A Design Study on ASPA's Rotating Space Station in Mitigating Long-Term Microgravity Effects of Space Habitation.

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DECLARATION

This report entitled

A Design Study on ASPA's Rotating Space Station in Mitigating Long-Term Microgravity Effects of Space Habitation.

Was composed by me and is based on my own work. Where the work of others has been used, it is fully acknowledged in the text and in captions to table illustrations. This report has not been submitted for any other qualification.

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Abstract

To be Completed

Contents

Chapter 1

Introduction[1]

1.1 Rationale

Space is often considered the final frontier in the development of the human civilisation, and this is true but only the beginning of the story. What started as a competition between the US and USSR in the 1960's to put an astronaut/cosmonaut in space and on the surface of the moon first, has since changed our interactions with space.[2] Since then, new avenue's for understanding our space environment have been developed and have improved the quality of life on Earth, as seen from our Satellite networks, to modern day CAT scanners and wireless headsets.[3]

Spaceflight is now more scientifically specialised compared to when it begun as the space race. Astronauts, Cosmonauts, scientists, engineers and other crew from all over the world have worked on multiple research projects in space. However, due to the adverse effects of microgravity on the human body, such as cardiovascular de-conditioning and bone density loss, the quality of life of any crew in space is reduced. This needs to change for the future of space exploration, we need gravity.

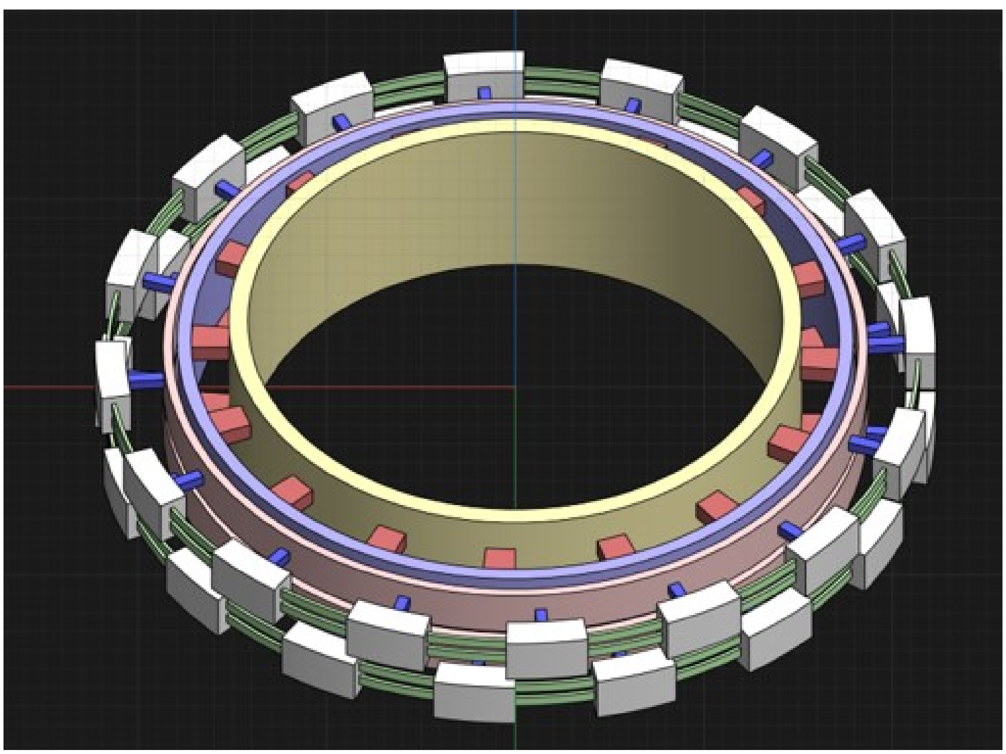

Figure 1.1. Rotating space station conceptual Design

We, the ASPA group are conducting research into designing a major technology that will improve the quality of life for any crew in space, not to facilitate competition, but a united collaboration of private and government agencies. We have designed a rotating space station called the ASPA Nexus, that generates artificial gravity through it's rotation and the design is shown in Figure 1.1. The ASPA group's motto is *Ad Astra Per Aspera*, because we understands that moving ever closer to the stars will be full of hardships, and we need to do it together.

To start, a feasibility design study was completed to assess the starting parameters that would lay the foundation for the station design. The main parameter was the gravity of the space station, which was decided to be equivalent to the gravity on Earth (1G). Looking into the research literature, the essential systems needed to realise the ASPA Nexus.[4] are outlined in Table 1.1.

TABLE 1.1. Rotating space station critical systems.

Rotating Space Station Systems
Attitude and Orbital Control System (AOCS)
Structural Design System (SDS).
Shielding and Protection System (SPS).
Life Support System (LSS).
Propulsion System.
Rendezvous and Docking System.
Command and Data Handling (CODH).
Robotics System.
Electrical and Power System (EPS).
Communication and Ground control system (C&TS).

From Figure 1.1 The station is designed to have 4 rings, with the central ring being about 75 meters in radius, and 100 meters in depth. This is to reduce the probability of wobble on one of the station's principal axes. The Middle ring is attached to the central via trusses and would contain lifts/transport vehicles to travel between rings. This would be an incorporation of elevator-like vehicles in space, working under microgravity and a gravity gradient. [i]

The central and middle rings are stationary and will experience microgravity conditions, where experiments, such as the ones conducted on the ISS[5] and Tiangong space station can continue to happen. The Middle and outer rings are connected via wheels that enable the outer rings to rotate with little friction. There are 2 outer rings which rotate in opposing directions to improve the stability of the station and prevent the central rings from rotating. These outer rings are then connected via high-strength materials to the habitation modules, located at a radius of 223 meters from the center of the station.

[i]The Introduction is based on the Front End Design Report

1.2 The ASPA Group Research Streams

The Project aims to develop through research, 4 of the work streams and systems listed in Table 1.1 in the development of a rotating space station, to generate artificial gravity to mitigate the long-term physiological effects that microgravity has on the human body. These work streams, the responsibility and contributors are outlined in Table 1.2.

TABLE 1.2. (To be updated)Work streams for the Rotating Space Station

Station System	Responsibilities	Contributor
Attitude and Orbital Control System (AOCS).	Research into the Engineering of generating artificial gravity on a rotating space station and the design of control systems to aid in station keeping.	Emmanuel E Airiofolo.
Structural Design System (SDS).	Research into the engineering of the structure and design of a rotating space station.	Wania Farooq.
Shielding and Protection System (SPS).	The research and development of shielding strategies around the rotating space station.	Abaas Nunow.
Life Support Systems (LSS), Docking and Rendezvous.	Research and Design of Existing Life Support technologies that can be integrated into the gravity conditions on a rotating space station.	Ilanthiraiyan. Sivagnanamoorthy

1.3 Summary of Key Findings on AOCS

Challenges addressed in each chapter

End of life(IADC)

The topic of my work stream is Attitude and Orbital Control System, which works to define the movement, orientation and propulsion necessary to keep the rotating space station at its desired position, orbit and station gravitational conditions, as the station spins, generating centripetal acceleration acting on any object within the circumference of the rotating rings. Control systems can be designed to assist in automating the motion and movements of the rotating space station.

The reference frames used in orbit determination are the ECI, ECEF, and Orbital frames, as shown in Figure . The reference frames for Attitude determination and control are the rotating frame, which accounts for the experience of the habitats of the station and the internal movements; and the inertial frame/non-rotating frame, which is considered during rendezvous and external movement around the station.

The centripetal acceleration is the component of acceleration on a body moving in a circular motion and is directed at the axis of rotation.[6] This is observed within an Inertial reference frame. The centrifugal acceleration is a virtual acceleration observed within the non-inertial reference frame of the moving station. This generates the artificial gravity effects on a body within the outer rings of the station.

Coriolis force is an important parameter to consider when dealing with circular motion. It's named after Gaspard-Gustave de Coriolis, a French scientist who studied fictitious forces in rotating reference frames.[7] This deflective force curves the path of an object with an initial tangential velocity within the rotating body and the curved path is perceived from the rotating frame.[8] Its perception from the rotating frame is often why it is considered a fictitious force, similar to centrifugal acceleration.[9] From an inertial reference frame - an observer outside the rotating body - the object's path continues in the direction of the tangential velocity.

The AOCS is responsible for station keeping[ii]. Station Keeping involves actions taken to re-orient the space station to its desired attitude and orbit, to counter any form of drag, change in trajectory and collision avoidance. The drag expected to be experienced by the station includes;[10] atmospheric drag due to its altitude; J_2 perturbation, which arises due to the oblateness of the earth; solar pressure;[11] and external torques. Internal torques can still be generated due to an imbalance of inertia in the system. Control systems are developed and used to automate the AOCS, as sensor input and feedback are important for detecting and measuring the effects of these drag on the space station.

[ii]The Introduction is based on the Front End Design Report

Chapter 2

Rotational Attitude and Orbit of The ASPA Nexus Space Station[1]

2.1 Station Parameters and Design Considerations

2.1.1 Station Radius, RPM and Target Centrifugal gravity

The Radius of the station, Revolution per minute and Target gravity are closely linked together through the centripetal acceleration, Equation 2.1.

$$a_g = \Omega^2 R \tag{2.1}$$

Various values for a_g and RPM were tested using a Python code that calculated the parameters automatically. These are shown in Table 2.1.

TABLE 2.1. Station Radius, Diameter and Angular Velocity using Python

a_g (m/s^2)	RPM	Radius (m)	Diameter (m)	Angular velocity (rad/s)
9.7819	0.5000	3568.0100	7136.0200	0.0524
9.7819	1.0000	892.0000	1784.0000	0.1047
9.7819	2.0000	223.0000	446.0000	0.2094
9.7819	3.0000	99.1100	198.2200	0.3142
9.7819	4.0000	55.7500	111.5000	0.4189

The target gravity is chosen to be approximately 1G of Earth's gravity (9.7819 m/s^2), to replicate the conditions on Earth in support of long-term habitation. From the Literature,[12] the optimum Revolution Per Minute on the human body without added training to adapt to high rotation rates is 2 RPM.[13] The graph shown in Figure 2.1, shows the relationship between the angular velocity in RPM and the radius of the structure. The comfort zone in green shows the acceptable combination of variables to maximise comfort as the study shows. The Angular Velocity shown in Table 2.1, for 2 RPM is calculated in Equation 2.2.

$$\Omega = 2\pi f = 2\pi \frac{1}{30} = 0.2094 rad/s \tag{2.2}$$

An RPM of 2 is equivalent to a frequency of, $f = \frac{2}{60} = \frac{1}{30} s^{-1}$. Substituting a_g for 9.7819 ms^{-2} and f for $\frac{1}{30} s^{-1}$:

$$9.7819 = (2\pi \frac{1}{30})^2 R \tag{2.3}$$

$$R = 223m \pm 1m \tag{2.4}$$

The station has an overall diameter of $446m \pm 2m$. The uncertainty in the radius and diameter of the station will be useful as more space for additional structures, thrusters and external hardware components of the station overall.

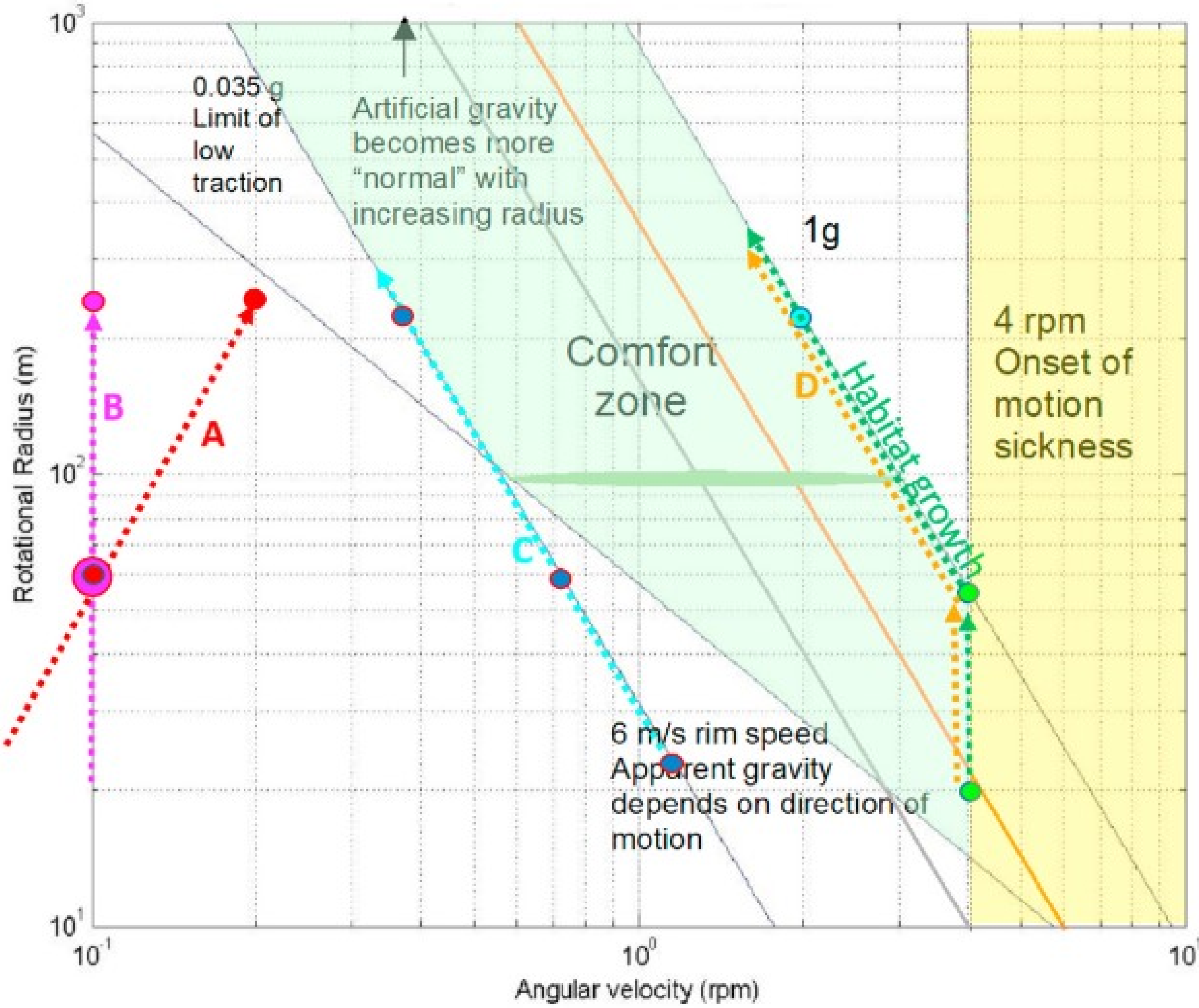

FIGURE 2.1. The Comfort Zone for artificial gravity.[14]

2.1.2 Gravity Gradient

[i]The Gravity gradient $\frac{a_g}{R}$, is calculated to be; $\frac{9.81}{223.64} = 0.0438s^{-2}$. This is the difference in centripetal acceleration from the center of the station to the outermost edge. Figure 2.2 shows the diameters of the station rings, which are proportional to the magnitude of centripetal acceleration.

[i]Chapter 2 is based ont he Front End Design Report

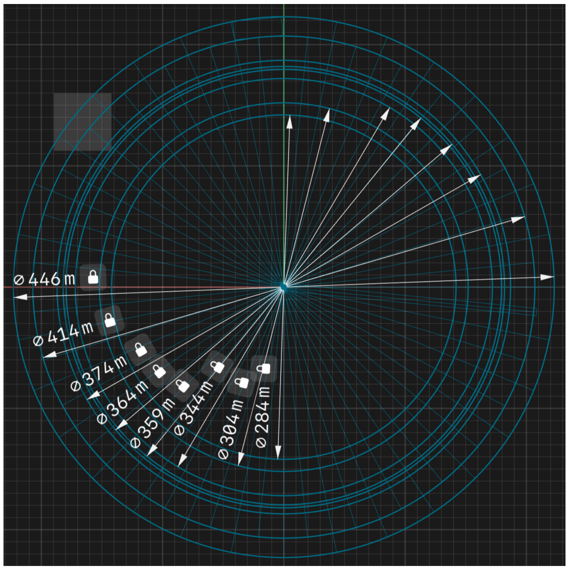

FIGURE 2.2. Diameter Distribution

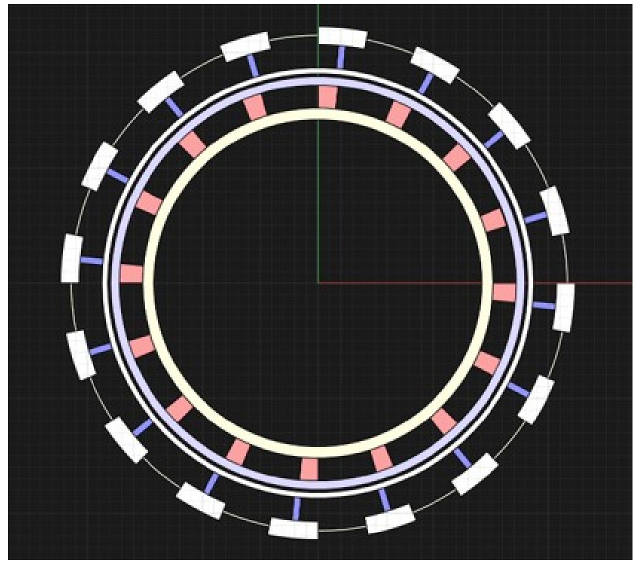

FIGURE 2.3. Top View of Station

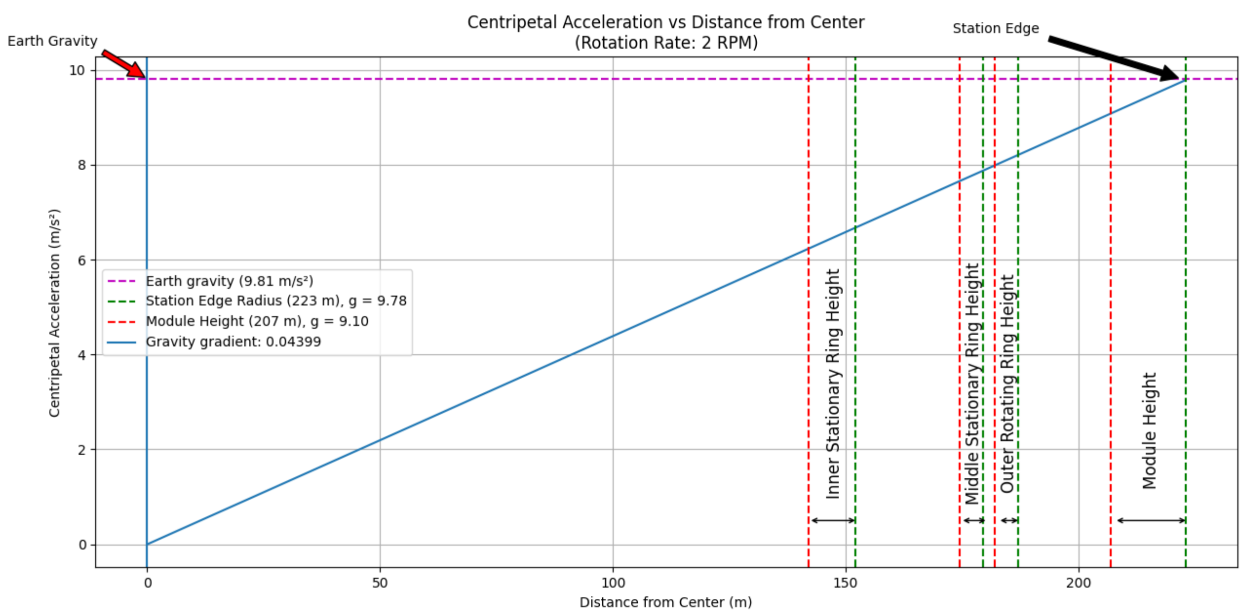

FIGURE 2.4. Graph of centripetal acceleration against radius of the station.

As shown in Graph 2.4, the expected gravity at the station edge is 9.78 ms^{-2}, and 9.10 ms^{-2} at the roof of the module as shown in Figure 2.3. With a Module height of 16 m, the gravity difference is negligible[15] on the human body due to the station being large enough for small differences in centripetal acceleration within the modules. The Coriolis force from the difference in gravity experienced by the crew will be significantly smaller.

2.1.3 Coriolis Force

The Coriolis force and acceleration are perceived during crew movement and velocity parallel or normal to the direction of the station's rotation. The literature for coriolis force on earth[8] introduces a coriolis parameter, f_c, which is defined in equation 2.5.

$$f_c = 2\Omega Sin\phi \tag{2.5}$$

Where Ω is the angular velocity of the rotating system (Earth in this context), and ϕ is the latitude of the earth. The maximum latitude calculated is approximately 3° as shown in equation 2.6.

$$\phi = arctan\frac{13.5}{R_s} = arctan\frac{13.5}{223} = 3.46^\circ \tag{2.6}$$

This parameter, f_c does not need to be accounted for in the rotating space station design, due to the assumption that ϕ is negligible. Further analysis of the Coriolis parameter and its overall effect will be completed as part of future work.[15]

Based on a study,[12] the coriolis force experienced by the crew in a rotating cylinder can be observed in figure2.5.

The main difference between the coriolis forces considered in this study in figure 2.5, and the conceptual space station design in figure 1.1; is the diameter of the rotating body. The coriolis force and acceleration can be calculated using Equations 2.8 and 2.7 respectively. Where V is the relative change in tangential velocity within the rotating body.[8]

$$a_c = 2\Omega V \tag{2.7}$$

$$F_c = -2m\Omega V \tag{2.8}$$

Assuming an average crew mass of 82 kg,[16] The coriolis force for the crew member moving closer to the center of the station (scenario (c) in Figure 2.5) between a radius of $223m$ and $207m$ (top of the habitation module), can be calculated. Using Ω from equation 2.2, V from table 2.2 for the outer edge of the station, $R = 223m$, to an estimated v of $43m/s$ at $R = 207m$:

$$V_{relative} = 46.71 - 43 = 3.71m/s \tag{2.9}$$

$$a_c = 2 \times 0.2094 \times 3.71 = 1.554m/s^2 \tag{2.10}$$

$$F_c = -2 \times 82 \times 0.2094 \times 3.71 = -127.41N \tag{2.11}$$

The sample calculations in equations 2.11 and 2.10 only account for movement within the module, where the distance travelled is $16m$. For larger distances, further data will need to be colected.[15]

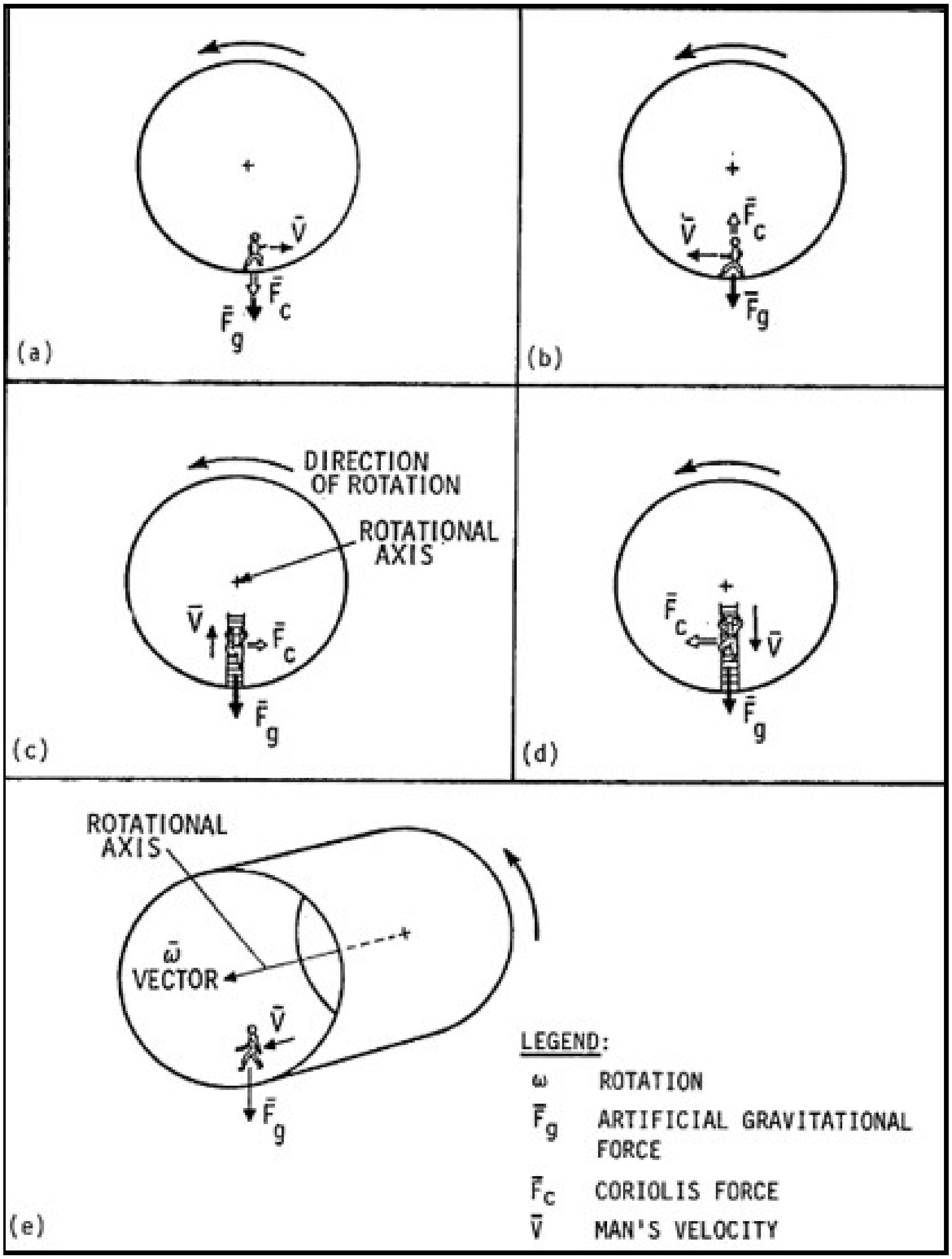

FIGURE 2.5. The Coriolis force F_c experienced when moving in a rotating body.[12]

2.1.4 Spin Up and Spin Down time

The calculations on the data in Table 2.2 were computed using Python and they show the chosen Target RPM of 2, with its corresponding Tangential velocity at the edge of the station diameter to be 46.71 m/s. The independent variable is the time it takes to spin the station up using its ion thrusters, and the dependent variable is the acceleration required during the duration that the ion thrusters are active.

Table 2.2. Station Spin Up and Spin Down time with Tangential acceleration required.

Target RPM	Tangential velocity (m/s)	Time (hours)	Tangential acceleration (m/s^2)
2	46.71	0.5	0.0259
2	46.71	1	0.013
2	46.71	2	0.0065
2	46.71	3	0.0043
2	46.71	4	0.0032

Further design decisions will be made using Spin up and Spin down time of 1 hour, corresponding to a tangential acceleration of 0.013 m/s^2. Based on its low effect on the station crew due to the Coriolis force during spin-up or down operations, this is decided.

Further factors that will affect the tangential thrust generated by the ion thrusters during spin-up and spin-down operations are the distribution of mass and inertia.

2.2 Orbit Perturbation and Modelling

[ii]An orbit is the curved path an object takes around another object due to gravity. For satellites and space stations, their mass is orders of magnitudes smaller than the body they orbit (The Earth for example). The operating orbit of the space station needs to be carefully decided based on solar array positioning, debris probability, ease of rendezvous from Earth, and average radiation exposure.

The ISS[4] orbits at an altitude between 370 and 400 km in altitude, with an inclination of 51.6°, RAAN and AOP approximately 184° and 306° respectively.[17] This is a Sun-synchronous orbit, and the station processes once every year.

2.2.1 Types of Orbits Considered

(ORBIT PARAMETERS DISCUSSION and what they are?)

Table 2.3 shows comparisons of SSO for the ISS, LEO and GEO. The orbit decided for the conceptual rotating space station design is the SSO conditions for the ISS. The orbital parameters are listed in Table 2.4.

[ii]Chapter 2 is based ont he Front End Design Report

Table 2.3. (TO BE UPDATED)Literature comparison of the ISS SSO, LEO and GEO[18]

	Sun-synchronous (ISS)	LEO	GEO
Properties	Lower earth orbit with rate of RAAN approximately 1° a day due to J_2 perturbation.	Between altitudes of 400km to 2000km.	exactly at 35,786km in altitude.
Inclination (i)	Typically around 98°	Any	0°
Period (T)	90 to 107 minutes	90 to 128 minutes	1436 minutes
Pros	Allows ease of orbital rendezvous for resupply and crewed missions. The trajectory is the most protected from solar and cosmic radiation due to the earth's magnetic field.	Highly protected orbit from solar and cosmic radiation due to the earth's magnetic field.	Lower debris probability, Low atmospheric drag.
Cons	There is a probability of debris contact at this orbit. The effects of J_2 perturbation on the orbit is at a maximum due to the orbit's proximity. Atmospheric drag disrupts the orbit of the station.	High debris probability. Atmospheric drag. Long term radiation exposure.	Not very protected from solar and cosmic radiation.

2.2.2 Station Orbital Parameters and Chosen Orbit

The Semi-Major axis (SMA) of an orbit describes the size of an orbit and it is half the largest diameter of the orbit. The eccentricity (e) determines how circular or elliptical the orbit is, where e = 0 means the orbit is circular and where e = 1, the orbit is elliptical as shown in figure 2.6. The inclination (i) is the angle between the orbital plane of the station and Earth's equator.[19]

RAAN describes the procession of the orbit per year, and for a sun-synchronous orbit, this is approximately 1° a day.

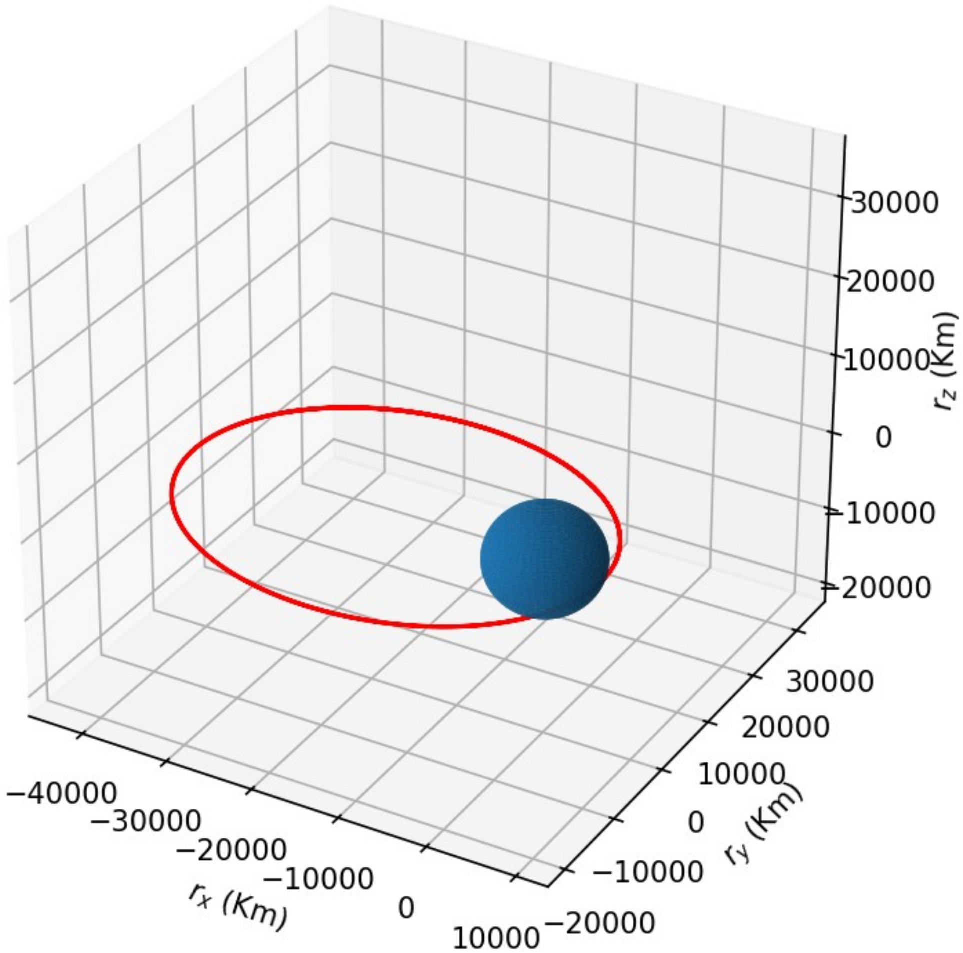

FIGURE 2.6. An Example of a 3D plot of an elliptical orbit around the earth.[20]

TABLE 2.4. (NEEDS UPDATING TO REFLECT ORBIT DEGRADATION)The Conceptual rotating space station design orbital parameters[17]

Parameter	Value
Altitude	411 km
SMA	6789 km
Perigee	411 km
Apogee	421 km
Eccentricity	0.001°
Inclination	51.64°
RAAN	184.21°
AoP	306.76°
Mean Anomaly	201.11°
Revolutions	15.5
Period	90 - 93 minutes

Using a python software,[21] these parameters are propagated to model the 3D orbit as shown in red in Figure 2.7 and The green circle marks the Equator.

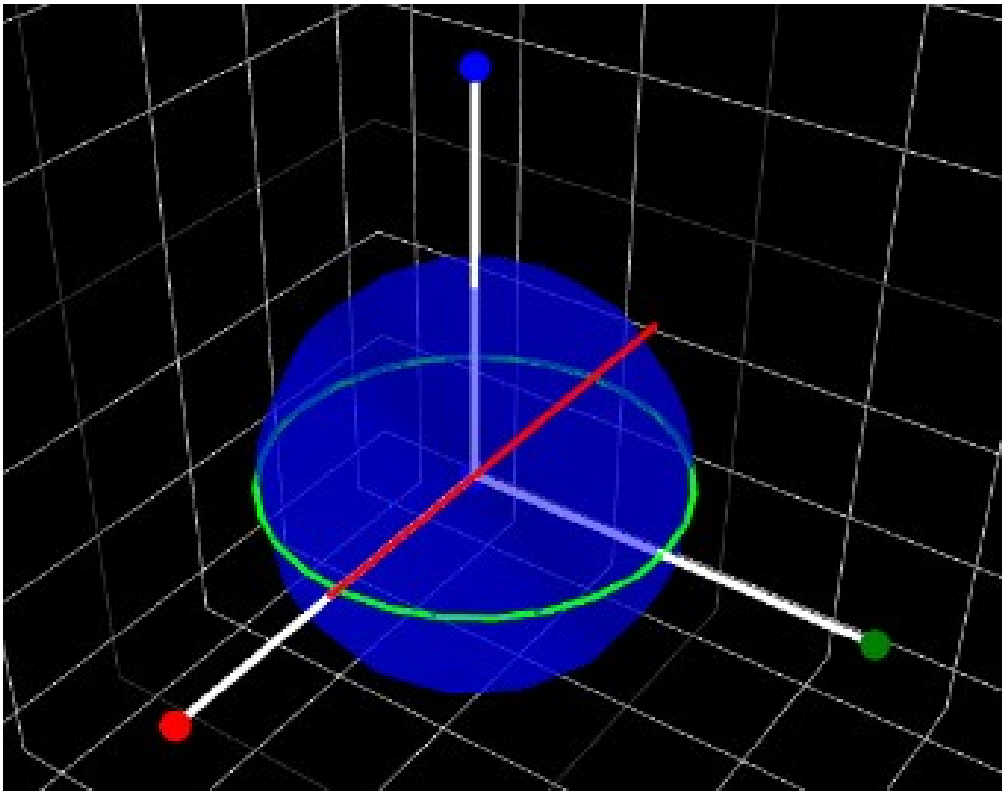

FIGURE 2.7. 3D orbit propagation from Table 2.4 for the Space station around the Earth[21]

2.3 Attitude and Orbital Spin stabilisation

[iii]3D objects have 3 axes of rotation and each axis corresponds to 3 separate moments or inertia. Assuming they are largest, middle and smallest ($I_1 > I_2 > I_3$), the axis of rotation of a rotating body that corresponds to the smallest (I_3), the system will be unstable.[22] This is known as the tennis racket effect.[23] The rotating space station design however has two moments of inertia equal to each other, hence the axis of rotation of choice (The axial, $\hat{\mathbf{k}}$) is not expected to be unstable.

To further reinforce this, the station is designed to have two outermost habitation rings, spinning in opposing directions for greater spin stability. The double outer rings are also present to better enable the non-rotating inner rings of the station to remain fixed relative to the station's inertial frame.

[iii]Chapter 2 is based ont he Front End Design Report

Chapter 3

Electric propulsion on The ASPA Nexus Space Station.

3.1 A Literature Review on Station Propulsion

- what are the 3 options for electrical thrusters - how will fuel be stored. - how will we position them. - compare those 3 thruster options in a decision matrix, while mentioning isp and so on.

- Would i need to develop the electrical power system? NO NO NO NO

Criteria	Weight	Gridded Ion Engine (GIE)	Field Emission Electric Propulsion (FEEP)	Electrode less Thrusters	Colloid / Electrospray	Pulsed Plasma Thruster (PPT)
Response Time	5	3 (15)	4 (20)	2 (10)	5 (25)	5 (25)
Thrust Level	4	4 (16)	1 (4)	4 (16)	2 (8)	2 (8)
Operational Lifetime	5	5 (25)	3 (15)	4 (20)	3 (15)	2 (10)
Power Requirements	3	2 (6)	5 (15)	1 (3)	4 (12)	4 (12)
Mass Efficiency	4	5 (20)	5 (20)	4 (16)	4 (16)	2 (8)
Integration Complexity	3	3 (9)	2 (6)	1 (3)	3 (9)	4 (12)
Impact on Station Dynamics	5	4 (20)	5 (25)	3 (15)	5 (25)	3 (15)
Plume Contamination	3	3 (9)	2 (6)	4 (12)	2 (6)	2 (6)
Thrust Variation	4	4 (16)	4 (16)	5 (20)	4 (16)	2 (8)
Technology Readiness	4	5 (20)	3 (12)	2 (8)	3 (12)	4 (16)
TOTAL SCORE		156	139	123	144	120

TABLE 3.1. Decision matrix for comparing thruster systems for ASPA Nexus space station applications[24252627]

3.2 Decision Matrix criteria definitions

(1) Response Time: How quickly its response to debris is. (How can we better quantify/measure this? by using isp? thrust to weight ratio)
(2) Thrust Level: Ability to provide sufficient thrust for station-keeping manoeuvres (Total Thrust needed?)
(3) Operational Lifetime: Expected service life before maintenance or replacement (Number of operations? and operation hours)
(4) Power Requirements: Power consumption relative to station resources (higher score = lower power needs) (Discuss how lower power is desirable)
(5) Mass Efficiency: Propellant efficiency (specific impulse) and overall system mass (GIE rating confirmed by specific impulse values of 3,000-4,000s for the 4-Gridded engine paper.)
(6) Integration Complexity: Ease of integration with station systems (higher is simpler)
(7) Impact on Station Dynamics: Minimal influence on station's rotational stability (higher is better) (how does a thruster impact rotational stability? through vibrations of the thruster? or precision of thrust?) (This can be minimised through correct positioning of the thrusters and and attitude control)
(8) Plume Contamination: Risk of thruster exhaust contaminating sensitive surfaces (two things, how much Contamination is produced, and how dangerous/inert is it.)
(9) Thrust Variation: Ability to vary thrust precisely for different manoeuvres. (What is the relationship between net thrust, power and propellant. Linear is better for fine control better control for attitude)
(10) Technology Readiness: Flight heritage and operational reliability.[28]

3.3 Electric Thruster Ranking.

- GIE (156): Strongest overall option with substantially better operational lifetime than initially assessed. NEXT-C and 4-grid developments have significantly improved throttleability and service life. Response time limitations are less severe than previously thought based on SMART-1 mission experience.
- Colloid/Electrospray (144): Remains a strong second option with excellent response characteristics. Recent research confirms their exceptional precision for small corrections with minimal impact on station dynamics.
- FEEP (139): Excellent for precise station-keeping but integration challenges are more significant than initially estimated, particularly regarding propellant management.
- Electrode-less Thrusters (123): Score decreased due to new data on power requirements and integration complexity. While promising, they remain less mature than other options.
- PPT (120): Score decreased due to new evidence of lower mass efficiency and thrust consistency issues documented in MDPI research.

3.4 Conclusion on Electric Propulsion systems

Primary System: Enhanced Gridded Ion Engines (GIEs) - specifically NEXT-C derivative or 4-grid technology

Secondary System: Colloid/Electrospray thrusters for rapid-response debris avoidance manoeuvres

Rationale: The enhanced GIE technology demonstrated in NASA's NEXT-C program and the 4-grid research provides substantial improvements in operational lifetime and throttleability. When combined with the rapid response capabilities of electrospray thrusters, this hybrid approach offers an optimal solution for both station-keeping and debris avoidance.

Implementation Strategy:

(1) Deploy GIEs in pairs on opposite sides of the station for balanced thrust during routine station-keeping.
(2) Install multiple smaller electrospray thruster clusters for rapid, precise adjustments during debris avoidance manoeuvres.
(3) Implement an integrated control system that can seamlessly transition between primary and secondary systems based on required response time.

Chapter 4

The ASPA Nexus Station Motion Prediction Models for Debris Avoidance

4.1 Drag and Debris Avoidance

- Sources of Drag: Atmosphere, J2 and Solar radiation. - How to avoid Debris. - Atmospheric modelling: CCMC instant run model on NRLMSIS - Remember using master for this?

4.2 Station Position and Orbit Prediction model

- I realised that the orbital parameters of the ISS are constantly changing and so i opted to build a prediction model instead. - The purpose of this model is to enable thruster burns for collision avoidance, and disturbances to the orbit perturbation.

-CAN THE NASA GMAT SOFTWARE BE USEFUL FOR THIS?

Chapter 5

Conclusions

To be Completed

Chapter A

Research Catalouge

Appendix is here

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