ORBITAL HABITABILITY:

ARCHITECTURAL DESIGN FOR EXTRA-TERRESTRIAL HABITATION

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BY

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This thesis is dedicated to those family members lost during its creation.

Andrew Gilmore. A fellow spaceman. I wish you could have lived to read this thesis

Margaret Tozer. I will always miss Christmas celebrations at your house on the hill.

Storm Tozer. I miss you everyday. Home will never be the same.

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ABSTRACT

Companies like SpaceX and Virgin Galactic are privatising the space industry. This privatisation will allow more and more people to inhabit space for more extended periods, with less training than prior astronauts. Space habitation brings with it a vast array of issues, which significantly limit the designs that are possible in orbit. This thesis explores how the challenges of inhabiting outer space can be mitigated through architectural design.

The theoretical basis for this exploration is research into habitability. Habitability is how conducive an environment is to living and working. This is crucial to understanding the risks of inhabiting environments in orbit and how these can be challenged through design.

The Framework for this exploration's site and program is asteroid mining. Asteroid mining is an exciting possibility for the next stage of human presence in space. Utilising asteroid resources could greatly aid in establishing orbital infrastructure around the Earth and allowing us to travel even further. As a framework, this defines a tighter scope than looking at space habitation in general and allows this thesis to dive deeper into the finer details of habitability for a specific group of people.

The aim of this thesis is to demonstrate designed solutions to issues of habitability within the constraints necessary to construct a space station.

This thesis considers how a design might be; designed and modelled, deployed in space, constructed, and most fundamentally, how it could mitigate the psychological and physiological issues of long-term space habitation.

This is accomplished through a research-led design process centred on self-evaluation through the habitability principles defined in this thesis.

This thesis fundamentally collates and builds upon our existing knowledge of space habitation and presents one possibility for the future of space habitation. This is merely one small step for the furthering of human habitability in space.

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Figure 01. Verne, J. (1865) Rocket to the Moon

1.0 INTRODUCTION

1.1 PROBLEM STATEMENT

1.2 AIMS & OBJECTIVES

1.3 DOUBLE TIER FLAT CYLINDER

1.4 SCOPE

1.5 STRUCTURE

This section introduces the problem, aims & objectives, methodology, scope, and structure of this thesis.

1.1 PROBLEM STATEMENT

This thesis looks at how design can be used to mitigate issues of habitability in outer space. This is a concept dating back as early as the 1890's with Konstantin Tsiolkovsky's technical design of a space station. Even then, the need for designed solutions to issues in orbit was understood. This became all the more important with the advent of Skylab project in the 1970's and has been a growing field of study ever since. This thesis aims to build on this and show how architectural design can be used to aid in the mitigation of established issues of habitability. This Thesis asks;

HOW CAN ARCHITECTURAL
DESIGN BE USED TO AID IN
MITIGATING THE ISSUES OF
INHABITING OUTER SPACE?

1.2 AIMS & OBJECTIVES

The overarching Aim of this thesis is to;

DEMONSTRATE DESIGNED SOLUTIONS TO KNOWN ISSUES OF HABITABILITY WITHIN THE RIGOROUS CONSTRAINTS OF CONSTRUCTING A SPACE STATION.

This is accomplished through the objectives:

1. Research and understand a currently viable use for a space station through literature and prior design studies. Establish a site context and program through this.
2. Research 'habitability' through literature and define it in the context of this thesis. Out of this research, create a system for evaluating design concepts.
3. Research and understand prior space missions, experiments and theory in order to identify the technical requirements for extra-terrestrial habitation. This includes: payload restriction, construction methods, agricultural methods etc...
4. Iterate through design several methods of improving 'habitability' in space, drawing on examples and evaluating these through research on habitability (step 3).
5. Continue to refine these concepts into a designed outcome of a space station showing how these concepts could be utilised.

A secondary aim of this thesis is to;

DEMONSTRATE HOW A (MODULAR) SPACE STATION COULD BE 3D MODELLED USING PARAMETRIC DESIGN.

This is accomplished through the objectives:

1. Develop a series of custom nodes for use in Grasshopper for Rhino for use in creating and attaching 3D space station modules with ease.
2. Document how these can be used for the development of various space station configurations.

1.3 METHODOLOGY

These aims and objectives are carried out through a research-led design process. The research methods employed are based on the seven conventional research methods defined by Groat and Wang: historical research, qualitative research, correlational research, experimental research, simulation research, logical argumentation, and case studies (Groat & Wang, 2013). This thesis utilises historical research, case studies, and logical argumentation in order to justify design decisions around habitability in outer space.

HISTORICAL

In order to understand the historical perspective of space habitation this thesis conducts an historical overview on past concepts dating back to Jules Verne in 1865. This overview focusses on drawing out justifications for the role of architectural design in extra-terrestrial habitation. Following this is a brief analysis of early ideas around habitability in outer-space and how these could be used in current and future designs. This provides historical evidence as to why design is important in space habitation and strengthens the arguments made through this thesis' design.

CASE STUDIES

Alongside this historical investigation is an analysis of the International Space Station (ISS). The ISS is the prime, and only current, example of human habitation beyond the Earth. This case-study is used to create a realistic and current justification for design decisions made in this thesis.

LOGICAL ARGUMENTATION

In conjunction with historical research and case studies, the main research method used in this thesis is logical argumentation. This is primarily through research into the concept of 'habitability'. The following is a brief discussion of the key theorists used in this thesis:

- Much of the work in this thesis is justified through work by NASA (cited under various authors). NASA laid the groundwork for a lot of work on space habitability and has had a huge influence on any work on the topic.

- Irene Lia Schlact is a scholar of human factors and design for future innovations in extreme environments. She has published a huge amount research on life in outer space and has defined the concept of habitability in clear terms.

- Tommaso Sgobba is another huge proponent for space architecture. Sgobba co-edited "Space Safety and human Performance" and co-wrote the chapter "habitability and habitat design" with Schlact. This chapter forms the basis of habitability research in this thesis.

- Much of this work is based on research carried out by NASA's Stanford Ames team, cited as Richard D Johnson, in their design of the Stanford Torus in 1975. This design is one of the most significant works of speculative space architecture and greatly influences the work in this thesis.

- Another theorist influencing this thesis is Kriss Kennedy. Kennedy has written a lot on space habitation and managed NASA's habitat demonstration unit project. Kennedy also defined basic steps for space habitation design greatly influencing this thesis.

Research on these theorists and many others is collated into a self-reflection rubric, which allows for the critical reflection and argumentation of design decisions within the scope of this thesis. The following page is a diagram of the methodology of this thesis.

Figure 02. Methodology Diagram

1.4 SCOPE

This methodology is used to demonstrate how architecture can be used to help mitigate habitability issues. In order to do so adequately the scope of work must be limited.

- This thesis defines asteroid mining as its program. This is in order to define a specific group of people and use of the station. However, this does not involve an analysis of how this process could be carried out.
- This thesis considers the design of a station and not any other type of rocket or moving vessel.
- This thesis does not consider locations beyond the main asteroid belt as our understanding and capability drops off beyond this point. Similarly this thesis doesn't consider a station orbit the planets of Venus or Mercury. There is no written evidence for these bodies being particularly more abundant in asteroid resources.
- This thesis considers aspects such as launch, construction, and agriculture but will not analyse these in depth. Nor does it claim to fully understand the limitations of these issues.
- This thesis does not deal with any detail design elements such as: structural connections, mechanical layouts, cost, maintenance routines, alternative launch options, agricultural analysis, etc...

This thesis is in an exploration of potential design solutions to be used in the design of a habitable space station. This is based around the habitation of spaces and is not resolved to any level of buildability.

1.5 THESIS STRUCTURE

This thesis begins by justifying why habitability and space architecture are important. This includes a justification for the program and design intent behind the resultant space station. Following this is an in-depth analysis of the concept of habitability through the discussed key theorists.

This leads into an historical overview of space habitation. This is an exploration of works by Konstatin Tsiolkovsky, Herman Noordung, Wernher Von Braun and Gerard O'Neill. Each of these theorists had huge impacts on the development of space architecture as a concept. This discussion of historical precedents ends with a case study of the International Space Station (section x). This is the most significant work of space architecture to date and has a huge influence on the work in this thesis.

Following this is an analysis of several viable locations for a space station. This analysis leads into the defining of several key concepts for this thesis, such as: station types, construction in space and module sizes.

Following the establishment of site and station type is the design phase, which involves the development and self-reflection of several concepts. This also involves the development of a 3D design tool for the iteration of module configurations.

Finally, this thesis refines and documents the designed space station and reflects on the results of this.

Figure 03. Hale, E. (1869). The Brick Moon.

2.0 LITERATURE REVIEW

2.1 WHY GO TO SPACE?

2.2 DESIGNS ROLE IN SPACE

2.3 HABITABILITY

This section briefly justifies why humans should go to space, including justifying the program of asteroid mining. Then is an analysis of designs role in space followed by a deep analysis of habitability as a concept.

Figure 04. Guidice, R. (1970) Cylinder Interior.

2.1 WHY GO TO SPACE?

There are several reasons for humanity to explore outer space. A major reason is scientific progression, not only to develop more powerful rockets and technologies but also to protect humanity from cosmic catastrophes such as asteroids or comets (Chapman, 1994). The reason that fuelled the space race of the 1950's and 60's was political as well as scientific – which country can conquer space first? Recently a new, environmental and economic, driving force is growing in popularity: Resources.

There is a foreboding sense that we are reaching the limits of Earth's capacity. Our exponentially growing population is pushing us ever closer to the inevitable destruction of our delicate ecosystem. Many look to colonising the solar system and beyond as a means of preserving humanity – ideas of Martian bases, orbital colonies or large generation ships traveling to distant stars. With our current capabilities, these ideas are still just dreams. Before we can establish long-term human presence in space, we need infrastructure in orbit (Sonter, 1997). To do this we need resources.

One major issue here is the cost of launching resources into orbit in order to build anything. SpaceX's Falcon heavy costs up to US\$3370 per KG to Low Earth Orbit (LEO) (SpaceX, 2019). There are people like Jeff Bezos, Richard Branson and companies like Virgin Galactic looking into the idea of space planes and single stage to orbit (SSTO) vessels. These vessels could lower the cost of establishing infrastructure however, they would still need to move large amounts of material into orbit if we are to establish anything significant. The problem here is really earth's gravity well;

*"Here we are on the Earth at the bottom of a gravitational mountain which is 4000 miles high. Your task is to build a permanent castle at the top of that mountain. Well it makes sense to quarry the stone for that castle right around the top of that mountain, not down at the base and then haul it up 4000 miles."
(Gerard K. O'Neill, 1981)*

2.2 DESIGNS ROLE IN SPACE

This brings us to the framework of this thesis. There have been several proposals of Insitu construction in space, such as using lunar regolith to construct a moon base (Foster+Partners, 2012). In recent years, there has been a lot of interest in the idea of farming near earth asteroids (NEA) for their resources. Several studies have found that most of these NEA's have valuable resources. This includes; rare metals like gold and platinum, building materials like iron and silicone, and most importantly water (Andrews et al, 2015; Ross, 2001). If these materials could be harvested, they could be used to generate orbital infrastructure or sent back for use on Earth. Water is among the most valuable of these resources. Not only can it be used to support human life in space as clean water, it could also be converted into oxygen and hydrogen, which could be used as life support or converted into rocket fuel. This would allow us to travel much further in space. The main cost of space travel is lugging all of the fuel into LEO, once there the lack of resistance, and use of the Oberth effect, makes propulsion much more efficient.

There are several methods for mining these resources. Most of which involve the use of robotic drones or automated mining ships. This is because sending humans, with life support and radiation protection, would add much more weight, thus increasing fuel needs. It would also put humans in a great deal of danger. However, it would be important to have people nearby (Andrews et al, 2015). One issue is communication delay from Earth's surface. This would improve by having a station closer to the operation. Beyond this, we would need people to tend to the drones and process the resources as well as act as failsafe's if anything went wrong with the operation. The operation would require overall management as well as specialists in robotics, engineering, chemistry, construction, medicine, psychology and potentially chefs, cleaners and other such amenities. Having people in space comes with many issues. A very important aspect of this is the design of the station these people will live on.

The importance of 'good design' in space colonisation was recognised as early as the 1960's when NASA began planning for long duration spaceflight post-Apollo.

A major consideration around this was "How to define and provide for man the habitability requirements for long duration living and working in space?" This culminated in the Skylab Mission in 1973, which saw several astronauts live in orbit for up to 84 days (Johnson, 1975). These early ideas of habitability consisted primarily of functionality. Habitability was measured as 'in-flight man-hours made available to productive operation.' Most of the findings of the program were to do with the design of equipment and general usability as opposed to the psychological impact of isolation within an enclosed environment (Johnson, 1975). As the occupants of these stations were specially trained astronauts the need for comfort was not yet a prime concern.

In 1969 Gerard K. O'Neill, American physicist and proponent of space habitation, tested this idea at a far greater scale. Almost as a joke, he began calculating the possibility of a large-scale human civilisation in space. The numbers were shockingly viable and by 1975 he had developed his proposal for a huge cylindrical colony (Fig. 4). The O'Neill Cylinder was covered in vegetation, detached housing and even waterways. This colony would provide all the environmental benefits and comforts of earth. Even gravity would be produced by centrifugal forces (1974). In a 1981 interview O'Neill postulates on the role of architects in space development:

"There are Two Time frames where Architects can become involved in the program of using the material and energy resources of space, the first is to work within the tight constraints of available pieces of hardware to design an attractive and comfortable work station in space out of shuttle external tanks... later on there is going to be the time when we are designing the big earth like human colonies in space, the sort of colonies that would be almost a mile in extent... (Gerard K O'Neill, 1981)"

Figure 05. Guidice, R. (1970) Toroidal Colony

O'Neill tended to focus on the latter through his cylinders. The focus of this thesis will be on the former - creating pleasant environments within tight constraints like those on Skylab. This is something NASA has been attempting since the 70's.

In 1975 a NASA design study effectively linked the findings of the Skylab mission with the grandiose sentiments of the likes of O'Neill. This study resulted in the 'Stanford Torus'. A huge rotating torus proposed to orbit the earth at a similar distance to the moon. The study discussed human needs in space extensively. The need for gravity, protection from radiation, and atmospheric requirements were all discussed in detail however the most important aspect, for this thesis and space-architecture as a whole, was on 'Environmental Design to Reduce Stress.' The Stanford-Ames team writes about the potential risk of inhabiting these isolated, artificial environments for long durations (Johnson, 1975). They emphasise the importance of the design of these spaces while discussing methods to minimise stress and improve habitability. For example, they discuss the importance of 'diversity and variability'; "the design of the habitat must not be so complete as to be sterile; it must avoid motel banality" (Johnson, 1975). The team wrote that this can be accomplished through 'manipulatable architecture' and the inclusion of living, growing things (such as planting) to allow for change within the environment. They discuss other architectural factors, such as; Lines of sight, views out, changing atmospheric conditions, natural light, availability of privacy, material usage, orientation, scale, the shape of the habitat and many more factors that need to be considered for habitat design (Johnson, 1975).

Following this were several studies and papers on similar topics drawing on both Skylab and the Russian Salyut stations from 1971-1986. During this time, we also see the development of the space shuttle and initial ideas about the International Space Station (ISS) (Rockoff, 1985). A particularly in depth study was published by NASA in 1985. This study built upon much of the same information as the Stanford-Ames one but in specific preparation for the construction of the ISS.

More recently NASA carried out the Habitat Demonstration Unit (HDU) project under Kriss Kennedy and Scott Howe. This was a physical test bed established in the Arizona desert for the experimentation of deep space habitation (Kennedy et al, 2013).

Another prolific, and recent, theorist on habitability is Irene Schlact. The following section is an analysis of habitability through Schlact, Kennedy, the Stanford-Ames team, NASA and several other significant works on the topic.

2.3 HABITABILITY

2.3.1 DEFINING HABITABILITY

2.3.2 ISOLATION

2.3.3 SOCIAL ENVIRONMENT

2.3.4 HUMAN NEEDS

2.3.5 INTERNAL ENVIRONMENT

2.3.6 GRAVITY

2.3.7 EVALUATION METRIC

This sub-section is an analysis of concepts of habitability and how these could be considered in the design of a space station.

Figure 06. Tsiolkovsky, K. (1933) Sketches of people in Zero-G

2.3.1 DEFINING HABITABILITY

What is habitability? The 'International Space Station Flight Crew Integration Standard' (SSP 50005) defines habitability as:

"The quality of life in an environment. It is a general term which denotes a level of perceived environmental acceptability. The term includes quality standards to support the crew's health and well-being during the duty and off-duty periods. The basic level of habitability deals with the direct environment, like climate, food, noise, light, etc., influencing primarily human physical condition.

The extended level of habitability is introduced to take care of the long-term condition of the on-orbit stay time and supply not only the individuals' physical health but also the mental/psychological health. Experience has shown that with the passage of time deleterious effects of isolation and confinement gain prominence" (NASA, 1999)

Mary Connors, part of the NASA Ames research centre, writes that habitability "connotes a level of environmental acceptability" (Connors, 1985). She continues to say that ensuring a good level of habitability is necessary to ensure good performance and that:

"Maintaining skilled performance during extended spaceflight is of critical importance to the health and safety of crewmembers and to the overall success of the mission" (Connors, 1985)

In a more metaphysical definition from Blume Novak "habitability is defined by the physical Interface between the human user and the system/environment" (2000).

Simply put **habitability is a measure of how conducive an environment is to human life.** *It is the way an environment affects a person's health and ability to perform. To this end, habitability is crucial for the long-term habitation of outer space.*

For this thesis aspects of habitability in outer space are grouped into five areas; Isolation, human needs, social environment, internal environment, and gravity. It should be noted that it is never a single aspect of this that produces stress but the compounding of various environmental stressors (Connors, 1985). The overall reduction of all aspects detrimental to habitability should be the main goal of any design regarding long-term habitation in outer space.

Figure 07. Habitability Issues

2.3.2 ISOLATION

Isolation is a major stressor in space habitation. In 1985, NASA conducted a study which utilised Antarctic and submarine habitation as design analogues. They studied these in conjunction with the Skylab and Salyut programs to try to understand the effects of living in these harsh environments. The study defined isolation as it "separates the individual or group from important parts of the normal environment" (Rockoff, 1985). That is to say, that isolation can be a lack of environmental familiarity as well as simply being separated. This highlights a distinction between physical isolation and psychological isolation.

Physical isolation relates to confinement. The crews of a space station are isolated from the external environment. This is to protect them from the effects of radiation, temperature, pressure difference, and debris. However, a result of this is a hard, enclosed, and claustrophobic environment. A solution to this is utilising larger volumes and a greater field of vision (Sgobba & Schlacht, 2018).

Maximising the physical habitable volumes of spaces, using techniques to increase the perceived volume of spaces, and wide, uninterrupted, fields of vision are great methods to minimise physical isolation. It is important to note that smaller spaces are also crucial to habitability (discussed in Section 3.2). A sensitive combination of varying volumes is an important aspect of habitability in orbit.

The negative effects of physical isolation are compounded by a habitat's distance from Earth. Physically this distance means if anything goes wrong, it could take a very long time for a rescue team to get there. Alongside this is the fear of never returning home which can have a deleterious effect on the human psyche (Sgobba & Schlacht, 2018). Views beyond the station, particularly of Earth, and other bodies, greatly help to minimise these issues (Johnson, 1975). Views outside of the station help to connect inhabitants to the world beyond their microcosm. In general, these views should be real physical windows (discussed in section 3.2). However, a technical solution with digital screens could offer a greater variety of views and even allow these views to be of the Earth's surface. This would further strengthen an occupant's connection to Earth.

Figure 08. Physical Isolation Issues

2.3.3 SOCIAL ENVIRONMENT

Psychological isolation relates to Aloneness. This is a separation from the world outside of the space station. Being only able to communicate with the same few people with minimal input from beyond that microcosm can result in loneliness. These astronauts are disconnected from their homes and come back to a world that has grown and changed without them (Rockoff, 1985). Minimising this means encouraging a sense of homeliness in the station through the personalisation of spaces (Sgobba & Schlacht, 2018). Allowing inhabitants to customise spaces to reflect themselves will imbue spaces with a sense of familiarity. Creating a strong connection with the crew's home on Earth, either through views out or communication is also key.

The main issues resulting from isolation identified by the 1985 study were; boredom, irritability, depression, anxiety, mood fluctuations, fatigue, hostility, social withdrawal, vacillating motivation, tension, sleep disorders and disorientation (Rockoff, 1985). A particularly interesting issue identified in some studies is the risk of Solipsism syndrome. Solipsism is a view that there is no reality outside one's own imagination (Johnson, 1975).

As a psychological state, this means a person sees life as nothing but a dream and becomes apathetic and detached. This is a particular issue during the 24-hour nights in the arctic and in space stations where there is no connection beyond your immediate reality. A wider field of vision helps to deal with this. It also helps to have something that grows and changes, such as planting, to allow for a process beyond the individuals control (Johnson, 1975). This shows that personal control of space is an important factor to consider in the design of spaces.

In order to minimise the effects of isolation a station must include; large and varied volumes, generous lines of sight, connections beyond the station, an allowance for personalisation and the ability for space grow and change.

The social environment in space has been shown to be crucial for the habitability of its inhabitants. Sharing an isolated environment with a small group of people can be extremely detrimental to a person's social health. This is compounded by the lack of privacy and external communications (Schlacht, 2012).

Long-term isolation can bring out the worst in people. People can become irritable and small issues become magnified. For these reasons crew screening processes become very important. People with a background of irritability, violence or other detrimental personality traits could negatively affect the whole team and jeopardise the mission. This could greatly reduce habitability for those involved (Kennedy & Capps, 2000). Even when the chosen team is near perfect these issues can still occur. A major factor is the lack of privacy in space missions. Skylab and ISS crews have commented frequently on the need for private, personal space. This privacy needs to come as acoustic and visual privacy as well as having ample personal storage space (Rockoff, 1985). Arranging volumes to allow for a mixture of personal privacy and social space – especially if this can be variable – would greatly aid in creating a positive social environment.

Alongside privacy is proxemics, which can be seen as one's personal space or 'bubble.' This is more complicated in orbit due to the three-dimensional use of space (Sgobba & Schlacht, 2018). Designing volumes to accommodate three-dimensional movement would help to minimise infringement on personal space and reduce crowding. Appropriate task scheduling can minimise the amount of people in a small space at any one time. Furthermore arranging volumes appropriately to minimise traffic throughout would help greatly. The current ISS configuration is very linear. People are constantly travelling through adjacent modules to get around. Increasing the perceived volume of spaces is another architectural method to improve this either through its organisation, geometry or colour. Increasing the separation of spaces would also help reduce crowding (Sgobba & Schlacht, 2018).

Figure 09. Psychological Isolation Issues

Figure 10. Social issues in privacy and proxemics

2.3.4 BASIC HUMAN NEEDS

Another consideration is the astronaut's ability to socialise. Current space missions focus heavily on work and research with very little time for socialisation. This has shown to be detrimental to crew behaviour (Rockoff, 1985). One way to improve this would be the inclusion of a large common space for crew to socialise in. Ideally, this would involve a variety of ways to use the space including varying degrees of privacy. This would allow people to either socialise with a large group or have smaller, more private social engagements.

As discussed in the isolation section, a relationship to Earth is also very important for the social environment. Having a strong connection back to Earth allows the astronauts to feel connected to a more complex social environment beyond their immediate interactions. Furthermore having regular crew changes helps to break the monotony and encourage dynamic social interactions (Connors, 1985). While these issues are not explicitly architectural allowing for this connection to Earth through the arrangement of communication facilities is important. Allowing living quarters to be easily changed to suit new arrivals would also help to ease any transitions.

In order to minimise the effects of the social environment a station must include: ample privacy and personal storage, an accommodation of movement in three-dimensional space, sensitive planning of volumes and their relationships to one another and a variety of dedicated social spaces.

Figure 11. Social issues in the layout and organisation of spaces

In space carrying out basic needs such as eating, drinking, cleaning, sleeping and going to the toilet are much more difficult. This is partly because up until now space habitation has been very functional, only meeting the minimum requirements for habitability. Alongside this, the lack of gravity further increases the difficulty of basic tasks (Sgobba & Schlacht, 2018).

Getting food and drink into your mouth can be difficult without gravity and because of this a lot of 'space food' comes in tubes or freeze dried packets. There has been much complaint about the catering in space and studies have shown that having fresh, nutritious meals really makes a difference. Currently aboard the ISS astronauts can request their favourite meal for special events like Christmas (Sgobba & Schlacht, 2018). Growing food locally would allow this to be a more frequent occurrence. Research is currently being done on zero-G agriculture through aeroponics (discussed in section 5.1). Incorporating a way to grow and harvest fresh food in space would be a huge benefit to habitability.

While our digestive system pushes food through the body with muscles it can be a bit more difficult getting it back out. Because of this, toilets in space are vacuum powered (Sgobba & Schlacht, 2018). This will need to be accommodated for with adequate design of bathroom facilities. Hygiene in space is also very different. Showering is accomplished by taking a ball of water, or damp cloth, and slathering one's self all over with it and some soap. Being aware of these differences in how mundane tasks are carried out in space, and designing around them, will greatly improve habitability.

Figure 12. Food in space

Figure 13. Hygiene in space

Sleep is also very different in space. An astronaut's circadian rhythm can vary due to the lack of a regular day cycle. The ISS orbits the earth every 90 minutes, meaning 16 sunsets per 24 hours. (NASA 2010). Higher orbits would result in near constant sunlight. Artificial Lighting and temperature could help create a false day-night cycle. Ensuring inhabitants shared similar rhythms would improve the social environment and aid in developing comfortable sleeping patterns.

Physically there is no gravity to hold an astronaut to their bed or the blankets to them. Some astronauts thrive in this environment and enjoy sleeping while floating however most people prefer the feeling of being snug beneath blankets (Sgobba & Schlacht, 2018). On the ISS astronauts are provided with effective sleeping bags hung from the wall in their bedroom capsule. Some astronauts have had success tightening the sleeping bag to its limit and sleeping like that however, this is not ideal. Designing around these unique sleeping conditions will be very important for creating a comfortable sleeping environment.

Figure 14. Sleeping in space

An underestimated need in space is leisure. Studies have found that when in the isolated environment of space astronauts tend to be very work focussed. This is in part due to the feeling of isolation, duty, and lack of an environment conducive to leisure. There are currently no major leisure activities possible in space – besides reading, music, and looking out the window (Sgobba & Schlacht, 2018). Designing spaces based around leisure activities could help to reduce stress and generally improve the mental state of all astronauts involved.

In order to minimise the difficulty of carrying out basic tasks a station must include: dedicated dining facilities, the ability to grow fresh food, sensitive design for hygiene facilities, a simulated circadian rhythm, comfortable sleeping quarters and dedicated leisure spaces.

Figure 15. Work and leisure in space

2.3.5 INTERNAL ENVIRONMENT

The internal environment is the major architectural feature of any space station. The geometry, scale and variety of internal spaces will be extremely important in conjunction with the atmosphere, temperature and even smells.

As discussed previously the size and shape of spaces will greatly affect the sense of isolation and confinement in these spaces. Furthermore, the layout and configuration of these spaces will affect the social environment. Current space station interiors have proven to be very monotonous which can lead to sensory deprivation. The space station environments are entirely artificial which means the astronauts inhabiting them experience far less sensorial stimulation than on Earth. There is no wind or weather, new voices or sounds; everything is very much the same, day in day out (Johnson, 1975).

This can be combatted by: including a larger variety of spaces that can be used in a variety of ways, allowing personalisation and re-configurability in these spaces, allowing for the station to add or take away modules, and planting – which acts as something that can change and grow thus reducing the artificial nature of the environment.

Another aspect of this is the atmosphere itself. An interesting idea to minimise monotony would be to include a sort of 'weather' simulation in it. While it would not be as varied as Earth the atmosphere could vary its temperature, make up and even the way it is blown around spaces each day in order to provide variance. Having this controllable in private spaces would also improve an occupant's sense of control. Minimising monotony this way will help in making the spaces feel more natural and real.

Figure 16. Monotony of environment in space

2.3.6 GRAVITY

Another consideration is the acoustic environment aboard space stations. The environmental control and life support systems (ECLSS) have proven to be quite noisy. Interestingly some amount of white noise from these is helpful in creating a pleasant environment however too much or large variances in this noise can cause discomfort (Rockoff, 1985). Thus acoustic considerations will be important not only for privacy but for minimising the impact of noisy equipment aboard the station.

Another important factor is mobility. The lack of gravity introduces a need for hand and foot holds for getting around. Orientation is also important. The lack of gravity allows for the use of a full 360 degrees of a space however, a local up/ down orientation is very important for the usability of a space (Johnson, 1975) (Discussed further in section 3.2). The way volumes connect with perpendicular modules and the general layout of transitional space will be very important to allow for simple navigation of the space station.

Another issue due to the lack of gravity is posture. In orbit a person's muscles and tendons relax producing a posture more similar to the foetal position than a traditional standing position. That means that different ergonomic considerations will be needed in the design of spaces and equipment. This is compounded by the three-dimensional use of space making for very unique consideration around the arrangement of work surfaces and furniture.

In order to minimise the effects of the internal environment a station must include: a large variety of spaces and uses, varying atmospheric conditions, personalisation and personal control, public planting, the ability to grow and change, a consideration for mobility in zero-G, local up/down orientation and a consideration for how this changes across the station, delicate organisation of transitional space.

Figure 17. Movement in space

Stations orbiting earth are in a state of microgravity. Which means the system is moving fast enough around the planet to counter its gravitational pull. This means the system is in a state of freefall – almost as if there were no gravity at all. The human body developed under gravity and so without it our bodies start to deteriorate. The lack of load on muscles causes them to atrophy over time – weakening to the point that astronauts can hardly walk on their return to earth. This can be helped with extensive exercise routines and rehabilitation on earth however bone loss cannot. The lack of compressive loads on the body results in bone mass deteriorating over time and there is currently no method to reduce this (Clement, 2007).

On earth our cardiovascular and pulmonary systems pump oxygenated blood around our body against gravity. Without gravity, the spread of this blood changes from being in the lower extremities to the upper areas of the body. This can result in discomfort, light-headedness and a diminished oxygen capacity. Over time, the entire cardiovascular system deteriorates leading to a low blood pressure and even fainting on re-entry (Clement, 2007).

Another important factor is sensory-motor deconditioning. This occurs due to the lack of stimulus to the vestibular organs in the inner ear and lack of somatosensory (touch, kinesthesia) cues associated with spatial orientation. This can result in space motion sickness and spatial disorientation. The anti-gravity muscles associated with maintaining posture and movement under earth's gravity are inactive in orbit, this can result in a misinterpretation of limb position and poor hand eye coordination (Clement, 2007). It can take a long period of rehabilitation on earth to recover from this.

Lastly the entire physiology of humans is altered in microgravity. This includes temperature regulation, fluid balance, biological rhythms and electrolyte levels. These issues can result in severe dehydration, abnormalities in cardiac function and irregularities in heart rhythm. So far, there is no effective way to minimise these issues. Fortunately, a recent study by NASA suggested that many of these issues could be returned to a baseline after a 340-day spaceflight with extensive rehabilitation (Garrett-Bakelman et al., 2019).

Figure 18. Effects of weightlessness

We can avoid these issues entirely however by simulating gravity. There are several methods of creating artificial gravity besides mass, most of which occur frequently here on Earth.

Linear acceleration occurs when a car accelerates and you feel yourself pushed back into the seat, this same concept could be used in spacecraft to simulate gravity. This is not ideal for a space station as the system would need to be in constant acceleration. If however a rocket were to accelerate to a point and then decelerate at a consistent rate its passengers could benefit from the effects of a constant downwards force (Clement, 2007). This is extremely inefficient for fuel and there are not currently rockets capable of this continuous acceleration.

Another idea is magnetism. This would however require magnets of incredible strength and a very particular use of materials. The magnets and materials needed would add tons onto a spacecraft making it currently unviable for practical implementation (Clement, 2007). The most currently viable way to generate artificial gravity is through rotation.

Rotational gravity is caused by centrifugal force due to the centripetal acceleration generated by circular motion. There are three main ways to generate this; spinning a spacecraft about its axis, rotating two spacecraft connected by a tether about their centre of mass, or by using a short radius, personal, centrifuge aboard a craft (Clement, 2007).

There are issues with this centrifugal gravity however. It has yet to be tested in space. There was initially a proposal for a rotating section on the ISS however due to cost it was not carried out (Behrens, 2009). It would also take a rather large radius or velocity to generate up to 1G. A small radius also results in a noticeable gravity gradient, which would mean a noticeable difference in the gravity felt at one's head and feet. A large radius also comes with the issue of people being stuck in the middle with no way to move.

There is also the issue of the Coriolis force. "The Coriolis acceleration is a direct result of any linear movement within the rotating reference frame" (Clement, 2007). That is to say that there will be always be an opposing force in the centrifuge. If one moves in towards the centre, they will be pushed sideways. If one jumps they will land to the side and if one runs fast enough opposite the rotation it will cancel out the downwards force holding them down (Clement, 2007). These issues go to show that having an entirely rotating station may not be feasible with current technology however having a section with this artificial gravity, and even just partial gravity, could greatly aid in the reduction of the issues of sustained weightlessness. Designs around this, in particular the transition from zero-G to greater than zero-G, would help make this a pleasant experience.

In order to minimise the effects of zero-G a station must include: ample exercise space and equipment, on-board health facilities, some form of simulated gravity to be utilised by occupants for a certain time each day.

Figure 19. Types of centrifugal gravity

Figure 20. Issues of centrifugal gravity

Habitability Rubric (How well has this design attempted to deal with these issues)

Isolation	Social	Int. Environment	Needs	Gravity
Diagram	Issue	Rating (0-4)	Description of mitigation strategies	
	Ergonomics, Scale & Field of Vision Can a human comfortably use these spaces. Are the spaces too big or too small? Are they perceived differently? How far can a person see?			
	External Views & Connection to Earth What are views out like? What are they of? Is there a connection to Earth? Communication to Earth?			
	Personalisation, Variability and Change Can spaces be personalised or changed? Is there any personal control? Can the station grow and change? Is there planting?			
	Variety Are there a variety of spaces, textures and/or uses available?			
	Privacy & Personal Space Is there private space /storage? How does this relate to other spaces?			
	Social, Dining & Leisure Spaces How do social / leisure spaces work? What activities can these spaces support how do these relate to other spaces			
	Mobility & Orientation How do occupants navigate the station?			
	Gravity How do OG spaces relate to Gravity spaces? What is the gravity like in the spinning module(s)?			
	Health Facilities & Needs Sleeping facilities, hygiene, Availability of Fresh food, atmospheric conditions, day/night cycle, acoustics etc			

2.3.7 EVALUATION METRIC

From this analysis of habitability in space a rubric has been created. This rubric will be used to evaluate these habitability issues in the designs of this thesis. Most aspects in this rubric pertain to multiple categories of habitability and have been colour coded to acknowledge this.

No Mitigation of this issue	
Minimal Mitigation of this issue This issue has been touched on but not considered in depth	
Moderate Mitigation of this issue This issue has been considered a little but is not incorporated into the scheme / deeply resolved	
Good Mitigation of this issue This issue has been considered but could be pushed further and incorporated more effectively into the design	
Excellent Mitigation of this issue This issue has been considered in a unique and effective manner. It is incorporated into the overall scheme very effectively	

3.1	TIMELINE OF SPACE HABITATION
3.2	PIONEERING SPACE ARCHITECTURE
3.3	INTERNATIONAL SPACE STATION

Figure 21. Tsiolkovsky, K. (1933) Greenhouses in Space

The Brick Moon - (Edward Hale, 1869)

From the Earth to the Moon- (Jules Verne, 1865)

3.1 TIMELINE OF SPACE HABITATION

3.2 PIONEERING HABITATION

1900-1960'S SPACE ARCHITECTURE

The following is an analysis of proposals for long-term space habitation aboard 'space stations.' This analysis focusses on the design of theoretical space stations. Tangential ideas on spaceflight for the purpose of travel have not been included. This analysis also deals only with some of the main concepts developed over the last century and as a result some contributions have not been discussed.

Fictional ideas of space habitation go back as far as Jules Verne and Edward Hale in the mid-19th century. However, the idea of a space station, on the level of theoretical science, did not come about until Konstantin Tsiolkovsky less than 50 years later (Johnson, 1975). First in his 1895 book "Dreams of Earth and sky" and built on in his 1903 article "The Exploration of Cosmic space by Means of Reaction Devices" Tsiolkovsky described the aspects of a space station for habitation, research and industrial uses. This is the first documentation of these concepts as well as the mathematical proof that a rocket could orbit the Earth (Noordung, 1929). Tsiolkovsky detailed concepts for a stations built entirely on Earth, entirely from the material of nearby celestial bodies and most importantly of those built in parts on Earth and assembled in Orbit.

He emphasised with detail the need for huge agricultural orangeries in order to clean the air and provide food for residents (Fig. 22). Tsiolkovsky proposed that this planting could be satisfied with only minimal carbon dioxide gas, nitrogen and water vapour. The plants would be grown in conical modules, which would maximise sunlight access. These plants would be separated from the inhabitants as they could get by with far lower atmospheric requirements. Furthermore he proposed to recycle human waste as food for the plants (Tsiolkovsky, 1967). This minimal resource, recycling based approach is important as it shows an early description of planting techniques reminiscent of aeroponics. The recycling of human waste and air through these plants is also something very crucial to modern space stations.

He proposed that the form of the habitable components should be cylindrical in order to best utilise the space and dimensioned this to a minimum of 2-3 meters in regards to human scale. This cylinder could then be compartmentalised in order to minimise damage in case of an issue in one compartment (Tsiolkovsky, 1967). This sets the precedent for cylindrical space stations very early - justified based on human needs.

Tsiolkovsky was incredible sensitive to how a human might inhabit his theoretical station. He proposed the station be at a $1/3$ inclination towards the sun in order to achieve a comfortable heating. He detailed how a person could inhabit a gravity-less environment (fig); the benefits of being able to choose one's own up and down, no longer needing shelving and desks he even wrote about the potential to use wings as a form of movement in the air filled, gravity-less environments.

Figure 23. Tsiolkovsky, K. (1926) Space Station Sketch

Figure 22. Noordung, H. (1929) Wohnrad render.

Figure 24. Noordung, H. (1929) Wohnrad Sections

Tsiolkovsky also wrote on the negatives of a gravity-less environment; how a human's body could break down and how movement can become difficult. To remedy these he proposed to rotate the station slightly in order to simulate gravity. He proposed not to simulate full gravity but only 1/100th of a G. In this way the rotation would not be too great to cause discomfort nor would it's residents be "burdened" by weight yet there would still be a slight drag towards the edges of the cylinder to allow for movement (Tsiolkovsky, 1967). This highlights the need for a sensitive consideration of gravity. It also proposes that 1G may not be the ideal level of gravity for humans to thrive and that lower levels could allow some of the benefits of weightlessness without the drawbacks.

Tsiolkovsky is an important precedent for space habitation as a whole. It was through him that the foundational concepts of what a space station could be were set. His work has influenced just about every space station design since. The term space station however, did not appear until 1923, in Hermann Oberth's book 'The Rocket into Planetary Space' (Noordung, 1929).

The German-Romanian Oberth mirrored much of the same ideas as Tsiolkovsky, such as his station's use a facility for research, industry and habitation and the use of centrifugal force to mitigate the issues of weightlessness. The difference was that Tsiolkovsky saw his station as separate from Earth where Oberth saw his as feeding back into Earthly infrastructure and life (Noordung, 1929). It was the combination of these, independently developed, studies which justified space architecture as real possibility and gave birth to the influx of work on that very concept.

In 1929 Herman (Potocnik) Noordung, designed the first wheel station, Wohnrad (Living wheel), accompanied by a machine station (Machinenhaus) and an observatory (Observatorium). Wohnrad was a station, shaped as a torus, undergoing constant rotation (Johnson, 1975).

This rotating torus became a popular station design in the decades to come. Noordung built upon Tsiolkovsky and Oberth's work in a huge amount of detail. Through Noordung we saw detailed drawings of his proposed station (Fig 24), visualisations (Fig 22), as well as diagrams of zero-G habitation. Noordung documented in depth the effects of zero-G. He introduced the importance of tethered space suits for extravehicular activity (EVA), proposed the behaviour of liquids in zero-G, and the detrimental effects of gravity on the human body (Noordung, 1929). Noordung also proposed a detailed solar power plant, controlled by mirrors, using steam power (Noordung, 1929). Noordung conceived of many of the issues of habitability in orbit before any human had even been there. He then documented these in detail resulting in a profound influence on space architecture.

A very clear influence of this is seen in Wernher von Braun's re-envisioned Wohnrad. While Braun refined many of Noordung's ideas, his greatest contribution was publicity. Braun worked with Colliers magazine to document his space station in an article titled "Crossing the Last Frontier." (1952). Brauns work with Colliers is greatly attributed to popularising the idea of the space station in the United States (Salkeld, 1975).

Beyond this, is the development of the O'Neill Cylinder and the Stanford Torus. These contributed greatly to the development of space habitation and have been briefly discussed in the previous sections.

This brief discussion of the development of space station ideas highlights some of the predecessors for ideas in this thesis as well as their progression and popularity. The culmination of a century of space station designs and growing popularity is seen through the International Space Station.

3.3 INTERNATIONAL SPACE STATION

Figure 25. Plan of the ISS layout

The best precedent for space habitation available to us is the International space Station (ISS). The ISS is an ongoing construction project with its first component (Zarya) being launched in 1998. As of now (2019) there have been 36 Space Shuttle, 5 Russian Proton and 3 SpaceX Dragon launches, each adding components to the 6 person orbital laboratory. As of 2018 the ISS is planned for de-orbit in 2030 (NASA, 2010).

The ISS is made up of 16 pressurised modules (fig. 25). Each module is sent up independently and docked / berthed with existing docking ports. The size of these modules was limited by the launch vehicles used. Most of the habitable modules are around 4m in diameter which was the limitation of the Space Shuttle Payload bay (NASA, 2010). The ISS offers many solutions to issues of habitability and construction in orbit.

ORIENTATION

Modules in the ISS are designed to have a consistent local vertical (NASA, 1999). This was a lesson learnt from Skylab in 1973/74. The astronauts on board claimed to be "most comfortable when they felt that they and the room were oriented in the same manner" (Kitmacher, 2002). This orientation is indicated in several ways. As shown in figure 26 all of the modules are more or less in the same plane which allows for a unified orientation.

Reinforcing this orientation are visual cues. In the U.S. section of the ISS this was attempted through the asymmetric design of hatches and position of lights. However, this was lost once all the equipment was installed (fig. 26). A more successful approach was used by the Russians who used colour to define the local vertical. Lighter colours signified down and darker colours signified up (Sgobba & Schlacht, 2018). This shows the need for a clearly defined up & down in the design of space stations. This cannot be accomplished through subtle hints and must be defined obtusely and as part of the space.

Orientation is also directly related to the size of a space. Astronauts aboard Skylab claimed to feel "most at home in the shallow space of the living quarters" (Kitmacher, 2002). The astronauts preferred being enclosed as their local vertical was more clearly defined and they could touch the surfaces easily. This was compared to the larger section which astronauts found more confusing. However, the astronauts also commented on the need for this larger volume. It would allow an escape from any claustrophobia they may feel and allow space for acrobatics (Kitmacher, 2002). This shows that a contrast of differing sizes is important to habitability in space. Specifically having more enclosed spaces for the heavily used spaces with larger spaces for exercise or even transition.

Figure 26. Empty Destiny Module orientation, Full Destiny module, Zvezda module colour orientation. NASA

MOBILITY

In micro-gravity you cannot walk or run and so movement is very different. Astronauts aboard the ISS primarily use movable Foot Restraints and Handrails to move around. Most of these restraints are adjustable and mount to aluminium seat tracks. These are in turn fixed to the modular experiments racks facing the astronauts (Sgobba & Schlacht, 2018). This allows the various forms of restraint to be moved around and adjusted to suit their use and the users personal comfort needs. This relates directly to habitability through personalisation and variability. Through a simple requirement it allows the user personal control over how they use their environment making it a very important aspect to carry forward.

An alternative method of mobility on the ISS is to propel yourself off surfaces and restraints. While this is potentially hazardous it was also one of the favourite activities of the Skylab crew. The crew had a game where they would propel themselves from one end of the lab to the other to see who could get the furthest without hitting anything (Kitmacher, 2002). Similar sentiments are made by ISS crew whom, after gaining confidence, find themselves rebounding off surfaces and doing flips (Sgobba & Schlacht, 2018). This shows that while handholds are necessary an allowance for people to flip and jump through the space would make the space more fun to use. This could also allow for some interesting opportunities in allowing various forms of movement through spaces.

CONSTRUCTION

It is crucial for the ISS to be protected from micro-meteoroid or debris impacts. The construction of the ISS walls vary from module to module (more than 100 different shields have been designed for different modules and components.). Typically the wall build up is a whipple bumper configuration. This involves a single plate material (generally aluminium) spaced a distance (approximately 100-300mm) from the underlying module wall. This is often 'stuffed' with 6 layers each of Nextel and Kevlar in order to improve it's ability to disperse broken up impact materials (fig. 28) (National Research Council, 1997).

Radiation protection aboard is typically accomplished through the whipple bumper configuration in conjunction with the equipment racks to provide mass between astronauts and space radiation. This is used in conjunction with polyethylene lining / radiation bricks in some areas of the ISS. Some modules, such as Zvezda, are outfitted with extra radiation protection to act as storm shelters in case of large radiation events (Shavers et al, 2004). The radiation protection aboard the ISS is often criticised as being ineffective as its crew are still exposed to large amounts of radiation. However, different techniques to mitigate impact, and radiation, are outside the scope of this thesis. For this reason a thicker variation of the typical stuffed whipple bumper configuration will be considered as the standard construction for designs in this thesis.

Figure 27. Window build up in the cupola module

Figure 28. Typical Whipple bumper wall

Windows are similarly made from several layers of glass and shielding (fig. 27) (NASA, 2010). An important aspect considered in the design of the ISS was whether or not to include windows or to just use cameras. The viewpoint of the flight crew was expressed simply through astronaut Gordon Fullerton, "give me a window and binoculars any day over a high tech solution" (Kitmacher, 2002).

This emphasises the need for a view out, even in the radiation environment in orbit. This means that simply using cameras and screens is not good enough. However, this may be useful for larger windows etc.

The interior set out of the ISS typically consists of modular experiment racks lining the internal periphery (fig. 29). These racks are used primarily for experiments, equipment and important services within the ISS. This is important for habitability as it allows for variability and change within spaces. Similar ideas could be improved upon for use in future stations.

Figure 29. Typical rack configuration

Figure 30. Typical equipment rack

ECLSS

The environmental control and life support systems (ECLSS) is crucial to the habitability of the ISS crew. This system carries out the crucial tasks for supplying and controlling the air and water on the ISS. As shown in figure 31 the ECLSS system is almost a closed system recycling urine and sweat to use as potable water and even turning some of this water into oxygen for breathing (NASA, 2010).

This regenerative system greatly cuts down on the amount of water and air that must be supplied to the ISS from Earth. A similar system could be utilised, specifically with the inclusion of agriculture, in future stations.

The ISS is a fantastic example of several methods of mitigating habitability and the threats of outer space. For these reasons the ISS has been a huge influence on this thesis and its designs.

Figure 31. ISS Regenerative ECLSS system

Figure 32. Depiction of site factors

4.0 SITE ANALYSIS

4.1 EXPLANATION OF UNITS

4.2 FACTORS CONSIDERED

4.3 POTENTIAL SITES

4.4 ANALYSIS SUMMARY

This is section begins with an overview of important factors of site in space. Following this is an analysis of 8 potential sites for an asteroid mining operation in our solar system.

4.1 EXPLANATION OF UNITS

There are several different locations with access to asteroids for mining. This thesis looks at locations most viable in terms of current technology and asteroid mining needs. Venus and Mercury have not been considered, as there is no written evidence of greater resources there.

Astronomical Unit (AU) is the distance from the sun to Earth. This unit is generally used to describe distances within our solar system.

Figure 33. Astronomical Unit

Delta-V (ΔV) will also be used to determine distances. This is the total 'change in velocity' needed to get to the desired location in space, for example:

This begins with the initial launch to a sub-orbital velocity. At the highest point of this trajectory the rocket will accelerate in the same direction of its travel to an orbital velocity (9.5km/s (Launch + orbital insertion). The rocket can continue to accelerate increasing the altitude of its trajectory on the other side of the planet into an elliptical trajectory which will eventually intersect the gravitational influence of the Moon. Once at the lowest point near the moon the rocket will then stabilise its orbit by burning its engines in the opposite direction to its trajectory (4.1km/s (ejection + capture)) (Walter, 2012),

This is an important factor as it relates directly to fuel use and thus the weight and cost of the vessel.

Figure 34. Delta-V

Similarly, bodies beyond the main asteroid belt, such as Jupiter, have not been considered as the resources required to get there are too great (Francis, 2018). The following are units crucial to this thesis' analysis of possible locations.

Solar irradiation (G_d) Expressed as a factor of the solar constant (G_e). A measure of the solar energy received by a surface facing the Sun near Earth. Solar irradiation tends to drop off exponentially as a craft moves further away.

This can be expressed through the equation $G_d = G_e(1/D)^2$ where:

G_d = the solar constant at target.
 G_e = the solar constant at Earth.
 D = the distance of target from the sun in AU.

Figure 35. Solar Irradiation

Gravitational constant (G) is the gravitational force on Earth's surface. Gravity at the selected sites will be expressed as a factor of this eg 1G = earth's gravity (9.8ms⁻²)

Figure 36. Gravitational Constant

4.2 FACTORS CONSIDERED

DISTANCE FROM EARTH

Measured as:

Astronomical Unit (AU): Used for gauging the effectiveness of communications as well as the visibility of earth. Low AU means less communication delay and higher visibility of Earth.

Delta-V (ΔV): Used gauging the cost of travel from the selected site to and from LEO. A low ΔV value means a more effective location with a higher chance of crew-cycling and emergency rescue. *Note: It is possible to aero-brake, using atmospheric drag to slow down, thus reducing ΔV , however this has not been considered for this analysis.*

DISTANCE FROM THE SUN

Measured as:

Solar Irradiation (G_s): As a factor of the solar constant and AU from the sun. Used to show how effective solar power will be in the selected location. Lower G_s values mean solar power will be less effective at this location. Very crucial in the development and operation of any human settlement away from Earth.

DISTANCE TO RESOURCES

Measured as:

Delta-V (ΔV): Used to gauge the cost of travel from a chosen site to and from it's nearest resources. The ΔV value for this will be very approximate as our understanding of asteroids and their trajectories is less known than planets and moons.

Note: Also of importance is the distinction between a station collecting from NEA's or MBA's. NEA's generally have a highly elliptical orbit meaning windows of opportunity for these are much slimmer than the 'abundant' source of asteroids in the main belt. Delta-V values for NEA's are taken from their nearest position to Earth.

RISK OF COLLISION

Estimated based on gravitational pull from nearby bodies and proximity to asteroids / space debris:

There is not a lot of data on collisions however we know that meteoroids are more likely to be drawn to large bodies due to gravity and that earth has a large amount of debris in orbit. A higher risk of a collision will require heavy shielding to protect from potential impact. This could greatly increase the cost of a station in this location. This also increases the risk of those on board and especially to those working on the exterior of the station.

DANGER OF RADIATION

Estimated based on proximity to the Earth's magnetosphere: Solar particle events (SPE's) and galactic cosmic rays (GCR's) are the 2 main forms of radiation in space. SPE's are influxes of solar wind/ solar flares from our sun while GCR's come from beyond our solar-system as particles jettisoned from distant dying stars.

The geological movement of the Earth generates a geomagnetic field, or magnetosphere, which helps to protect from this radiation. A side effect of this is the Van Allen belts - belts of trapped radioactive particles from SPE's and GCR's. This poses a significant threat to humans travelling through them, however not so great as the threat of travelling beyond Earth's magnetosphere. Protection from radiation requires considerable amounts of heavy/ costly shielding and even 'storm-bunkers' to protect from particularly harsh radiation events.

GRAVITY ENVIRONMENT

Measured as a factor of the gravitational constant (xG):

Most of space is not greatly affected by gravitational forces causing objects to float. This is known as zeroG and is the gravitational environment for most of the proposed locations of this station. An object in orbit of a celestial body experiences similar effects even though it experiences the full effect of the body's gravitational pull. This is because the object is moving fast enough while perpendicular to the force of gravity to counteract it entering a state of constant free-fall around the body. This is what is known as micro-gravity. The physical difference of this is not noticeable and will thus not be considered and separate from zero-G for this analysis. There is however the possibility of a surface base benefitting from the partial gravity of a body.

4.3 POTENTIAL SITES

4.3.1 MAIN ASTEROID BELT

4.3.2 MARTIAN ORBIT

4.3.3 SOLAR ORBIT

4.3.4 LUNAR ORBIT

4.3.5 EARTH: LOW EARTH ORBIT

4.3.6 EARTH: GEOSTATIONARY ORBIT

4.3.7 EARTH: LAGRANGIAN ORBIT

4.3.8 EARTH: ELLIPTICAL ORBIT

This sub-section is an analysis of 8 different potential sites for an asteroid mining operation.

Figure 37. Depiction of Potential Sites

4.3.1 MAIN ASTEROID BELT

$\Delta V = 7.18 \text{ km/s}$ (2.15 AU) (median for 4000 known MBA's. (Taylor et al, 2018)

0.21Gs Solar power is fairly inefficient. Low potential of asteroids blocking the sun.

$\Delta V = \sim 1 \text{ km/s}$. $\sim 50\times$ more asteroids in the main belt than NEO. Small amounts of ΔV will be needed to get around once in the belt. (Taylor et al, 2018)

Contrary to popular belief the asteroid belt is fairly sparse. The chance of impact here is not much if any greater than being in empty space (Elvis et al, 2011)

No natural protection from radiation. (Kecskes 570, 2000)

0G - any gravity from asteroids is negligible (Kecskes 570, 2000)

A promising location due to its abundance of resources however, the risk of impacts, lack of radiation protection, distance from earth and un-effective use of solar power reduces its applicability.

4.3.2 MARTIAN ORBIT

- $\Delta V = 5.7 \text{ km/s}$ (Francis, 2018)
- $0.43 G_s$ Solar power less than half as efficient as around Earth. Access can be constant in a polar orbit perpendicular to the sun.
- $\Delta V = 2\text{-}3 \text{ km/s}$ ($6\text{-}7 \text{ km/s}$ from surface). Access to the main belt asteroids. (Taylor et al, 2018)
- Moderate potential of micro-meteoroid impact due to Mars' gravitational pull.
- No natural protection. Mars has no magnetosphere. Thin atmosphere could provide minor protection on the surface. (Frazier, 2015)
- $\sim 0G$ ($0.38G$) - Microgravity environment or partial gravity on the surface (Young, 1999).

A low orbit Martian station could provide a great opportunity to study the red planet and act as a stepping-stone beyond it. There would be decent access to resources through the Martian moons, and the asteroid belt. However getting resources back to earth could prove costly (though aero braking could reduce this greatly – potentially as low as ΔV 2km/s).

4.3.3 SOLAR ORBIT

- $\Delta V = 9.4 \text{ km/s}$ for L4/5 (3.2 km/s for L1/2)
- $1 G_s$ Solar power very effective (Same effective distance as Earth). Constant.
- $\Delta V = \sim 1 \text{ km/s}$ (Less than Earth due to lack of gravity well). Access to Near Earth asteroids.
- Very minor risk of potential micro-meteoroids as this would be empty space.
- No natural protection. Mars has no magnetosphere. Thin atmosphere could provide minor protection on the surface. (Frazier, 2015)
- $0G$ - empty space

A base at the Lagrangian point of the Sun could have a very easy access to NEA's. However, a station at any points other than L1 & L2 would be very distant from earth making travel to and from it very costly. A station at L2 would be constantly eclipsed by the Earth making solar power inefficient. An L1 station could be promising with easy access to resources and relatively easy access to Earth.

4.3.4 LUNAR ORBIT

$\Delta V = 4.1 \text{ km/s}$ (+2.2 km/s to surface) (1.3 km/s return to LEO with aerobraking) (Stationkeeping needed)

~1G Solar power effectively the same as Earth orbit. Access can be constant in the right orbit.

$\Delta V = 2-3 \text{ km/s}$ (4-5 km/s from surface). Access to the near earth asteroids (Elvis et al, 2011).

Moderate Potential for micro-meteoroid impact due to lunar gravitational pull.

No Natural protection. Potential increase in risk during periods within Earth's magnetotail (Phillips, 2008).

~0G (0.16G) - Microgravity environment or partial gravity on the surface.

A lunar orbit would put the station very close to the Earth. However, there would be times of darkness as it passes behind the moon and a greater amount of ΔV is needed to escape its orbit than a Lagrange point orbit. Could be more beneficial for lunar infrastructure or harvesting resources from the moon (much less than NEA's) but not necessarily a benefit for the mining of NEA's.

4.3.5 EARTH: LOW EARTH ORBIT

$\Delta V = 0$ (9.5 km/s from Earth surface)

1G Solar power very effective. Can be constant with a polar orbit perpendicular to the sun.

$\Delta V = -4 \text{ km/s}$. Access to the near earth asteroids (Elvis et al, 2011).

High risk due to orbital debris and potential micro-meteoroids (Rongier, 2013)

Natural protection through Earth's magnetosphere. Potential risk in Van Allen Belts and South Atlantic Anomaly (Kennedy, 2000).

~0G - Micro gravity environment.

Arguably the simplest location for the site – easiest access for tourism / research. Allows for crew cycling due to its close proximity to earth as well as fast communications. Radiation protection and the ability to control solar power access is also great. However, the risk of impact is higher than any other location (though this can be mitigated – the ISS does alright) the distance to NEA's is also greater than other locations.

4.3.6 EARTH: GEOSTATIONARY

- $\Delta V = 3.5 - 4 \text{ km/s}$ (0.7-0.8 km/s return to LEO with aerobraking) (Francis, 2018).
- 1G Solar power very effective. Can be constant with a polar orbit perpendicular to the sun.
- $\Delta V = < 4 \text{ km/s}$. Access to the near earth asteroids.
- Moderate-High risk due to orbital debris and potential micro-meteoroids (Rongier, 2013)
- Partial protection of Earth's magnetosphere (~1/3 of the time) potential risk of increased radiation during interception with Earth's plasma sheet (Phillips, 2008).
- ~0G - Micro gravity environment.

A Geostationary station would be very similar to LEO. It would offer the benefit of being in the same position relative to the Earth's surface at all times making travel & communication to and from it somewhat easier. However, this is better suited to satellites and communication facilities.

4.3.7 EARTH: LAGRANGE

- $\Delta V = 3.5 - 4 \text{ km/s}$ (0.7-0.8 km/s return to LEO with aerobraking) L4/5 are stable L1-3 require station keeping
- 1G - a halo orbit at L1/2 would allow for constant solar access (Farquhar, 1972). L3, L4 & L5 have constant sunlight with rare, Partial eclipses of the Sun by the
- $\Delta V = < 4 \text{ km/s}$. Access to the near earth asteroids. (potentially closer to 1.2 or 2.4 km/s) (Elvis et al 1410, 2011)
- Moderate-Low risk due to orbital debris and potential micro-meteoroids (Rongier, 2013)
- Partial protection of Earth's magnetosphere (~1/3 of the time) potential risk of increased radiation during interception with Earth's plasma sheet.
- ~0G - Micro gravity environment.

A very promising location. A Lagrangian point is a point in space where the gravity of 2 bodies effectively cancels out. These create gravity valleys (L1-L3) and bowls (L4-L5) which can allow a craft to orbit with minimal need for station keeping.

Each Lagrange point offers more stability than other orbits. L1-3 are semi stable, requiring minimal effort in a single direction to hold their position, while L4-5 are entirely stable require little or no station keeping. This combined with their proximity to the Earth, Moon and NEA's make them very promising sites for a potential asteroid mining operation.

4.3.8 EARTH: ELLIPTICAL

- $\Delta V = 3.2\text{km/s}$ for apoapsis.
- 1G Solar power very effective. Can be constant with a polar orbit perpendicular to the sun.
- $\Delta V = \sim 1\text{km/s}$ (Less than Earth due to lack of gravity well). Access to Near Earth asteroids.
- Moderate-High risk due to orbital debris and potential micro-meteoroids (Rongier, 2013)
- Partial protection through Earth's magnetosphere. Potential risk in Van Allen Belts and South Atlantic Anomaly (Kennedy, 2000).
- $\sim 0\text{G}$ - Microgravity environment

This proposal would pass through both LEO and the very edge of Earth's SOI. The idea being that it could fly close to earth for crew/ resource transfer as well as closer to NEA's for resource gathering. However, in practice this system would be moving very fast past the earth requiring a large amount of Delta-V to slow down. Aero braking could do away with this however having such an elliptical orbit could make it difficult to acquire intersects with NEA's

4.4 ANALYSIS SUMMARY

MAIN BELT ASTEROIDS						
MARS						
MOON						
EARTH: EARTH ORBIT						
EARTH: LANGRANGIAN						
EARTH: GEO						
EARTH: ELLIPTICAL						
SUN						

* No / minimal stationkeeping required

This analysis has shown that a base in orbit of Earth is the best option. A base orbiting Mars or in the Asteroid belt would provide a greater access to resources through the abundance of asteroids in the main belt. This benefit however is outweighed by the difficulty of sending these resources back to earth, the lack of protection from radiation and the inefficiency of solar power. There is a potential for operations here in the future but it makes sense to develop Earth's space infrastructure in Earth orbit.

Low earth orbit is the best location for supporting life-based operations. This is due to natural protection from radiation, access to earth for crew cycling and communications, as well as opportunities for commercial research and tourism. However, of all the locations considered Earth Orbit has the worst access to resources. For this reason, a station at Lagrange Point 5 (or L4, which is effectively the same as L5) would be the optimum location for habitation in conjunction with asteroid mining. L5 has no need for station keeping and would require a minimal amount of delta-V to escape the Earth's SOI and access NEA's, being closer to potential targets would also reduce communication delay.

For these reasons, the main station for asteroid processing will be at L5 with an auxiliary station at LEO.

Figure 38. Orbital map of selected station positions

5.0 PRELIMINARY ISSUES

- 5.1 PROGRAM
- 5.2 STATION TYPES
- 5.3 CONSTRUCTION METHODS
- 5.4 MODULE DEFINITION

This section defines the program for the design of a space station. This is followed by an exploration of different types of station and the definition of the optimum type for this thesis. Following this is an analysis of various construction methods for use in orbit and the definition of the module parameters for use in this thesis.

5.1 PROGRAM

This station will be an asteroid mining facility.

This will require:

- **Overseer (1-2).** Needed to oversee the operation
- **Administration (2-3).** Needed to aid management and account for data gathering on resources acquired, resources needed and keeping track of station needs and any changes to crew or the station itself.
- **Navigation & Astronautics experts (1-2).** Needed to control the station's position, track NEA's and potential micrometeoroids and to accommodate other specialised needs.
- **Computing & Robotics (3-5).** Needed to control the stations digital elements, ECLSS, communications and the control and maintenance of the miner drones.
- **Engineering & Construction (3-5).** Needed to maintain the station, deal with the creation of new materials on the station and overlap with robotics in the maintenance of miner drones.
- **Cleaning / Maintenance (1-2).** Overlap with Engineering and Construction. Needed to keep the station in clean working order.
- **Agriculture & Nutrition (2-3).** Needed to manage the growing of fresh food and manage meals aboard the station.
- **Medicine & psychology (1-2).** Needed to manage the health of crew.

Total crew = 14-24.

Numbers were estimated based on priority in the station program. Computer and Engineering have the most people, as the dominant purpose of the station is the harvesting and processing of asteroid resources. Whereas the Cleaning, Agriculture and Medicine are support staff for the rest of the crew.

The station design will accommodate the highest number of crew aiming for a maximum population of 30. Refer to fig. 39 for personnel relationships and Fig. 40 for the Module requirements developed from these.

Figure 40. Station Personnel

Figure 41. Station Module Needs

Figure 42. Fjeld, P. (1975) Artists concept of Apollo-Soyuz Test Project.

5.2. STATION TYPES

5.2.1 MODULAR STATION

5.2.2 CYLINDRICAL STATION

5.2.3 RING STATION

5.2.4 VARIABLE TETHER STATION

5.2.5 SUMMARY COMPARISON

This sub-section is an analysis 4 different station types and the selection of the station type used in this thesis.

5.2.1 MODULAR STATION

Figure 43. Modular Station Diagram

The modular station is the 'standard' space station design used by the ISS and Mir.

POSITIVES

- Well understood.
- Very flexible in terms of configuration.
- Can have modules added or taken away.
- Relatively simple / cheap.
- Tracking etc is easy from a stationary system.

NEGATIVES

- Microgravity (Zero-G) – This is a huge negative as discussed in section 2.3

OPPORTUNITIES

- Potential to use rotating modules to allow for gravity generation in localised areas.
- Potential for ISRU construction to create much larger open spaces.

5.2.2 CYLINDRICAL STATION

Figure 44. Cylindrical Station Diagram

A fully rotating station would allow for simulated gravity across the entire system. This could be greatly beneficial for it's inhabitants. Refer to appendix A for an analysis of this rotation with regards to the selected module size.

POSITIVES

- Simulated gravity everywhere
- Large open spaces / surfaces

NEGATIVES

- Large radius or spin needed for adequate gravity.
- Fast rotation could cause motion sickness
- Rotation makes docking and construction difficult
- Rotation makes it hard for solar panels to track to sun.
- Rotation makes tracking foreign bodies and communications difficult.
- A large radius would make for a large open space which people could get stuck in with no way to propel themselves back to the surface
- Potential gravity gradient with smaller radii.
- Required power to generate rotation

OPPORTUNITIES

- If rotation can be generated freely (see variable tether) power could potentially be generated through this
- Could potentially support huge colonies in space.

5.2.3 RING STATION

Figure 45. Ring Station Diagram

A fully rotating station would allow for simulated gravity across the entire system. This could be greatly beneficial for it's inhabitants. Refer to Appendix B for a deeper analysis of some of the aspects of a ring Station.

POSITIVES

- Simulated gravity everywhere

NEGATIVES

- Large radius or spin needed for adequate gravity.
- Fast rotation could cause motion sickness
- Rotation makes docking and construction difficult
- Rotation makes it hard for solar panels to track to sun.
- Rotation makes tracking foreign bodies and communications difficult.
- A large radius could make it difficult to circulate around the station.
- Potential gravity gradient with smaller radii.
- Required power to generate rotation

OPPORTUNITIES

- Potential for docking, solar panels, tracking etc facilities in the centre of rotation where torque forces are lower.
- If rotation can be generated freely (see variable tether) power could potentially be generated through this
- Potential for ISRU construction to create much larger open spaces.

5.2.4 VARIABLE TETHER STATION

Figure 47. Figure . Tether Station Diagram

A variation of the ring station wherein modules can be tethered by a variable connection. This would be easier, less energy intensive, control of the rotation through a variable moment of inertia. The Positives and Negatives are the same at the Ring however there is one Unique opportunity.

A possibility with the counter-weighted tether is the opportunity to generate rotation by adjusting the systems moment of inertia. This is the same principle that allows figure skaters to speed up by pulling in their arms.

Forces in space, such as radiation, sunlight, and residual forces from it's initial positioning ensure the stations base rotation will be above 0. If this is the case by reducing the radius (r) we also reduce the moment of inertia (I). A lower moment of inertia means the system has less resistance to rotational forces thus increasing it's angular velocity.

Figure 46. Moment of Inertia Diagram

5.2.5 STATION COMPARISON

This analysis has shown that while gravity is very important for long term habitation of space it comes with a lot of issues when compared to a non-rotating station. A rotating station is;

- More complex to construct and maintain
- Limits module configuration in relation to a 0G station
- Makes it difficult to track objects beyond the station
- Makes it difficult for solar panels to track the sun
- Is difficult to dock with
- Makes crew escape difficult in the event of failure

For these reasons this thesis will consider a hybrid modular station with rotating components as the optimum station configuration

Figure 48. Station Type Comparison Chart

5.3.1 CONSTRUCTION METHODS

STANDARD - DOCKING / BERTHING FROM EARTH

The standard method of space construction is building modules on Earth and then launching them into space to be either docked or berthed with the station.

Figure 49. Standard construction launched from Earth.

DOCKING

Docking usually requires 2 active vessels which will approach one another very precisely in order to line up their docking ports. They will then commence a 'soft dock' where they will touch and begin damping residual forces such as roll, yaw and pitch. Following this is the hard dock where the two pressurised modules are fully connecting and sharing ECLSS. This whole operation must happen as fast as possible to minimise risk of expansion and contraction of metal elements due to the sun among other things.

Figure 50. Docking Diagram

BERTHING

The second method is berthing. This was utilised very heavily in the construction of the ISS. Berthing is the use of robotic arms (one on the shuttle and one on the space station) to fix modules together. This is generally slower than docking but poses less risk due to a greater level of control and a lack of people on board the module being added.

Figure 51. Berthing Diagram

Though this method is the simplest and best understood it is also very costly. The Space X Falcon Heavy costs \$80-\$270 million per launch (\$1,509-5094 per Kg to LEO) (United States Government Accountability Office, 2017). Payload dimensions and aerodynamic requirements also greatly limit the geometry that can be utilised in the design on space habitation.

IN-SITU RESOURCE UTILISATION

In referencing back to Gerard O'Neill why not "quarry the stone for that castle right around the top of that mountain" (citation) This is know as In-situ Resource Utilisation (ISRU). ISRU could make for much cheaper space station construction due to not needing to launch parts from Earth. While this thesis has already proposed to generate fuel and life support materials from asteroids could we also construct the station from it? How could we go about it?

PRODUCTION LINE

The most straight forward interpretation of this is to create a sort of production line in orbit. This would involve breaking down the mined resources, sorting out the elemental composition and re-combining / processing these into workable components such as, metal plating / fixings, plastics, and even concrete. These would then need to be pieced together to become habitable modules on site.

While this is an exciting prospect the equipment needed to process these materials, eg; smelting equipment, mills, lathes, welding equipment etc. Is heavy industrial equipment. A lot of this equipment would not work in 0g or in a sealed environment and any faults with the equipment would be hard to fix without easy access to Earth based workshops. Traditional 'subtractive' manufacturing also produces a lot of wasted material. (Dunn, 2010).

For these reasons traditional construction methods are not a viable option for construction in orbit.

3D PRINTING

An alternative method of orbital construction is additive manufacturing, a collection of processes, of which many are known as, 3D printing. These processes are reliant on filaments and powders, which are much easier to produce, and minimise waste, compared to traditional methods (Dunn, 2010). This is ideal in orbit where resources are more difficult to acquire than on Earth.

3D printing has also already been tested on the ISS. Made in Space currently has two 3D printers on board the ISS with a third (metal) printer on its way (Made in Space, 2019). Made in space are also working on the 'Archinaut' which is a 3D printer specifically for the manufacturing of large-scale structures in orbit. This could build satellites or even space station modules using ISRU (Made in Space, 2019).

There are two methods for the fabrication of additional modules in orbit. One method would utilise an external craft or robotic arm, which could construct modules in the vacuum of space (Fig. 51). This would allow for an immense level of freedom in the design and geometry of space station modules. The printer would need to be designed to defend itself against the rigours of space such as, expansion and contraction due to temperature gradients, radiation and meteoroid impacts.

The second method would involve printing additional modules within the station (Fig. 52). This would allow for safer, easier construction due to the established protection of the station. This would also allow humans inside to work on the more detailed components that the printer cannot and work as fail-safes in case anything goes wrong.

This shows that 3D printing space station modules is definitely a possibility. If robotics continues to develop this process could become entirely automated and remove the need for human's altogether. However, with current technology, fully utilising asteroid resources requires humans nearby for processing and maintenance (Made in Space, 2017). Furthermore, removing the need for humans in space goes outside the scope of this thesis as a human-centric exploration of habitability in space.

Additive manufacturing will only be considered for the construction of components beyond the initial processing facility and program requirements.

Figure 52. A production line in space.

Figure 53. External 3D printer

Figure 54. Internal 3D printer

5.3.2 CONSTRUCTION CONCLUSION

This analysis has shown that a standard production line type construction is not feasible in outer space. It has also shown that 3D printing is a very real possibility for the construction of space modules however; 3D printing a whole space station in orbit is still a ways off.

For this thesis, the station will be constructed as modules on the Earth and docked in orbit. This is to be augmented by the use of 3D printing in the construction of the interiors and the addition of further modules beyond the initial station design.

As modules are launched from the Earth, they require a specific rocket payload. This will set the limits for modules dimensions and define how many launches are necessary for the stations completion. The following is an analysis of various rocket payloads and the selection and definition of the payload restriction for this thesis.

Figure 55. SpaceX. (2019) Starship| First test Vehicle

5.4. MODULE DEFINITION

5.4.1 ROCKET PAYLOAD COMPARISON

5.4.2 BIG FALCON ROCKET PARAMETERS

5.4.3 MODULE PARAMETERS

5.4.4 TEMPLATE SHEET

This sub-section is a comparison of several rockets and their payloads. From this a rocket is selected and the module parameters are defined.

5.4.1 PAYLOAD COMPARISON

	manufacturer	Payload (KG)			Cost (US Millions)	Service Dates	Payload Dimensions	Reference
		LEO	GTO	TLI				
Saturn V	Boeing, North American, Douglas (USA)	118,000		47,000	\$185	1967-1973	6.4m	(NASA 1964, p. 475)
Space Launch System (SLS)	Orbital ATK, Boeing, United Launch Alliance, Aerojet Rocketdyne (USA)	70,000 - 130,000		26,000 - 45,000		~2020	286m ³ - 906m ³	(NASA 2018)
Big Falcon Rocket	SpaceX (USA)	100,000+		100,000+		~2020	9m x 55m (Starship) +1000m ³	(SpaceX 2017, "Making life multiplanetary")
Energia	NPO Energia (USSR)	100,000			\$240	1987-1988		(Zak 2018)
Falcon Heavy	SpaceX (USA)	63,800	26,700		\$90-150	2018 - present	5.2m x 13.1m (Fairing)	(SpaceX 2017, "Falcon Heavy")
Falcon 9	SpaceX (USA)	22,800	8,300		\$61.20	2010 - present	5.2m x 13.1m (Fairing)	(SpaceX 2013)
Long March 5	China Academy of Launch Vehicle Technology (China)	25,000	14,000	8,000		2016 - present		(Space.com 2012)
STS Space Shuttle	Alliant, Martin Marietta, Rockwell (USA)	24,400	3,810		\$450	1981-2011	4.5m x 37.2m (Payload bay)	(NASA 2017)
Delta IV	United Launch Alliance (USA)	23,040	13,130	9,000		2002 - present	5.1m x 40.8m (Second Stage)	(Krebs 2019)
UR-500 Proton	Khrunichev (USSR / Russia)	23,000	6,920	5,680	\$65	1965 - present	4m x 9.7m (Fairing)	(GAO 2017)
Ariane 5	Airbus (EU)	21,000	10,735		\$165 - \$220	1996 - present	5.4m x 4.7m (ECA Fairing)	(Federal Aviation Administration 2009)
Ariane 6	Airbus, Safran (EU)	21,500	11,500		\$115	~2020		(Federal Aviation Administration 2009)
H-II, IIA & IIB	Mitsubishi (Japan)	19,000	8,000		\$90 - \$112	1995 - present		(Mitsubishi 2014)
Titan I,II,III,IV	Martin Marietta (USA)	21,900	5,773	8,600	\$350	1959-2005		(Krebs 2018)
Atlas V	United Launch Alliance (USA)	18,850	8,900	2,807	\$109 - \$153	2002 - present	4.2m x 11m (Fairing)	(United Launch Alliance 2019)

In Development

Active

Retired

Due to its immense payload advantage and re-usability SpaceX's 'Big Falcon Rocket' is the optimum rocket for the construction of an orbital asteroid processing facility.

5.4.2 BFR PARAMETERS

SpaceX's Big Falcon Rocket is broken into two parts, the Super Heavy Rocket and the Starship. SpaceX's promotional videos and graphics indicate that the payload section of the Starship is roughly 25m of the overall 55m (45%) (2018) (Appendix D).

While this is a tapered cone SpaceX have confirmed that they are developing a payload specific variation of the Starship (citation). This will be designed for hauling space station components and larger payloads into orbit.

The following drawing is an approximation of an allowed geometry. The Starship is 9m in diameter. To allow for tolerances the proposed module is 8m in diameter. A 15m long module would fit within the existing Starship hull. If the fairing bows out towards the base (such as it does on the SpaceX Falcon Heavy) this could be estimated to allow for up to 20m without increasing the overall length of the Starship component.

Alternative Fairing Form

Minimum Fairing Form

Starship Form

PROPOSED MODULE SIZE
1:300 @ A3

BIG FALCON ROCKET ELEVATION
1:400 @ A3

STARSHIP SECTION
1:300 @ A3

5.4.3 MODULE PARAMETERS

MODULE SECTIONS
1:200 @ A3

MODULE ISOMETRIC
1:200 @ A3

From this established module size an A3 template sheet was created. This has been used for scale experimentations looking into what can fit within this module and how the cylindrical geometry could be used and arranged.

5.4.4 TEMPLATE SHEET

Figure 56. Phase 1 - Hub Interior

6.0 PHASE 1

6.1 SKETCH EXPERIMENTS

6.2 PHASE TWO DESIGN

This section documents the development of the first, conceptual, phase of design for this thesis.

IF

CM weighs 10,000 #
SM weighs 50,000 # (Full)
Total 60,000 #

and if a 2-stage Sat V
can lug 220,000 # payload
everything above S-II into a
low orbit; and if all "shells" incl. the
high another 20,000 #,
then "Space station equipment
module" may still weigh
220,000
- 80,000
140,000 # (incl. RCS)

Sat. V converts
into a S-II
space station
by means of
a cylindrical,
movable
"equipment
module"

WV
11/29/64

Space station
equipment module
in boost flight position
(Note ideal serviceability
during prelaunch preparation)

S-IV B "shell", I.V. and adapter
are removed for activation
of S-II stage as
orbital station.

After injection into orbit
and subsequent complete vent
of S-II hydrogen tank, equipm
module is moved (hydraulically
into hydrogen tank, converting th
latter into space station.

Expandable platforms (exte
from central module

Insulated walls

6 ft man

S-II stage

S-II surface, covered
with solar cells, can
easily provide 5 kW power
even if station is not
attitude-stabilized.

Common
may be used
for continued
oxygen storage

Apollo (or
Gemini)
docking cone.

Room for
antennas, windows,
additional docking cones
etc.
To get from
Apollo or Gemini into
space station, astronauts
pass through this 10 ft tunnel.

Space station
"equipment module" in
final position
Accommodates environment.
Control equipment,
communications equipm,
search gear,
water supply,
oxygen and water
supply, sanit.

Equipment, food storage,
radiation "storm" shelter, etc etc

6.1 SKETCH EXPERIMENTS

1:200 @ A3

This sub-section is a series of sketch experiments using the template sheet
created in the previous section.

Figure 57. Braun, W. (1964) Sketch of a Saturn V fuel tank as a space station!

A hand-drawn floor plan of a space station module, oriented vertically. The plan is divided into several functional areas:

- Top Section:** A long, narrow corridor labeled "Lobby Space" runs vertically. To its left is a room labeled "Shower Hygiene". To its right is a room labeled "Docking".
- Middle Section:** A large rectangular area labeled "Med Bay" is on the right. To its left is a room labeled "Storage". Further left is a room labeled "Admin & Control" with a "Plant" area below it.
- Bottom Section:** A large rectangular area labeled "Add. Hvac Manufacturing" is on the left. To its right is a room labeled "Fuel" with "Electrolysis" and "Fuel" labels. Below the "Fuel" room is a room labeled "Recovery" with "CO2", "SO2", "NH3", and "Water" labels. Below the "Recovery" room is a room labeled "Devil" with "Rock" labels. Below the "Devil" room is a room labeled "Crushed + Soil" with "Rock" labels. Below the "Crushed + Soil" room is a room labeled "Pond" with "Rock" labels.
- Other Labels:** "H2O" is labeled near the "Med Bay". "A" is labeled near the "Admin & Control" room. "A" is labeled near the "Storage" room. "A" is labeled near the "Devil" room. "A" is labeled near the "Crushed + Soil" room.

A hand-drawn sketch in blue ink on a grid background. The central figure is a person in a dynamic, possibly dancing or performing pose, with one leg raised and arms extended. The person is wearing a simple top and pants. In the background, there is a sign that reads "Waste Management". The sketch is composed of loose, expressive lines, with some areas filled in with darker strokes. The overall style is informal and artistic.

Waste Management

Section A

Agriculture

Bicycle

Optimal security areas

6.1.1 CONCEPTUAL LAYOUT

1:200 @ A3

Figure 58. Conceptual Orthographic Rendering of the Phase One Design

6.2 PHASE ONE DESIGN

6.2.1 OVERVIEW

6.2.2 EXPLODED AXONOMETRIC

6.2.3 DRAWINGS

6.2.4 VISUALISATIONS

This sub-section is the documentation of the first phase of design for this thesis. It begins to lay the foundational concept of the later designs in this thesis.

6.2.1 OVERVIEW

This design was modelled after the conceptual layout proposed in the previous section. It is a modular station with two rings of docked modules. Each module is designed to fit within the BFR payload bay as defined in section 5.3. They are 8m in diameter and protrude outward from a central module. On one side of the central module is a 50m long centrifugal leisure and exercise component. On the other side is a docking hub. The modelling of this initial phase is very basic but acts as the basis for the 3D generation tool discussed in Section 7.1.

6.2.2 EXPLODED

1. INTERNAL FORMS

Undulating internal forms would allow occupants more opportunity to propel themselves around open spaces. This would improve mobility and could allow more a larger variety of spaces to occupy.

2. AGRICULTURE

The most effective way to grow plants in space is Aeroponics. A Lightweight aeroponic system could be incorporated into the 3-dimensional modules of the space station to maximise growing area. Aeroponics can reduce water usage by up to 98%, fertilizer usage by 60% and pesticide usage by 100%. Furthermore, this technique has shown to maximise crop yields, produce food faster, and even yield more nutrient rich vegetables (NASA Center for AeroSpace Information, 2006).

6.2.3 SECTIONS

SECTION A: ALONG LIVING

1:200 @ A3 (Ring 2 shown in same plane for clarity)

3. FLOW

The modules are arranged to minimise crowding. A central hub space will ensure easy access to all modules in the station without the need to pass through occupied spaces as is the case aboard previous space station designs.

4. VIEWS

Having large openings is not possible in outer space due to the high level radiation environment. This could be remedied by the use of external cameras and flexible LED displays inside. However, these should not be a replacement for actual windows. This has been remedied in future designs.

SECTION B: ALONG PROCESSING

1:200 @ A3 (Ring 2 shown in same plane for clarity)

5. ORIENTATION

Down is established towards the central 'Faux planets.' These act as social hubs. Colour gradients are used to amplify to definition of down, similar to how the atmosphere on earth darkens at higher altitudes.

6. WALL CONSTRUCTION

The linings of this station are of a soft material, potentially silicone, to minimise risk of impact injury. These would be manufactured as modular panels and fixed to a lightweight bracket system to ensure easy replacement. This would also allow easy access to services running behind.

Habitability Rubric (How well has this design attempted to deal with these issues)

Isolation	Social	Int. Environment	Needs	Gravity
Diagram	Issue	Rating (0-4)	Description of mitigation strategies	
	Ergonomics, Scale & Field of Vision Can a human comfortably use these spaces. Are the spaces too big or too small? Are they perceived differently? How far can a person see?		The internal curvilinear forms allowed for a wide, unimpeded FOV. In General the spaces were very large in order to minimise feelings of confinement. The sizes were based on maximising the proposed module without considering how a person might interact with these spaces. <i>Future iterations will consider this with more sensitivity.</i>	
	External Views & Connection to Earth What are views out like? What are they of? Is there a connection to Earth? Communication to Earth?		Views out were considered through the external cameras however the positioning and framing of these views was not carefully considered. <i>Future iterations will consider not only the position of the views in the station but also the location of Earth, Moon & Sun in relation to these.</i>	
	Personalisation, Variability and Change Can spaces be personalised or changed? Is there any personal control? Can the station grow and change? Is there planting?		Planting in common areas allowed for aspects of the station to grow. The modular wall panels would also allow for the station to change however this was not considered deeply. There was no allowance for further modules to be added or changed. <i>Future iterations will expand on these while introducing variable geometry and personalisation in rooms etc</i>	
	Variety Are there a variety of spaces, textures and/or uses available?		The internal forms allow for a variety of spaces and uses however this is not strong (What could be done in these spaces? How? etc) There are a variety of different spaces and activities alluded to but not resolved. The colour and planting aid in this but once again is not very thought out. <i>Future iterations will resolve these spaces and activities.</i>	
	Privacy & Personal Space Is there private space /storage? How does this relate to other spaces?		There is an allowance for large private bedroom space as well as semi-private social spaces. These have not been resolved nor has their relationship to other spaces. There has been no consideration to proxemics. <i>Future iterations will resolve these spaces and consider more deeply how they, and the people within them, interact.</i>	
	Social, Dining & Leisure Spaces How do social / leisure spaces work? What activities can these spaces support how do these relate to other spaces		There is an allowance for large social, dining & leisure spaces. These spaces, and how they interact have not been resolved. <i>Future iterations will resolve these spaces and consider more deeply how they, and the people within them, interact.</i>	
	Mobility & Orientation How do occupants navigate the station?		Orientation through colour gradients and the 'faux planets' is good but could be pushed further. The internal curvilinear forms show a consideration for movement. The use of handles for mobility could be explored further. <i>Future iterations will push these concepts further and attempt to reconsider movement (either through handholds or otherwise).</i>	
	Gravity How do 0G spaces relate to Gravity spaces? What is the gravity like in the spinning module(s)?		There was a consideration for both 0G and 1G spaces. The 1G space was not resolved and the relationship between the two needs consideration. <i>Future iterations will consider the relationship between these spaces in more depth. This will also involve understanding how simulated gravity differs from typical gravity</i>	
	Health Facilities & Needs Sleeping facilities, hygiene, Availability of Fresh food, atmospheric conditions, day/night cycle, acoustics etc		0G Agriculture was considered with depth (public planting placements could be better). There was an allowance for health facilities but no resolution. The Atmosphere, lighting and acoustics were not considered. <i>Future iterations will resolve these spaces and consider more deeply the atmosphere, lighting and acoustics.</i>	

In summary this initial phase is a good starting point. All the issues were considered but very little is resolved. Orientation was good. The 'Faux Planets,' gradients, and central hub spaces are carried through to later designs.

In general, there is a need for greater sensitivity to what these spaces would be like, how people would interact with them and how they could change. In particular incorporating some variable elements would help the station feel more organic. More emphasis is needed on the scale of these spaces and what kinds of activities could be carried out within them.

No Mitigation of this issue	
Minimal Mitigation of this issue This issue has been touched on but not considered in depth	
Moderate Mitigation of this issue This issue has been considered a little but is not incorporated into the scheme / deeply resolved	
Good Mitigation of this issue This issue has been considered but could be pushed further and incorporated more effectively into the design	
Excellent Mitigation of this issue This issue has been considered in a unique and effective manner. It is incorporated into the overall scheme very effectively	

7.0 PHASE 2

7.1 3D GENERATION

7.2 MODULE CONFIGURATION EXPERIMENTS

7.3 PHASE TWO DESIGN DOCUMENTATION

This section explores six unique module configurations and defines how spaces can be oriented in zero-G. This includes a look at orientation systems informed by the ISS and completely different systems defining local vertical through spherical space.

Figure 59. Phase 2 Station exploded Axonometric

Figure 60. Depiction of various module connections

7.1 3D GENERATION

7.1.1 OVERVIEW

7.1.2 MODULE PARAMETERS

7.1.3 MODELLING CONCLUSIONS

This sub section documents the parametric modelling script developed for the iterations within this thesis.

7.1.1 OVERVIEW

At this stage the limitation of 2D sketches became apparent. These spaces needed to be understood in 3D. To do this a tool was created using Grasshopper in Rhino. This tool allowed for the easy iteration of differing module configurations and arrangements.

Grasshopper is a visual coding software used with the 3D, modelling program, Rhino. This software uses nodes with connected values to perform operations and generate geometry. These values can be connected to subsequent values ensuring dependency across the script. This means when one value is changed, eg the radius of a base module, anything else dependent on this will reflect that change simultaneously.

Below is an example of a node in grasshopper. This is a custom node created for the purpose of this thesis. As shown the module is based on a point, in this case 0,0,0 and a direction. Values, such as length and radius, are then inputted to form the geometry. This node then outputs the geometry as well as the necessary values for the connection of subsequent modules. For example the start point of subsequent modules can be defined through this ensuring that as this base modules changes so to do the connected ones.

Figure 61. Example node from within Grasshopper

Following this is a discussion of the specific parameters of each module and how they can be connected.

7.1.2 MODULE PARAMETERS

One starting point is the basic cylinder. This is defined by: length, radius, the length of the tapered ends, and the length of the docking ports at each end.

These base parameters can be manipulated. This includes individual values for each docking port, the ability to offset docking ports and adding a second port on the same face.

Modules, spherical or cylindrical, can then be added in parallel to the base module. These subsequent modules can be manipulated the same way as the base module. (the Sphere will be discussed at the end of this section).

Modules can also be added radially. This is defined by a plane cutting across the cylinder. These modules hold all the same manipulatable parameters as the base.

A sphere can also be used as the base module.

The sphere can have modules added radially in any axis defined by a plane. These are all manipulatable based on the base parameters.

7.1.2 MODELLING CONCLUSIONS

This same logic is applied to the interior fit out of the modules as well. The placement of floors, light rings, etc. are defined as proportions of the overall module length. Variable surfaces are placed on the grid coordinates of the internal module surfaces. These are then controlled by values for their X & Y coordinates.

This system of modelling is incredibly valuable in terms of a modular space station. Being able to easily manipulate and swap our modules allows the station to change to suit any further needs that may arise during its development. This is something that happened a lot with the ISS. Modules would be proposed and then removed at later dates. Furthermore, several different configurations were experimented with before the current one was determined. With this system all of these changed can be accommodated without losing existing work.

Across is a diagram of how modules can be connected in this system. These basic connections can lead to increasingly complex station configurations. For this thesis six possible configurations were created through experimentation. These will be discussed in the following section.

Figure 62. Module Configurations

7.2 MODULE CONFIGURATIONS

7.2.1 ORIENTATION

7.2.2 SINGLE PLANE CYLINDER

7.2.3 DUAL PLANE CYLINDER

7.2.4 VERTICAL CYLINDER

7.2.5 PHASE ONE REVISION

7.2.6 TRI-SPHERICAL BASE

7.2.7 SINGLE SPHERICAL BASE

This sub section documents the parametric modelling script developed for the iterations within this thesis.

7.2.1 MODULE CONFIGURATIONS

This design phase began with an exploration of potential module configurations. Each of these had unique reasons behind their layout which will be discussed in this section. Within these was an alternate form of orientation based on the ISS. As opposed to orientation defined as toward or away from a central axis (Axis-oriented), orientation could be achieved as a section across each cylinder (fig). Going forward this alternate orientation system was not utilised. An axis orientated station allows better for rotation, maximises module space and allows for modules to propagate at all angles from a central core.

While outside the scope of this thesis a deeper analysis of this system may find it to be better, for instance it more closely resembles the orientation of rooms as on Earth. In this case, design considerations for an axis-oriented station could easily be applied to this alternate system due to the parametric and modular design used in this thesis.

All orientations are based on the diagram below. Zenith is the local up, Nadir is the local down. Port is towards the Earth, Starboard away from Earth and Forward is towards the moon with aft away from the moon. Port, Starboard, Forward and Aft

Figure 63. Orientation Axis in orbit (person facing into page)

View From Earth
View Towards Earth

7.2.2 SINGLE PLANE CYLINDER

A flat configuration based on the ISS precedent. In this configuration all modules are arranged parallel in relation to the stations orbit. This would allow for a very strong orientation system. However, this configurations limits how modules can join within this plane. It also becomes for difficult to split and separate spaces within the modules while retaining a unified orientation across the station. In this configuration bedrooms may end up located along the effective "floor" or "ceiling".

View From Earth
View Towards Earth

7.2.3 DUAL PLANE CYLINDER

This configuration is similar to the 'Single Plane Cylinder' station. In this configuration however modules would be designed to allow connections at the top and bottom. This would result in a denser station design with many more pathways through it. A drawback of this scheme is the necessity to offset modules in order to fit so many of a single base. Because of this the arrangement in this modules could become more difficult.

7.2.4 VERTICAL CYLINDER

This configuration is also based on the ISS orientation system. However, in this configuration up (zenith) is always towards the Earth (Port). This station would have large central cylinders with modules splayed out from the sides. In this way it reduces the limitations shown in the 'flat cylinder' and 'two tier flat cylinder' configurations while retaining the simpler external orientation

ORIENTATION KEY:

Starboard

Aft

Nadir

Port

Forward

Zenith

View From Earth
View Towards Earth

7.2.5 PHASE ONE REVISION

This configuration was based on improving upon the phase 1 design. This saw the addition of a 3rd ring to better deal with the program requirements.

SECTION A: FORWARD - AFT
1:400 @ A3

SECTION B: PORT - STARBOARD
1:400 @ A3

View From Earth
View Towards Earth

7.2.6 TRI-SPHERICAL BASE

This configuration was based on the idea of having a sphere for each programmatic base. A spherical base allows a space to be oriented in all directions away from a centre – this maximises the usable space in the central core. A spherical base also allows for modules to come off from all directions.

ORIENTATION KEY:

Starboard

Port

Aft

Forward

Nadir

Zenith

7.2.7 SINGLE SPHERICAL BASE

Similar to the triple spherical base this station can be oriented in all directions away from the centre. A benefit to this single spherical base is allowing for movement around the station all centred around a single point. This allows for a clearer orientation system and for a single meeting point.

View From Earth
View Towards Earth

SECTION A: FORWARD - AFT
1:400 @ A3

SECTION B: PORT - STARBOARD
1:400 @ A3

7.1.2 CONFIG CONCLUSIONS

Each of these configurations has its benefits and negatives. There is no real 'best' module configuration. However, the 'single spherical module' is the one most favourable for this thesis. This is because;

This configuration utilises an orientation system based off the central sphere. This allows for modules to be docked in either direction and still retain a consistent Zenith – Nadir.

Similarly the spherical base acts as a spacious and unique central hub. The sphere allows people to flow all the way around the space organically. A single sphere also allows for a singular hub space as opposed to the tri-sphere, which breaks this up.

In relation to this, the sphere allows for the station to rotate on its central axis. Provided the major modules are arranged in one axis around the sphere this should not have a major effect on any secondary modules arranged in odd directions.

Finally the sphere allows for a more unique exploration of zero-G habitation in relation to the 'single plane', 'dual plane' and 'vertical cylinder' configurations. These configurations are based on the ISS orientation system, which may be the better option, however; this axial orientation system is unique to this thesis and may provide a more interesting result.

Figure 64. Phase 2 Station

Rotation

Assembly

In developing the spherical station, a secondary spherical base was added to act as the hub for processing and management. While this weakens the point of having everything coming off a central sphere, it makes the arrangement of spaces much easier and allows for a separation of the living and working programs within the station. In this iteration, the entire station would rotate.

This would be a very slow rotation, similar to Tsiolkovsky's 1903 proposal. Under this small rotation, objects and people would very slowly move towards the outer edges of the station when left floating. This would subtly influence the sense of orientation in the station.

Orientation is further defined with colours. Green, and other earth tones, signify down while blue signifies up. This mimics the colours already associated with up and down on Earth and is represented through bands of colour in the living and bedroom modules.

7.3.2 EXPLODED

AGRICULTURE MODULES

Within each agricultural module, the internal surface would be morphed, creating protrusions to house the aeroponic planting system (as well as other services). In this way the agricultural modules take on a very natural geometry, reminiscent of rolling hills or the human body. At the lowest points of the internal surface would be the grid & clip system. This would allow for mobility as well the fixing of agricultural equipment such as lighting, storage and harvesting utensils.

Each agricultural module could be configured to best suit specific planting needs, such as lighting and atmospheric qualities. In this way, each module acts as a different biome allowing for a larger variety of planting and spatial qualities. These spaces would not simply be for the growing of plants but also act as an all-encompassing natural environment in amongst the mainly artificial station.

1 Agricultural Module

7.3.3 DRAWINGS

GRID / CLIP SYSTEM

Across the station would be grid bays constructed of silicon rope. These would allow for modular furniture to be easily fixed and moved around the station. This would help to improve variability within the station effectively allowing furniture to be re-arranged the same as in Earthen homes. New components could be printed on the station to fit any new needs that may arise. This would encourage personalisation within the spaces.

A simple clip system, similar to a Lego hand, would suffice to fix components to this grid. The lack of gravity reduces the need for strong connections. However this clip system will be reconsidered in future designs.

Figure 65. Grid / Clip System

SECTION C: ACROSS LIVING MODULE
1:100 @ A3

VARIABLE SURFACES

Movable surfaces, based on the grid & clip system, would be utilised in the living module. These surfaces would be stored in compartments at each end of the module. The surfaces, and compartment lids, could easily be moved around in 0G to allow for quick and easy re-arrangement.

These surfaces would act as spatial separators. This separation would allow for a variety of spaces, and uses, to exist at once within the living module. Residents would be able to create their own social, or semi-private, spaces to inhabit and use as they like. These could then be easily re-arranged throughout the working day to accommodate a variety of uses, such as dining, leisure and acrobatics.

Figure 66. Variable Surfaces

SPHERE ASSEMBLY

The huge 12m diameter central sphere would be constructed as 8 pieces spliced together across 2 launches. This is quite a monumental task and will need to be reconsidered in further designs. Having splice joints across airlocks could also result in costly design requirements. However, the benefit of this is a unique and huge open hub space. This will help reduce isolation issues and help circulation around the station.

Figure 67. Sphere Assembly

ORIENTATION KEY:

Starboard	→	Port
Aft	→	Forward
Nadir	→	Zenith

Habitability Rubric (How well has this design attempted to deal with these issues)

Isolation	Social	Int. Environment	Needs	Gravity
Diagram	Issue	Rating (0-4)	Description of mitigation strategies	
	Ergonomics, Scale & Field of Vision Can a human comfortably use these spaces. Are the spaces too big or too small? Are they perceived differently? How far can a person see?		The central node and the holes through the orb allow for a long, unimpeded FOV. There is a good mixture of large (hub, living room), medium (corridor, agriculture), and smaller spaces (bedrooms). More detailed consideration of human scale is needed. <i>Future iterations will consider this with more sensitivity.</i>	
	External Views & Connection to Earth What are views out like? What are they of? Is there a connection to Earth? Communication to Earth?		Views out have been well considered through the framing of celestial bodies. Though minor, there is not much consideration of the position of the Sun. <i>Future iterations could consider the sun's movement and include spaces that interact with this.</i>	
	Personalisation, Variability and Change Can spaces be personalised or changed? Is there any personal control? Can the station grow and change? Is there planting?		The grid system allows for a huge amount of variability and personalisation. However, the variable nature of the spaces takes some agency away from the design. The overall growth of the station has not been well considered. <i>Future iterations will refine the grid system further. Station growth also needs to be considered.</i>	
	Variety Are there a variety of spaces, textures and/or uses available?		There is a good variety of different spaces in the station. In particular having the bedroom modules offset creates a different space to centrally docked modules. There is a need for more consideration around textures within the station. <i>Future iterations will add to the variety of spaces and consider the tactile experience more deeply.</i>	
	Privacy & Personal Space Is there private space /storage? How does this relate to other spaces?		The bedroom spaces allow for ample privacy and storage. Their relationship with other spaces is considered somewhat through the added threshold however this could be stronger. There is also an allowance for semi private spaces in the living room however this could be refined. <i>Future iterations will consider more deeply how these spaces co-exist.</i>	
	Social, Dining & Leisure Spaces How do social / leisure spaces work? What activities can these spaces support how do these relate to other spaces		Social and leisure spaces are good. There is a consideration for activities that could be carried out in them. However, this needs to be deeper. There is an allowance for dining within the living modules however this needs refinement. <i>Future iterations will refine these spaces and resolve the food prep module.</i>	
	Mobility & Orientation How do occupants navigate the station?		The resolution of the central orb is good but needs to more clearly indicate which port is which. The coloured stripes aid orientation. The grid allows most of the station to be traversable. However, more consideration is needed around movement. <i>Future iterations will make the station for navigatable and refine movement through the spaces.</i>	
	Gravity How do 0G spaces relate to Gravity spaces? What is the gravity like in the spinning module(s)?		There was a consideration for both 0G and 1G spaces. The 1G space was not resolved and the relationship between the two needs consideration. <i>Future iterations will consider the relationship between these spaces in more depth. This will also involve understanding how simulated gravity differs from typical gravity</i>	
	Health Facilities & Needs Sleeping facilities, hygiene, Availability of Fresh food, atmospheric conditions, day/night cycle, acoustics etc		Agriculture is nicely resolved - needs some more consideration into how planting bays would actually work. There was an allowance for health facilities but no resolution. The Atmosphere, lighting and acoustics were not documented. <i>Future iterations will resolve these spaces and consider more deeply the atmosphere, lighting and acoustics.</i>	

In summary this second phase was a great improvement on phase 1. The design was more refined and the solutions to the problems of variability, variety, scale and leisure spaces were well considered. However in some cases these solutions need more finesse. The grid system is great but in some spaces, like the bedroom, there is simply too much going on. The variable nature of the space also subtracts from the actual design. The documentation of these spaces through 3D images and animations was successful. However, sections need to have more depth in order to properly understand these complex spaces.

Moving forward these spaces will be refined. Missing areas, such as the work spaces, gravity module and the hygiene spaces will be designed and the scheme will be documented with more detail and rigour.

No Mitigation of this issue	
Minimal Mitigation of this issue This issue has been touched on but not considered in depth	
Moderate Mitigation of this issue This issue has been considered a little but is not incorporated into the scheme / deeply resolved	
Good Mitigation of this issue This issue has been considered but could be pushed further and incorporated more effectively into the design	
Excellent Mitigation of this issue This issue has been considered in a unique and effective manner. It is incorporated into the overall scheme very effectively	

8.0 PHASE 3

8.1.0 OVERVIEW

8.2.0 EXPLODED AXONOMETRIC

8.3.0 DRAWINGS

8.4.0 REFLECTION

This section documents the third and final phase of iterations for this thesis. Beginning with a rough overview and proceeding into a series of sections, diagrams and perspective visualisations.

Figure 68. Phase 3 Station

8.1 OVERVIEW

The phase 3 station was developed to include a design for the spin module, hygiene module, kitchen module, and the admin & navigation module. This also saw the inclusion of Cupola modules, based on the ISS module of the same name, and airlock modules for human egress. These modules come off the spherical base at angles, however the rotation will not greatly effect these as they are relatively short.

This phase also involved the refinement of existing spaces. In particular, the capabilities of the grid system were explored in much greater depth. The core space was also refined to better reflect its role as the defined up.

Looking In

View of the Earth & Moon

View from Spin Module

8.2 EXPLODED

VOLUMETRIC SCALES

In order to minimise spatial monotony the station has a considerable variety of volumes. Not only do these vary in total volume but also in geometry. This helps to provide distinct and unique spaces. The below table showcases some of the major volumetric differences across the habitat.

Figure 69. Volumetric Scales Chart

8.3 DRAWINGS

SECTION A: ALONG PORT - STARBOARD
1:200 @ A3

Core

CUPOLA 2.0

Research into the ISS showed that many astronauts cited the cupola module as their favourite place to be on the station. A similar space has been designed protruding from the core in four directions. This increases views out of the station and allows users a 360 view out instead of the flat windows used in the previous phase.

2. Cupola to Station

3. Cupola to Earth

4. Agricultural Module

PRIVACY SCALES

Similar to the volumetric variety aboard the station is a variety of privacy conditions. The open living area and core are fully social, encouraging interaction amongst the whole station. The bedroom corridors encourage interactions amongst those utilising those spaces. The variable spaces in the living room allow inhabitants to pull up fabric walls creating social spaces for smaller groups. Finally, the bedrooms are completely private spaces.

Figure 70. Privacy Scales Chart

MOBILITY

Movement, or the lack thereof, is undertaken using several methods aboard the station. The grid system acts as an elastic hand and foot hold. Similarly, furniture and fixtures are designed to include 'graspable elements.' For example, light rings have a small groove along either side which allows them to be grabbed. Similarly, planter boxes and other bits of furniture will have similar grooves and handles (Fig 72.) to allow everything in the station to be graspable. Finally, for times when an inhabitant must stay still they can use variable foot loops. These clip onto the grid system and rotate in 3 Axes.

Figure 71. Mobility Diagrams

ORIENTATION KEY:
 Starboard → Port
 Aft → Forward
 Nadir → Zenith

SECTION C: ACROSS PROCESSING HUB
 1:200 @ A3

5. Bedroom Corridor (to Nadir)

WORK SPACES

These spaces are important for station administration, navigation to potential NEA's, and the overall management of the station. The admin office would be an open space with room for up to six workstations and two meeting spaces with the option of becoming a single large meeting space

These workstations would be fully variable; allowing for the customising of ergonomic considerations such as, desk, foot and monitor height / angle, and for the personalisation of one's desk space. This could also include privacy buffers between desk spaces.

The navigation deck sports four large consoles for the control of the stations ECLSS systems and other digital elements. These consoles would also be used for locating NEA's, commanding miner drones, docking of visiting ships, detection of potential hazards and control of the solar array.

6. Admin Office

7. Navigation Deck

SECTION A: ALONG PORT - STARBOARD
1:200 @ A3

SECTION A: ALONG PORT - STARBOARD
1:200 @ A3

HYGIENE FACILITIES

This phase saw the inclusion of hygiene facilities at the end of each bedroom module. This includes four toilets in each block of 15 people and 2 wash rooms. The equipment in these spaces would need to be specifically designed. This would involve vacuum powered toilets, water recycling systems and water dehumidifying capabilities in the washrooms.

SLEEP

There are two proposed methods for sleeping in this station. The first is based on the current ISS configuration; this is effectively a padded closet with a sleeping bag clipped to the wall, which creates an enclosed space for a person to sleep. An alternative to this is a 'space hammock'. This would act similarly to a hammock on Earth but instead of gravity, the inhabitant would produce to force to pull the hammock snugly around them. This could simply be a drawstring with a quick release mechanism similar to venetian blinds.

Figure 72. Sleeping Options

BEDROOM VARIABILITY

Pictured across is an empty bedroom. From this, inhabitants could clip on wall panels, screens, storage boxes, planter boxes, desks, agricultural panels and just about anything else that could be created on the station through additive manufacturing. This allows the users to fully personalise their bedrooms and rearrange them at will. Ideally, this would result in several unique spaces and create a culture of space building - with people sharing their ideas and tips for creating great bedrooms.

SECTION E: ACROSS BEDROOMS
1:100 @ A3

SECTION D: ACROSS HYGIENE
1:100 @ A3

9. Minimalist Bedroom

11. Circular Bedroom

10. Personalised Bedroom

12. Green Bedroom

13. Bedroom Corridor (to Zenith)

KITCHEN MODULE

This phase saw the inclusion of a food storage area. This module includes a view out of the Earth and moon, emulating the classic kitchen bay window often seen on Earth. This module is split in thirds: one third for storing dry foods, similar to current ISS solutions, one third would store the fresh fruit and vegetables from the agricultural facilities, the final third would be for the preparation of food.

This could include food heaters, hydrators, baking equipment, space for chopping fruit and vegetables and any other technology available to the station. Any new equipment could simply be slotted into the open space in the surfaces.

14. Food Module

LIVING ROOM ACTIVITIES

Part of the revision of the grid system was an exploration of what spaces could be created in the huge living module. This included the development of a mixed space incorporating more private social spaces at the zenith, open performance and lounging spaces in the middle and dining space to the nadir, close to the food module. This space could be a constantly evolving and varied space to suit the regular day to day needs of the station. Alternatively the entire space could be re-created into several variations using the modular grid system.

This includes:

An acrobatics space, based on comments of Skylab and ISS crew about their enjoyment of zero-G acrobatics.

An entertainment space, either for viewing media or performances. This is inspired by the tradition of movie viewing and music playing already existent on the ISS.

Or finally a banquet hall for full station shared meals on occasions such as Christmas thanksgiving or any other cultural events. Once again based on the tradition of shared holiday meals aboard the ISS.

SECTION F: ACROSS LIVING
1:100 @ A3

SECTION G: ACROSS KITCHEN
1:100 @ A3

15. Mixed Living Space

17. Acrobatics Space

16. Entertainment Space

18. Banquet Space

19. Mixed Living Space (From Top)

SIMULATED GRAVITY

Rotational gravity differs greatly from gravity on the Earth. There has not been a huge amount of research into this topic as it is quite difficult to test on Earth. However, more recently the topic has been revisited, in particular by Theodore Hall. Hall has written a huge amount on the architectural implication of centrifugal force. This includes how to visualize artificial gravity and several methods of mitigating issues in artificial gravity. These include:

- A floor surface must be curved so that the local vertical of any point in perpendicular to the tangential velocity (Hall, 1995).
- It must be apparent which way the space is rotating at all times. This ensures people do not fall into a false sense of security and forget they are moving, stand up and promptly fall back down. Solution to this are having visual cues, such as arrows to show this rotation (Hall, 1999).

- In smaller radii objects will not fall straight down but will fall on a parabolic arc (Hall, 1995). In the design of the gravity module the walls have been sloped to align with this trajectory. This means any object falling will fall parallel to the wall giving the illusion of a straight line. Similarly this arc is shown through the light rings along the walls. This also aids in showing the direction of rotation.
- Ladders must be used on opposite sides for ascent and descent (Hall, 2006). Descent must occur on the frontward facing side and vice versa. This ensures the Coriolis force does not pull users away from the ladder but instead pushes them into it for this gravity module this has been accomplished through a ladder on either side. However this could also be accomplished with a single lade approachable from either side.
- Any view out, showing their velocity, could cause disorientation or motion sickness as such only screens, displaying a virtual view are used in this space.

Figure 73. Comfort Index. Hall, 2006 "Artificial Gravity Visualisation, Empathy and Design"

Figure 74. Curved Floor Surfaces under Centrifugal Gravity

Figure 76 depicts the trajectory of an object dropped at eye height in centrifugal gravity. Due to the support force of the floor, a person moves along with the rotation however, a falling object will not. As shown a fallen object moves in a straight line until it intersects the floor. This point of intersection is somewhat behind where the person now is. This demonstrates how the centrifugal force is felt. It is not a straight line but a curve sloping retrograde to the angular velocity (figure 77).

This concept has some big implications for vertical movement in space. In particular ladders can become far more difficult. As a person climbs up the ladders their relative rotation decreases, thus increasing their relative velocity. This creates the effect of the ladder sloping in the direction of the rotation, almost as if the person were climbing the underside of a cliff (fig 77). This means ladders must be designed to accommodate this.

To deal these issues the walls of the gravity module have been curved to reflect the true nature of up and down in this space. Similarly ladders are curved and defined as two separate ascent and descent ladders. The floor surface is also curved along the circumference of the rotation arc. The light rings are curved in relation to the forces indicating the nature of 'gravity' in the space. More obtuse iconography is used along the tops of walls as a square denoting the face against the rotation and a circle for the face in the direction of the rotation. Similarly, the floor patterns indicate an abstracted comet

Figure 76. Experience of Gravity. Hall, 2006 "Artificial Gravity Visualisation, Empathy and Design"

Figure 75. Falling Object Trajectory under Centrifugal Gravity

SECTION K: ACROSS GRAVITY LOUNGE
1:100 @ A3

SECTION J: ACROSS SPIN MODULE
1:100 @ A3

20. Gravity Lounge

21. Gravity Lounge

Habitability Rubric (How well has this design attempted to deal with these issues)

Isolation	Social	Int. Environment	Needs	Gravity
Diagram	Issue	Rating (0-4)	Description of mitigation strategies	
	Ergonomics, Scale & Field of Vision Can a human comfortably use these spaces. Are the spaces too big or too small? Are they perceived differently? How far can a person see?			
	External Views & Connection to Earth What are views out like? What are they of? Is there a connection to Earth? Communication to Earth?			
	Personalisation, Variability and Change Can spaces be personalised or changed? Is there any personal control? Can the station grow and change? Is there planting?			
	Variety Are there a variety of spaces, textures and/or uses available?			
	Privacy & Personal Space Is there private space /storage? How does this relate to other spaces?			
	Social, Dining & Leisure Spaces How do social / leisure spaces work? What activities can these spaces support how do these relate to other spaces			
	Mobility & Orientation How do occupants navigate the station?			
	Gravity How do OG spaces relate to Gravity spaces? What is the gravity like in the spinning module(s)?			
	Health Facilities & Needs Sleeping facilities, hygiene, Availability of Fresh food, atmospheric conditions, day/night cycle, acoustics etc			

For this final critical reflection the reflection text has been moved from the rubric itself and onto this page for clarity.

ERGONOMICS, SCALE & FIELD OF VISION

Ergonomics and scale vision have not changed much from Phase 2. The various volumetric scales and have been defined much more clearly and there has been some ergonomic consideration in work spaces, bedrooms and the living module. After placing real people into spaces, it became very clear that the workstations are not very ergonomic. **Going forward there MUST be a stronger relationship to use and ergonomics in the design of workspaces and the rest of the station.**

EXTERNAL VIEWS & CONNECTION TO EARTH

External views are not much different. The cupola modules allow for a wider field of vision beyond the station and even allow views back at the station. **In the future, consideration needs to be given to communication beyond the station. There are currently no allocated facilities for this.**

No Mitigation of this issue	
Minimal Mitigation of this issue This issue has been touched on but not considered in depth	
Moderate Mitigation of this issue This issue has been considered a little but is not incorporated into the scheme / deeply resolved	
Good Mitigation of this issue This issue has been considered but could be pushed further and incorporated more effectively into the design	
Excellent Mitigation of this issue This issue has been considered in a unique and effective manner. It is incorporated into the overall scheme very effectively	

PERSONALISATION, VARIABILITY AND CHANGE

The grid system has been nicely resolved in this iteration. The representation of the bedrooms shows a very strong sense of personalisation through specific arrangements. Similarly, the living room configurations show a much better image of how inhabitants could utilise the large space. However, this level of specific design and personalisation would require many resources to be constructed on the station and would require a huge amount of storage space when not in use. **Future iterations also need to better consider how the station might grow and change over time.**

VARIETY

Variety is greatly improved by the bedroom and living room configurations. Furthermore, the textural variation showed behind the grids, planters, and in bedrooms helps to make the spaces feel less artificial. This could resolved further with research into actual materials and using more materials in other areas. This iteration also included several more spaces, such as the admin spaces and gravity module. These spaces help to include a greater variety of spatial experiences on the station. The gravity module in particular is in stark contrast to the rest of the station while retaining a similar character. Unfortunately there is still no design for the med bay, processing hub, processing modules, docking module, or plant / waste management module. **Future iterations will resolve these spaces and define the use of materials aboard the station.**

PRIVACY & PERSONAL SPACE

The private spaces and their relationships have not changed much beyond Phase 2. More consideration is needed in terms of thresholds and how they could work in these spaces. **Future iterations will consider thresholds in more depth.**

SOCIAL, DINING & LEISURE SPACES

The dining and food preparation areas are far more resolved in this iteration. In particular, the banquet hall configurations in the living room show how the whole station could interact en mass. **Future iterations will consider a greater variety of activities in greater depth for these spaces.**

MOBILITY & ORIENTATION

Mobility has been improved by the use of foot pads and the indication of hand holds in the design of furniture aboard the station. These ideas still require a large amount of resolution. In particular movement through the station and ensuring there are no 'blind spots' where inhabitants could get stuck. **Future iterations will consider movement more deeply and further resolve mobility solutions.**

GRAVITY

The gravity spaces show a great understanding of the issues associated with centrifugal force. The curved surfaces and design language help to reinforce the direction of the spin subconsciously in order to minimise risk of falling over. There is still little consideration of the lift and the access area for this. **The transition from zero-G to a gravity environment is very important will need careful attention in future designs.**

HEALTH FACILITIES & NEEDS

These aspects need to be understood in much greater depth before they can be considered in the design. Sleep has been considered through the design of space hammocks and closets. Similarly, the agricultural spaces feel much more resolved in terms of their use. However, this rubric category is difficult to fulfil through architecture, at least at the current level of development. **Future iterations need to mostly resolve the design of a station and consult experts in order to fulfil the intent of the evaluation category.**

DESIGN CONCLUSION

Overall the design of this final phase is very good. The circulation core in particular is very nice space now compared to its last iteration. However, there is a lot of detail missing. In particular, thresholds between modules and rooms are not very well understood. Storage is also a real issue with only minimal space allocated for the storage of unused components in the living room and bedrooms. The design of this station includes some great concepts for mitigating habitability issues. However, these are not all particularly resolved.

The overall aim of this thesis was to "Demonstrate designed solutions to known issues of habitability within the rigorous constraints of constructing a space station. "This aim was certainly accomplished through the design and emphasises how much needs to be considered in the design of space habitation.

The design itself however is somewhat lacking. Somewhere along the line, classic architectural principles of proportion, materiality and scale were lost. Part of this was through the limited methods used - sketches and parametric modelling. In revisiting this, a greater variety of design methods MUST be employed.

Architecture in space is still architecture however there are much fewer precedents. Designing in space is a very new field. Design work, like this thesis, is exceedingly important for its development and adds greater precedents for future work to draw from. Eventually the same level of resolution we see on terrestrial buildings could be applied in orbit.

Figure 77. NASA. (1966) Earthrise 1966

9.0 REFLECTION

- 9.1 REVIEW
- 9.2 METHODOLOGY & SCOPE
- 9.3 RESULTS
- 9.4 CHALLENGES
- 9.5 FINAL REMARKS

This section is a reflection of this thesis as a whole.

9.1 REVIEW

This thesis has been an exploration of architecture's role in human life beyond the Earth. The prime concern of this is the creation of habitable environments in space. While space programs have been aware of this since the Skylab missions in the 1970's those projects, and their successors, were heavily limited by engineering requirements and cost. These spaces, designed for highly trained astronauts, were only inhabited for short periods. As it becomes easier to get into orbit, through better technology and the privatisation of the space industry, architecture's role becomes all the more important. This thesis has investigated how the creation of habitable environments differ in the hostile vacuum of space through research into habitability.

9.2 METHODOLOGY & SCOPE

RESEARCH

The methodology of this thesis was very limited. This thesis's understanding of habitability was limited to historical research, a case study of the ISS and logical argumentation through a literature review of habitability.

The historical research provided a solid background in the concept of space habitation. This helped to augment the habitability research. However, only a few of the concepts established were carried through. While it was interesting to understand the origins of space habitation, it was not inherently necessary for this thesis.

The case-study of the ISS was incredibly valuable. Much of this thesis stems directly from concepts drawn from this study. However, it would have been good to have carried out further case-studies on other proposed future space habitation, such as Boeings B330 inflatable habitation, or theoretical designs such as the Stanford Torus. These could have contributed to more unique solutions of habitability issues. This thesis, in many cases, built on the established principles aboard the ISS.

The arguments presented by the research into habitability were very compelling. These were deeply researched and justified through multiple sources. The majority of influence in this thesis stems from these initial arguments.

These arguments could have been greatly strengthened by using more methods of justifying habitability's importance. This could have included qualitative research through interviews or surveys, particularly of those who have inhabited restrictive environments. This would have allowed a better, more personal, understanding of the requirements in these environments.

DESIGN

The methods used to design in this thesis were limited to sketching and 3D modelling. These produced some great results. In particular, defining the module size on a template sheet allowed for very easy sketch iterations and was used throughout the thesis. The 3D modelling system created within Grasshopper also allowed for easy iteration and manipulation of module configurations.

More varied methods would have allowed for more varied results. For instance, physical modelling, or other mixed media design, would have brought with it a unique interpretation of these modular spaces and potentially resulted in some uniquely valuable insights.

SCOPE

The scope of this thesis was quite limited. This was in order to better understand the needs of a specific program. This resulted in a greater depth of understanding of the issues this program would face. However, this was only one interpretation of a habitable environment in orbit. Through research this thesis narrowed its design solutions down to a primarily modular station launched from Earth. However, a modular space station may not be the best solution. Perhaps the most habitable environment is created in orbit or one that constantly moves, creating an everchanging view.

This thesis limited itself to what was most applicable now in terms of cost, understanding and efficiency. However, there could be technological shift at any point resulting in newer and more exciting potential habitats. This limited scope resulted in a deeper understanding of a particularly realistic solution but held the design back from exploring more extraordinary solutions. This does not defeat the validity of this thesis' conclusions however.

9.3 RESULTS

RESULTS

Before the discussion of the main aim of this thesis, this will be a brief discussion of its secondary aim:

"Demonstrate how a (modular) space station could be 3D modelled using parametric design."

This was accomplished in two parts. The first was the development of the Grasshopper script used to model module configurations in this thesis. This script was particularly successful and ensured the modelling of this design was a relatively fast process. However, the script itself was somewhat flawed. In some cases, modules would break beyond certain limits and operations could take some time to load if they affect too many components. Going forward this script would need a considerable amount of revision, including looking into methods to minimise processing power required and refining the sub-components themselves. Overall, the script shows excellent potential for modelling modular space stations with ease. With further development, parametric modelling software, such as Grasshopper for Rhino, could become a powerful asset in the space industry.

The next step of this was documenting the use of the modelling system. This was successful through the documentation of the module connections but was lacking in terms of the interior fit-out. It is difficult to document such a process in a booklet. In the future, animations and videos would provide much better documentation tools for parametric modelling processes. These would greatly help in the primary aim of this thesis:

"Demonstrate designed solutions to known issues of habitability within the rigorous constraints of constructing a space station. "

This was accomplished in five steps. The first was to understand why a space station should exist in the first place. This was justified by a need for resources and resulted in the station's program – an asteroid mining facility. This program was potentially underutilised in the final design. However, an in-depth analysis of this program was outside the scope. The program sought to aid in specification of the site and definition of the number, and types of people needed; to this end, it accomplished its purpose. In the future, a deeper understanding of program, site, machinery requirements and exact crew specifications will be needed. This would allow for a far more resolved design in the production areas and the likes. Alternatively, there would be benefit to exploring alternative programs or even taking the idea of variable spaces to the next level, allowing the station to suit any potential need.

The next step was an analysis of habitability requirements in orbit. This was clearly defined as "a measure of how conducive an environment is to human life." This was extrapolated on and broken up into concepts of isolation, socialisation, needs, internal environment and gravity. This was then formed into a rubric which allowed designs to be self-evaluated within this thesis. The implications of this are discussed in the following 'conclusions' section.

Following this was an exploration of the more technical requirements of space habitation through different station types and construction methods. This allowed the thesis to justify its decisions in a technical manner and juxtapose these concepts with habitability requirements. The analysis of station types and the subsequent definition of the module restrictions was a substantial part of this step. This led directly to the creation of the Grasshopper script and greatly informed the final design. However, the analysis of construction methods was somewhat lacking. The justification of using a modular system was weak and sought only to limit itself. However, this thesis was very much an exploration of designing within limitations. The modular system allowed the station to be considered within finite dimensions allowing the design to flow naturally from this. As a result, the design is harmonious through its simple and shared geometry – though somewhat chaotic in the busier, more variable spaces.

While this fit for this thesis explored deigning within limitations, future work should explore the idea of stations created entirely in orbit. This type of station would have far more variables to consider however, this would allow a greater level of freedom, and creativity in how these problems could be dealt with.

Following this step was an iterative process leading into the final design. The limitations of this process has been discussed in the previous section. Aside from these limitations, the process itself explored several aspects of habitability. These were iterated primarily in sketch and then finalised in 3D model. These two methods worked fantastically in tandem and allowed for a considerable amount of exploration. However, there was much that was not considered. One major flaw in the iterative process in this thesis was the tendency to hold onto successful ideas. For instance, the central orientation orb was developed through the design process. However, an alternative to this was never really considered in depth. Ideas needed to be treated more fluidly and thrown away more easily. This would have resulted In several more, unique, iterations and experiments.

Finally, these previous steps were refined to their optimum point and shown as a demonstration of habitability mitigation methods. The documentation of these was somewhat basic. The renders worked really well as indications of how these spaces could be inhabited however, they did not give an idea of the movement in these spaces. The visualisations of these spaces could have been greatly improved with internal animations or simulations – though that was perhaps outside the scope of this thesis. This would allow for a much deeper understanding of how people, objects and plants move within these spaces. This is crucial for our future understanding of zero-G habitats.

CONCLUSIONS

This thesis was a research led design project on the idea of habitability in outer space. This is an emerging field. As more is understood about habitability, the aspects defined in this thesis will need to be reconsidered. Going forward these aspects should be weighted against each other – it is unlikely that issues of hygiene are equal to issues of gravity. Furthermore, these could be collated into entirely different groupings.

This thesis has proposed several methods of potentially mitigating habitability issues in orbit. The main concepts dealt with are Orientation, Views, Grid System, Planting, Mobility, Volumetric Scale, Privacy Scale, Artificial Gravity, Sleep & Furniture.

These proposed methods are not definitive solutions to habitability issues and only touch on what these issues mean. The ideas in this thesis are a demonstration of designed concepts for aiding in space habitation. These ideas are simple explorations and need huge amounts of refinement. The use of these methods show the potential for researched design to create wonderful, personal spaces within the rigorous design constraints of outer space. This thesis showed that space habitation does not have to be cold and artificial. Living in space is, and will be, fun.

Fundamentally, this thesis has shown that design in space is not so different from design on Earth. In each situation, a good designer is striving to create a space that is enjoyable to inhabit.

9.4 CHALLENGES

The design of this station saw its fair share of challenges. One of the most significant hurdles was trying to conceive spaces that would be inhabited in full 360°. Plans and sections didn't mean as much without gravity, and so 3-dimensional representation was the best way to understand the modules. This led to the development of the grasshopper script which allowed for these modules to be easily created and fitted out in 3D. The spatial understanding of these spaces would have significantly benefited from the use of VR or AR techniques. These would have allowed for a much more immersive experience than the computer screen and potentially result in different solutions.

Another challenge was understanding human ergonomics in zero-G. This has been discussed briefly in this thesis; however, its impact on the design was minimal. Producing images with real astronauts in them made this more apparent. It became self-evident that the positioning of foot-pads, monitors and other aspects of the space were not quite right. Going forward, it would be a good idea to do tests with photos of people experiencing zero-G much earlier in the project.

In relation to this was the design of the fit-out itself. Zero-G furniture is a difficult concept to grasp and perhaps these spaces should have appeared emptier. Desk spaces may be entirely pointless; however, these could be digital and used as keyboards, mouse pointers or the screen itself. It could be argued that the variable surfaces proposed in the living room were utterly pointless. However, these surfaces, if nothing else, create spatial separation and a means to attach objects at various angles. The most difficult aspect of zero-G furniture is trying to understand how people congregate. On Earth, people collect at edges, seats and surfaces; in cylindrical, zero-G spaces this loses its meaning. This thesis proposed pliable, 'lounger-like', surfaces and hammocks an inhabitant could pull themselves into; there is no way to know if these would work. In future projects, the design of zero-G furniture will prove to be a significant concept which would require a good amount of new research in zero-G environments.

9.5 FINAL REMARKS

POTENTIAL APPLICATIONS

The methods used in this investigation are universally applicable. The final design of this thesis is one interpretation of how habitability could be designed for in a 30 person asteroid mining operation program. This thesis emphasised the spaces used between work hours. These are spaces that will be needed in any long term space operation which gives them some broad applicability. The grid system, orientation and even circulation design could all be applied in other scenarios. This is strengthened with parametric modelling. This exact design could be completely re-configured and translated to a variety of programs.

The methods in this thesis could also be applied on other planets or moons. These planets will have differing gravity conditions than on Earth. This means sensitive design around gravity, such as that in this thesis, will be important. Similarly, terrestrial bases will likely be modular to some degree. That means the design methods used will be just as relevant there. Fundamentally, this thesis is a demonstration of methods to create habitable environments in inhospitable places. This includes Antarctica or even the bottom of the ocean.

FURTHER STUDY

Many of the concepts here were directly built upon from the International Space Station. The variable grid system is simply a more versatile, human-centred, variation of the ISS rack system. This creates an expectation that this system could then be built upon again in future projects in this burgeoning field. A significant way this could be done is through experimentation and testing.

The ideas in this thesis have not been tested, to do so would be outside the scope of this thesis. However, without testing them, these ideas can not be proved to aid in mitigating habitability issues. These ideas are simply proposals through research of literature. This gives them validity, but these methods must be tested.

A testing method, already in use by NASA, is the use of physical prototype environments. The prime example of this is the Habitation Demonstration Unit discussed earlier in this thesis. By creating mockups utilising some of these methods, an examiner could observe how these spaces work in reality. However, a physical mockup would not be able to account for weightlessness.

Another method for testing is virtual simulations. VR or AR would allow examining how people are affected by these spaces. A virtual space would allow for the effects of weightlessness to be simulated. This would be very important for genuinely understanding these habitability methods, as many of them are to do with dealing with a zero-G environment.

Another area of further study is design at the furniture scale. This is where ergonomic consideration around zero-G habitation becomes very important; something greatly lacking in this thesis.

FINAL REMARKS

In the future, work like this thesis will contribute to humanity's habitation of space. This is a concept we have worked towards for as long as we have been humans. This thesis hopes that when humans are inhabiting space in great numbers; they are doing so comfortably, in beautiful spaces, designed with habitability in mind.

Figure 78. Davis, D. (1970) Bernal Sphere Construction.

10.0 APPENDICES

- 10.1 GLOSSARY
- 10.2 APPENDIX A
- 10.3 APPENDIX B
- 10.4 APPENDIX C
- 10.5 APPENDIX D
- 10.6 FIGURES
- 10.7 REFERENCES

10.1 GLOSSARY

TERMS

Oberth Effect - the effect of conducting aeronautical maneuverers at the periapsis of an orbit. This is the most efficient potential burn as the gravitational potential is lowest.

Burn - The term used to denote a burst of propulsion from a rocket.

Geosynchronous Orbit - An orbit of Earth where the orbital period is equal to the Earth's rotation.

Geostationary Orbit - A circular geosynchronous orbit around the Earth's equator at an altitude of 35,786 km. This causes the object to appear in a fixed position from the Earth's surface.

Langrangian Point - 5 points in the orbit of any 2 bodies where the gravitational force effectively cancel out creating stable points of orbit. Anything at these points will appear to orbit an empty point in space. However, it is orbiting the Earth in such a way that its orbit fluctuates up and down due to the influence of the moon.

Periapsis - the point of an orbit with the lowest altitude

Apoapsis - the point of an orbit with the highest altitude

Prograde - West-East rotation. In Earth orbit, a prograde burn propels the ship in the same direction as the earth's rotation along the equator.

Retrograde - East-West rotation. In Earth orbit, a retrograde burn propels the ship in the opposite direction as the earth's rotation along the equator.

Station Keeping - Orbits slowly decrease in altitude due to the microscopic amount of air resistance. Regular burns are needed to maintain an orbit and stop an object from falling back to Earth.

Sphere of Influence - The edge of a body's gravitational influence.

Delta-V - The change in velocity needed to reach particular orbits.

Astronomical Unit - The distance from the Earth to the Sun.

Solar Irradiation - An expression of the solar energy received at a point in relation to the solar constant and distance from the sun.

Solar Constant - A measure of the solar energy received by a surface facing the Sun near Earth.

Gravitational Constant - the gravitational force on the Earth's surface (9.8 ms⁻²)

Solar Particle Events - influxes of solar wind / solar flares from the sun.

Galactic Cosmic Rays - particles jettisoned by distant dying stars.

Magnetosphere - protective geomagnetic field generated by the Earth's geological movement. Protects the Earth from radiation.

Van Allen Belts - radioactive particles trapped within the Earth's magnetosphere.

Aero braking - using the drag induced by a planet's atmosphere to lower the altitude of an orbit.

Microgravity - An object with enough tangential velocity to counter downward pull of gravity. Objects in microgravity experience free-fall and are effectively in zero-G. It is worth noting that LEO objects are still experiencing much the same force of gravity as on the surface.

Zero-G - a lack of direct gravitational influence (for the purpose of this thesis microgravity is referred to as zero-G also)

Insitu Resource Utilisation - using resources already in space to construct.

Additive Manufacturing - use of technology such as 3D printing to construct.

ABBREVIATIONS

LEO - Low Earth Orbit

ISS - International Space Station

MBA - Main Belt Asteroids

SSTO - Single Stage To Orbit

NEA - Near Earth Asteroid

ECLSS - Environmental Control and Life Support Systems

EVA - Extra-vehicular activity

GSO - Geosynchronous Orbit

GEO - Geostationary Orbit

SOI - Sphere of influence

SPE - Solar Particle Events

GCR - Galactic Cosmic Rays

ISRU - Insitu Resource Utilisation

BFR - Big Falcon Rocket

UNITS

ΔV - Delta-V

AU - Astronomical Unit

Gs - Solar Irradiation

Ge - Solar Constant

1G - Gravitational Constant

10.2 APPENDIX A

HABITABLE SPACE CONFIGURATIONS

Configuration of the rotating elements can be linear to minimise gravity gradient. This could make for large distances to travel between parts of the station and a large amount of traffic through modules.

A less linear configuration would allow for more flexible planning of spaces and more opportunity for circulation routes. There would however be a difference in gravity between the levels dependant on the overall radius of the system.

Figure Linear Arrangement

Figure Non-Linear Arrangement

ROTATING SYSTEM CONFIGURATIONS

Figure 81. Rotating Station Configurations

A rotating station can be configured as components rotating around their shared centre of mass. The number of rotating 'arms' can be increased to allow for more components or the entire system can be a ring allowing for habitable space along the entire circumference of the system. An alternative to this with a single habitable space is also possible.

10.3 APPENDIX B

ROTATING THE BFR MODULE

Below is an analysis of the qualities of rotating modules based on the 8m x 50m payload restriction of the SpaceX BFR. As well as an ideal size and rotation.

SINGLE MODULE. $R=4M$

A single 8m diameter modules rotated around it's central axis could generate; 1G at 14.9 RPM, 0.5G at 10.6 RPM, and 0.3G at 8.2 RPM.

These speeds are far above the accepted maximum rotation of 6RPM and would also have a huge gravity gradient from a person feet to their head. Coriolis force would also be very large.

FOUR MODULES. $R=8M$

4 modules (launched separately or bundled within the same payload) could generate; 1G at 10.6 RPM, 0.5G at 7.4 RPM, and 0.3G at 5.8 RPM.

A slight improvement from the single modules however these speed are still not ideal. The gradient and coriolis forces will likely still be an issue at this size.

NINE MODULES. $R=12M$

9 modules (launched separately or bundled within the same payload) could generate; 1G at 8.6 RPM, 0.5G at 6.1 RPM, and 0.3G at 4.7 RPM.

Another jump in potential. 0.5G at 6.1 RPM is a possibility. However at this point we start to risk people getting stuck in the large open volume. Furthermore needing 8 separate modules for construction could prove quite cumbersome. Insitu construction could be a possibility.

IDEAL RADIUS. $R=50M$

The radius must be increased all the way up to 50m before we start seeing some good values. This radius could generate; 1G at 4.2 RPM, 0.5G at 2.9 RPM, and 0.3G at 2.3 RPM.

As shown here it is possible to have a relatively small scale cylinder with promising centrifugal forces however the construction of this would prove monumental. Cylinders like the O'Neill cylinders are better used as huge kilometre across structures for large scale colonies which is beyond the scope of this project.

Figure 82. Single Module

Figure 83. Four Module

Figure 84. Nine Module

Figure 85. Ideal Module

MOVING A SPACE STATION

Figure 86. Reaction control system

There are 2 main ways to move a spacecraft in orbit. The first is 'reaction control system' (RCS). These are small thrusters used to provide attitude control to a craft. Since these require fuel they can be quite costly and are more useless for short terms spaceflights. In more recent years electrical variations of these such as arcjets and ion thrusters have been used to a similar effect.

The second way to move a spacecraft is through 'control moment gyroscope' (CMG) which are a form of reaction wheel with a controllable axis. These wheels spin to apply torque forces rotating the craft. A downside of these is that they are very heavy and require power to run making them more suitable for long-term missions such as the ISS which uses CMG's to control it's attitude. Furthermore these wheels eventually become 'saturated' and no longer able to absorb momentum. This can only be fixed using an external torque force and so the ISS utilises RCS thrusters to 'de-saturate' it's CMG's.

Figure 87. SpaceX Starship Dimensions

10.6 FIGURES

Figure 01. Verne, J. (1865) Rocket to the Moon. Retrieved From https://fr.wikipedia.org/wiki/Fichier:Arrivee_Projectile_DTAL.jpg

Figure 02. Methodology Diagram

Figure 03. Hale, E. (1869). The Brick Moon. Retrieved From https://en.wikipedia.org/wiki/The_Brick_Moon

Figure 04. Guidice, R. (1970) Cylinder Interior. Retrieved From <https://picryl.com/media/cylinder-interior>

Figure 05. Guidice, R. (1970) Toroidal Colony. Retrieved From <https://picryl.com/media/toroidal-colony>

Figure 06. Tsiolkovsky, K. (1933) Sketches of people in Zero-G. Retrieved from https://commons.wikimedia.org/wiki/File:Tsiolkovsky_Album_11.jpg

Figure 07. Habitability Issues

Figure 08. Physical Isolation Issues

Figure 09. Psychological Isolation Issues

Figure 10. Social issues in privacy and proxemics

Figure 11. Social issues in the layout and organisation of spaces

Figure 12. Food in space

Figure 13. Hygiene in space

Figure 14. Sleeping in space

Figure 15. Work and leisure in space

Figure 16. Monotony of environment in space

Figure 17. Movement in space

Figure 18. Effects of weightlessness

Figure 19. Types of centrifugal gravity

Figure 20. Issues of centrifugal gravity

Figure 21. Tsiolkovsky, K. (1933) Greenhouses in Space. Retrieved From https://commons.wikimedia.org/wiki/File:Tsiolkovsky_Album_55.jpg

Figure 22. Noordung, H. (1929) Wohnrad render. Retrieved From https://www.nasa.gov/multimedia/imagegallery/image_feature_1217.html

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