unavailable to previous generations.

The exploration into folding patterns in this research showed that an expanding module, combining aspects of more conventional deployable structures and the newer soft-wall inflatable technology, could feasibly be used to produce a suitable structure for an artificial gravity module. While further study is necessary to determine specific characteristics of the structure, particularly relating to pressurisation where high-fidelity finite element analysis (FEA) should be conducted, initial analysis suggests that a Square Bellows pattern would be the best option for the ring structure as the large panel size, simplicity of the pattern, and flat outer surface being capable of forming the internal floor all make it a favourable choice.

4.2.2 - Producing artificial Gravity in Small Radius Modules

Producing artificial gravity by rotation is not a new idea and has been explored repeatedly since it was first conceived in 1903 by Konstantin Tsiolkovsky. It was most notably expanded upon during the 20th century by Herman Potocnik who developed many of the foundational principles that allowed us to explore space, and later by Werner Von Braun who brought the idea into the public consciousness where it featured on many occasions in works of science fiction. Previous studies on the limits of human comfort in a rotating environment provided boundaries for determining suitable size ranges for a rotating artificial gravity habitat; modelling these factors in this study showed that suitable conditions may be achievable in smaller modules than was previously thought.

The results of this study suggest that for a supplementary module attached to a more conventional space station such as the ISS, a relatively small ring structure with a radius of 10m would be capable of providing a space station crew with gravity to offset the harmful health effects of prolonged exposure to microgravity. Such a module would allow the crew of a space station to eat, sleep, and enjoy recreational time with Earth-like gravity, further enhancing quality of life.

4.2.3 - Feasibility of Material Science

The field of Material Science has progressed far beyond what was available when previous concepts were produced; materials are lighter, stronger, more cost effective to produce, and with smart materials becoming increasingly common and offering a wide range of properties, there are many ways a module such as the one proposed in this research could be produced.

Using more exotic materials, such as smart materials, could produce a more optimised design than the relatively simple options explored in this study however this would be offset by a much higher mission cost which makes the system less attractive to the market; for this reason, the material options covered in this study are, for the most part, common, affordable, and well tested in the required environment or to meet similar requirements.

Simple calculations, based on the mass and approximate surface area of the Bigelow Aerospace 'BEAM' module, allow for preliminary estimates of the overall mass of the habitation ring that can then be compared to the maximum payload mass of the launch vehicles. According to the Bigelow Aerospace website [12], BEAM has a mass of 1400kg and by approximating the module's shape as a sphere, a guideline for the mass per square metre of surface area can be calculated. The following tables, 4 and 5, were produced using an Excel spreadsheet to compare the difference in mass for each panel material. Table 4 uses a comparison of the fracture toughness of different materials to suggest a panel thickness, and table 5 uses these thicknesses to estimate a mass for the total panel coverage.

Conventional shielding on the ISS is made up of a “Stuffed Whipple Bumper” design, produced using two layers of Aluminium with Nextel and Kevlar stuffing to fill the gap between the aluminium panels [25]. Due to their thickness and the likelihood of interference with the compressibility of the structure, Whipple Bumpers are not suitable for use in an origami structure, despite the benefits they offer, unless they were installed manually after the structure had been deployed. The outer panels range in thickness between 1.3mm and 2.5mm while the inner panels are all 4.8mm in thickness. Combined with the shielding properties of the soft-wall composite, it is possible that the suggested panel thicknesses given in Table 4 would be excessive, however they are estimated based on an aluminium panel approximately twice as thick as the internal panels on the ISS to provide a margin of error. Estimating the thickness of the other materials was done by comparing the average fracture toughness of each material with aluminium, according to Figure 22 that was taken from a Cambridge University Material Databook [26], and then using the ratio of the fracture toughness to estimate the thickness.

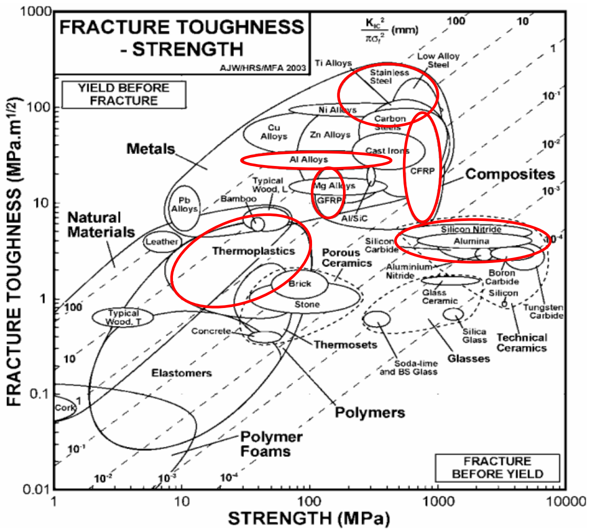
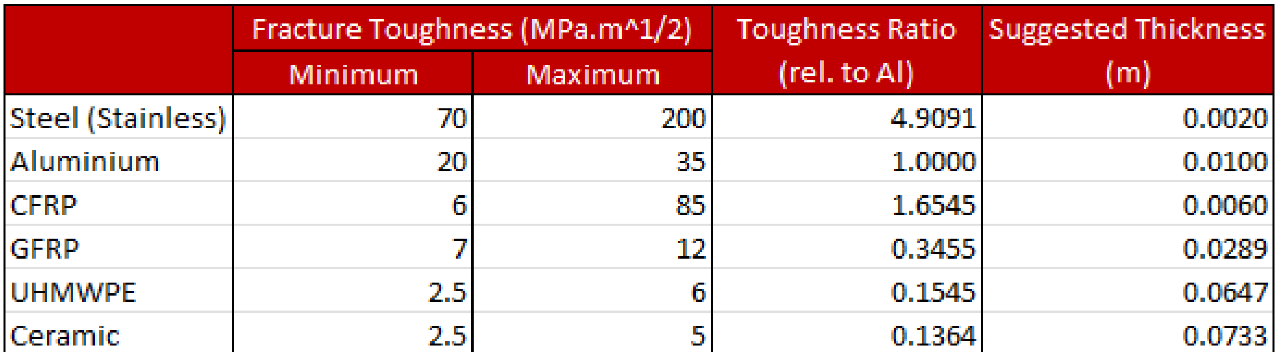


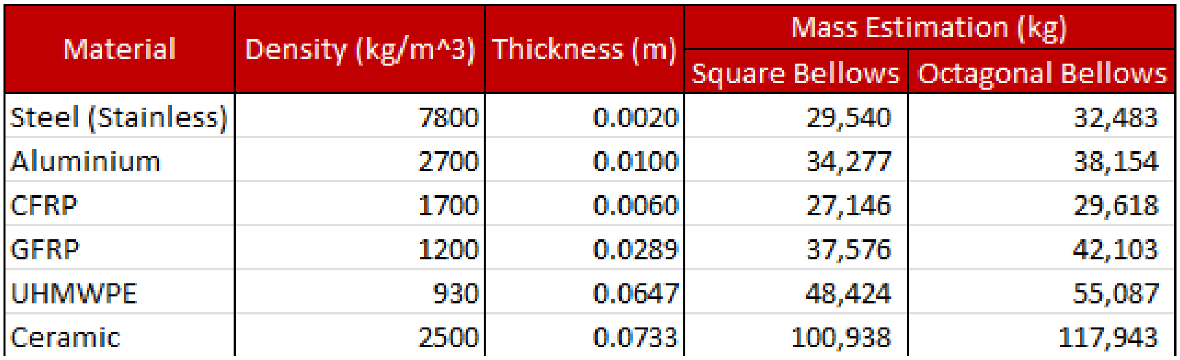
Figure 22: A plot of the fracture toughness of a wide range of materials, taken from a Cambridge University Materials Databook.



	Fracture Toughness (MPa.m^1/2)		Toughness Ratio (rel. to Al)	Suggested Thickness (m)
	Minimum	Maximum		
Steel (Stainless)	70	200	4.9091	0.0020
Aluminium	20	35	1.0000	0.0100
CFRP	6	85	1.6545	0.0060
GFRP	7	12	0.3455	0.0289
UHMWPE	2.5	6	0.1545	0.0647
Ceramic	2.5	5	0.1364	0.0733

Table 4: An excerpt from an Excel spreadsheet calculating the toughness of the material options, relative to Aluminium, in order to make a panel thickness estimate.

By calculating a ratio between the average fracture toughness of each material and the average of aluminium alloys, a suggested thickness for each material can be calculated by dividing the aluminium panel thickness by the relevant toughness ratio.



Material	Density (kg/m^3)	Thickness (m)	Mass Estimation (kg)	
			Square Bellows	Octagonal Bellows
Steel (Stainless)	7800	0.0020	29,540	32,483
Aluminium	2700	0.0100	34,277	38,154
CFRP	1700	0.0060	27,146	29,618
GFRP	1200	0.0289	37,576	42,103
UHMWPE	930	0.0647	48,424	55,087
Ceramic	2500	0.0733	100,938	117,943

Table 5: An excerpt from an Excel spreadsheet displaying the mass estimations of both square and Octagonal Bellows patterns with a range of armour materials with estimated thicknesses.

Table 5, above, shows that the mass estimations, while significantly larger than current space station modules, fall very comfortably within the limits of current or near future rocket technology; this of course excludes ceramics which fall much closer to the limits of such launch vehicles however, as covered previously, ceramics are a poor choice for the panel material regardless of their weight. These mass estimations were calculated using the surface areas calculated previously along with the thickness and density of the panels, assuming a coverage ratio of 80% to allow for flexible areas where the module must fold for launch. The resulting value was then added to an estimated value for the flexible hull mass, which was found by multiplying the previously calculated surface areas of the square and Octagonal Bellows patterns and the stated mass per square metre of the Bigelow Aerospace module hulls. While these estimations cannot be considered accurate to what the final module would weigh, the estimation is enough to show that the final mass is very unlikely to exceed the maximum payload capacity of the launch vehicle. Furthermore, it is likely that the launch vehicle could carry the pressurisation tank as well as basic internal furnishings within a single launch, further minimising the costs for deploying the system.

4.2.4 - Launch Vehicles

The consideration of potential launch vehicles is important for a concept module design such as this one as the module will naturally be larger and heavier than a standard space station module and will therefore require more specialised launch equipment. Recent developments within the aerospace field suggest that SpaceX's Super Heavy Booster and NASA's Space Launch System (SLS), both of which are currently in development, are key contenders for fulfilling the launch requirements of the module.

According to the information page of the SpaceX website [27], the Super Heavy Booster's maximum payload mass, to LEO, is 150 metric tonnes, with the diameter of the standard payload fairing being 9m; this information provides critical limits regarding the stowed size and the overall mass of the final concept, both of which will influence design choices moving forward. Another option for the launch vehicle is NASA's Space Launch System (SLS), described within the information page [28] as "a super heavy-lift launch vehicle that provides the foundation for human exploration beyond Earth's orbit." It is among the most powerful rockets ever created, being designed to carry the Orion spacecraft, crew, and payload to the Moon as part of the Artemis program. It is also stated that this system makes considerations in the design for use as a general-purpose super-heavy launcher in the future. The 'Block 2' configuration of SLS is capable of launching up to 130 tonnes to low earth orbit and has a payload fairing diameter of 10m [29]. The height of the fairings in both launch vehicles are much larger than what would be required for the module itself, allowing for the simultaneous launch of separate inflation tanks, supplies for furnishing the interior of the ring in a flat-packed design, etc, provided there is sufficient available payload mass. As both fairings are very close in diameter to the estimated stowed diameter of the ring module, a flared fairing like those used on many other rockets such as the Falcon 9 [30] or Atlas V [31] may be required to provide the appropriate internal space to properly secure the module during launch.

SpaceX's Super-Heavy Booster and NASA's SLS can both be expected to provide suitable launch solutions for the module proposed in this thesis, each boasting stated goals for implementation within the near future. Due to the current stage of development of each of these systems, it is highly likely that one or both would be readily available for use by the time this artificial gravity module can be fully developed. This fact alone greatly increases the feasibility of the proposal, as having the capability to launch the final module is critical for the success and implementation of the technology.

4.3 - Future Work & Recommendations

The “Technology Readiness Levels” (TRL) [32] are a set of categories used to track the development progress for a given technology and as such, they can be used to suggest a timescale for this and future projects. A table outlining the definitions for the TRL system has been included in the appendices. Levels 1-3 cover the most basic stages of development, starting with the observation of the basic principles, the creation of a concept, and analytical demonstration of critical functions. The first three levels have been covered by this research, providing a foundation from which a longer program could further the development.

A longer program, such as a PhD project, could fulfil levels 4-7, which cover laboratory testing of the technology using low and medium-fidelity prototypes and advanced testing of a high-fidelity scale model within an operating environment.

Finally, levels 8 and 9, which cover real testing and flight qualification, would then need to be fulfilled through manned missions. A 2022 report from the Interagency Operations Advisory Group (IOAG) titled “The Future Mars Communications Architecture” [33], while focussing primarily on the communications capabilities of the various space agencies, included a general timeline of missions related to Mars, including a range of mission types such as “science orbiters, science landers, science rovers, sample return vehicles, robotic precursors for human exploration, infrastructure platforms, dedicated relay satellites, crewed surface vehicles, and human habitats in Martian space and surface.”

The report suggests that the first proposed human Mars mission will be launched in 2039 collaboratively by NASA and the European Space Agency (ESA) and will involve two prolonged trips through space lasting many months on the outbound and return trips with a short stay on the surface, exposing the crew to previously unseen degenerative physiological effects due to extended exposure to microgravity. This mission would provide a perfect opportunity to test the system as an artificial gravity module may be critical for maintaining the health of the crew during the prolonged trips between the planets. It is also critical that the crew be medically fit and able to perform their duties effectively while on the surface and, as such, having the crew properly adapted to Martian gravity before arriving, without atrophic issues from exposure to microgravity, will greatly improve the outcome of the mission.

It is evident that the future of human space exploration is, in part, reliant on our ability to provide artificial gravity to crew members and that it is critical that the development of such systems begins very soon. Before this technology can be put into production and use, further study is required on specific aspects of the concept including the following critical studies:

Firstly, a study comparing specific panel materials and optimising the thickness required for each material to minimise the weight and thickness of each panel while maintaining proper protective value must be completed to make a final decision on the best option. This study should replicate the operational conditions of the panels to analyse the longevity and maintenance requirements of each panel material.

Secondly, dedicated research into how origami structures handle pressurisation is critical to verify the safety of the module. Due to the angular nature of an origami shape, stress concentrations may be formed and as a result, further testing using both high-fidelity FEA and physical prototyping should be carried out.

After these studies have been carried out, work developing the final design can begin; the mission discussed previously provides a deadline for this development timeline and because of this, it is imperative that this further work is completed as a matter of priority.

5. Conclusion

The questions posed at the beginning of this thesis provide a simple framework for summarising the outcomes and conclusions of the project and can be concluded as below:

The first question was in regard to the capability of origami-type structures to produce the required properties in an expandable habitation module; the experimentation with paper models discussed in section 3.2.1, combined with the existing work on rigid-panel origami conducted by Dr Tomohiro Tachi [34], demonstrates that a concept making use of origami principles with rigid armour panelling is capable of fulfilling the expandability needs of this technology while providing superior shielding from orbital debris than could otherwise be achieved due to the ability to replace damaged panels.

The second question, regarding the basic principles of artificial gravity, was explored by producing graphs comparing different configurations of the fundamental factors that influence artificial gravity. These factors, including module radius, spin rate, and the resulting perceived gravity level, were then analysed for crew comfort using boundaries found within previous studies such as those referenced on the SpinCalc website [3]. This analysis found that a module radius of 10m provides an acceptable balance between crew comfort and the overall module size. Whilst the spin rate is higher than would be considered ideal for a full-station artificial gravity environment, previous studies have shown that the required spin rate for a module of this size can be adapted to by the inhabitants with relative ease and is therefore suitable for a supplementary module.

Finally, in order to form a conclusion about the system's feasibility, a multifaceted approach to the analysis was required. The use of paper models facilitated an analysis estimating the stowed size of a module making use of origami principles; this analysis showed that the module will be able to be carried by the proposed launch vehicles, either using the standard fairings or custom flared fairings if necessary.

The flexible wall of the module is best created using a similar composite structure to that used in ‘BEAM’ produced by Bigelow Aerospace as this material has been flight proven on board the ISS. GRANTA EduPack material property charts were used to compare a variety of material classes in order to estimate the optimal material type for use in the rigid panels. The results of this analysis show that metals and polymers present the best balance of benefits and drawbacks, with the final decision requiring further analysis as detailed previously.

A mass estimate, using an estimation of the ring structure’s surface area to scale up the mass of ‘BEAM’ and then adding the mass of the armour panels in the material options analysed earlier, demonstrated that the module can be expected to fall far below the maximum payload mass of the launch vehicles. This is critical as the remaining payload mass may be used to launch the compressed air tanks and internal furnishings required to deploy the module and bring it into operation.

The combination of this analysis has shown that the limitations that once prevented us from providing artificial gravity to astronauts are no longer a concern and because of this, the technology can be considered feasible with current or near-future technology.

The ability to provide spacecraft crews with artificial gravity will be critical to the success of future space exploration as the negative impacts of microgravity exposure to the health of a crew are significant and degenerative; this fact threatens mission success for any mission involving long-term isolation from Earth where no artificial gravity measures are deployed. Planned missions to Mars will involve many months of travel between Earth and Mars, resulting in astronauts being exposed to microgravity for much longer periods than previously undertaken and, if completed without artificial gravity, could pose serious long-term health consequences for the crew. It has been suggested that providing artificial gravity may become an ethical requirement, representing a core element of life support systems, if it is possible to do so as space agencies should prioritise the health and wellbeing of their crews over minimising mission costs or complexity, particularly in larger missions where the cost of providing an artificial gravity system would be relatively small.

Concept spacecraft making use of the principle of artificial gravity, particularly those developed in the 20th century by scientists such as Herman Potocnik and Wernher Von Braun, have been limited by the technology available; this resulted in these structures being much larger and heavier than the rocket technology could accommodate without multiple launches. This fact made the proposals prohibitively expensive. These early concepts also required complex orbital construction, further increasing the costs and risk of failure, and as a result the concepts were never developed further and implemented. The idea of artificial gravity ring stations or modules ultimately fell into the realms of science fiction in the late 20th century however this research has shown that, having overcome the previous limitations, this concept should be reconsidered for use, developed, and implemented in order to better facilitate human space exploration with the maximum chances of success.

6. Appendices

Python Script – Producing a graph to show he relationship between the module radius, perceived gravity, and the required spin rate.

```python
# A script plotting the optimisation of artificial gravity ring configurations #

# Figure 1: A 3D surface plot where X = Module Radius (m), Y = Perceived Gravity (g), Z = Spin Rate (RPM) #

import matplotlib.pyplot as plt

from mpl_toolkits import mplot3d

import numpy as np

import math

import matplotlib.colors


ax= plt.axes(projection="3d")

x = np.linspace(1,250,30)          # x = Module Radius (m) #

y = np.linspace(0,1,30)           # y = Perceived Gravity (g) #

X, Y = np.meshgrid(x, y)

Z = ((((Y*9.81)/X)**0.5) * (60/(2*math.pi))) # z = Spin Rate (RPM) #

custom_cmap = matplotlib.colors.LinearSegmentedColormap.from_list("Custom", ["Green", "Yellow", "Red"])

ax.plot_surface(X, Y, Z, cmap=custom_cmap, vmin=1, vmax=12)

ax.set_title("Spin Rate at Varying Module Radius & Perceived Gravity")

ax.set_xlabel("Module Radius, m")

ax.set_zlabel("Spin Rate, RPM")

ax.set_ylabel("Perceived Gravity, g")

plt.show()
```

Technology Readiness Levels (TRL) - Developed by NASA to better standardise the development timeline of a technology.

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experi-mental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
6	System/sub-system model or prototype demonstration in an operational environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results.

7. Glossary

- **‘Microgravity’**: A definition of a gravity level derived from mathematical theory where micro is used to describe 10^{-6} and as such, only truly weightless environments such as low Earth orbit (LEO) meet this definition.
- **‘Partial gravity’**: Any level of gravity falling between microgravity and Earth gravity.
- **‘Artificial gravity’**: Simulated gravity, provided to astronauts in orbit, via physical phenomenon separate to conventional gravity such as the use of centrifugal forces from rotation.
- **‘Perceived gravity’**: The level of gravity, as perceived by the crew of the vessel, from rotation.
- **‘Full-Station Artificial Gravity’**: Referring to space stations, such as those proposed by Potocnik and Von Braun, that provide an artificial gravity environment throughout the entire station.
- **‘Single launch’**: Launched into orbit by a single rocket as a completed object, thus requiring no further construction in orbit.

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