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

By Emmanuel Ehimeme Airiofolo

Individual Third Year Project Report April 2025

Supervisor: Dr. Angadh Nanjangud

SCHOOL OF ENGINEERING AND MATERIALS SCIENCE
ENGINEERING/MATERIALS
THIRD YEAR PROJECT
EMS600U/EMS690U

APRIL 2025

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.

Name: *Emmanuel E Airiofolo*

Signed: . . . EMMMANUEL . . .

Date: . . . 25/04/2025 . . .

Emmanuel E Airiofolo
Date: 06/12/2024
Aerospace Engineering

Abstract

The feasibility of an Attitude and Orbital Control system (AOCS) in a rotating space station design is investigated in this report. To minimise the physiological effects of long-term space habitation on the human body, and maximise comfort, the gravity gradient, coriolis effect, centripetal forces and station accelerations have been discussed through literature reviews, Engineering software and existing technologies.

The rotating station design is generated and informed from multiple systems, which will be covered by my colleagues as mentioned in the report. Further work will also be completed on the integration of each system; deciding the necessary hardware for the station to operate; the use of Chemical thrusters against ion thrusters, and detailed mission planning; in future reports.

Contents

Chapter 1

Introduction

1.1 WHAT IS MY DESERTATION STORY?

1.2 Project Mission

The human body faces astronomical physiological challenges when exposed to microgravity for long periods, such as muscle atrophy, bone density loss, and cardiovascular deconditioning. To reduce these effects, research into components, sections and systems of a rotating space station that generates centrifugal force, creating gravity artificially will be investigated by Team ASPA (Ad Astra Per Aspera). Based on the literature, there are essential systems to be investigated for any space station.[1] these are outlined in Table 1.1.

Table 1.1. Work streams for the Rotating Space Station

Station Systems
Attitude and Orbital Control System (AOCS)
Structural Design System (SDS).
Command and Data Handling (CODH).
Propulsion System.
Flight Crew System.
Robotics System.
Shielding and Protection System (SPS).
Life Support System (LSS).
Electrical and Power System (EPS).
Communication and Tracking 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. The central and middle rings are stationary and will experience microgravity conditions, where experiments, such as the ones conducted on the ISS[2] 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.

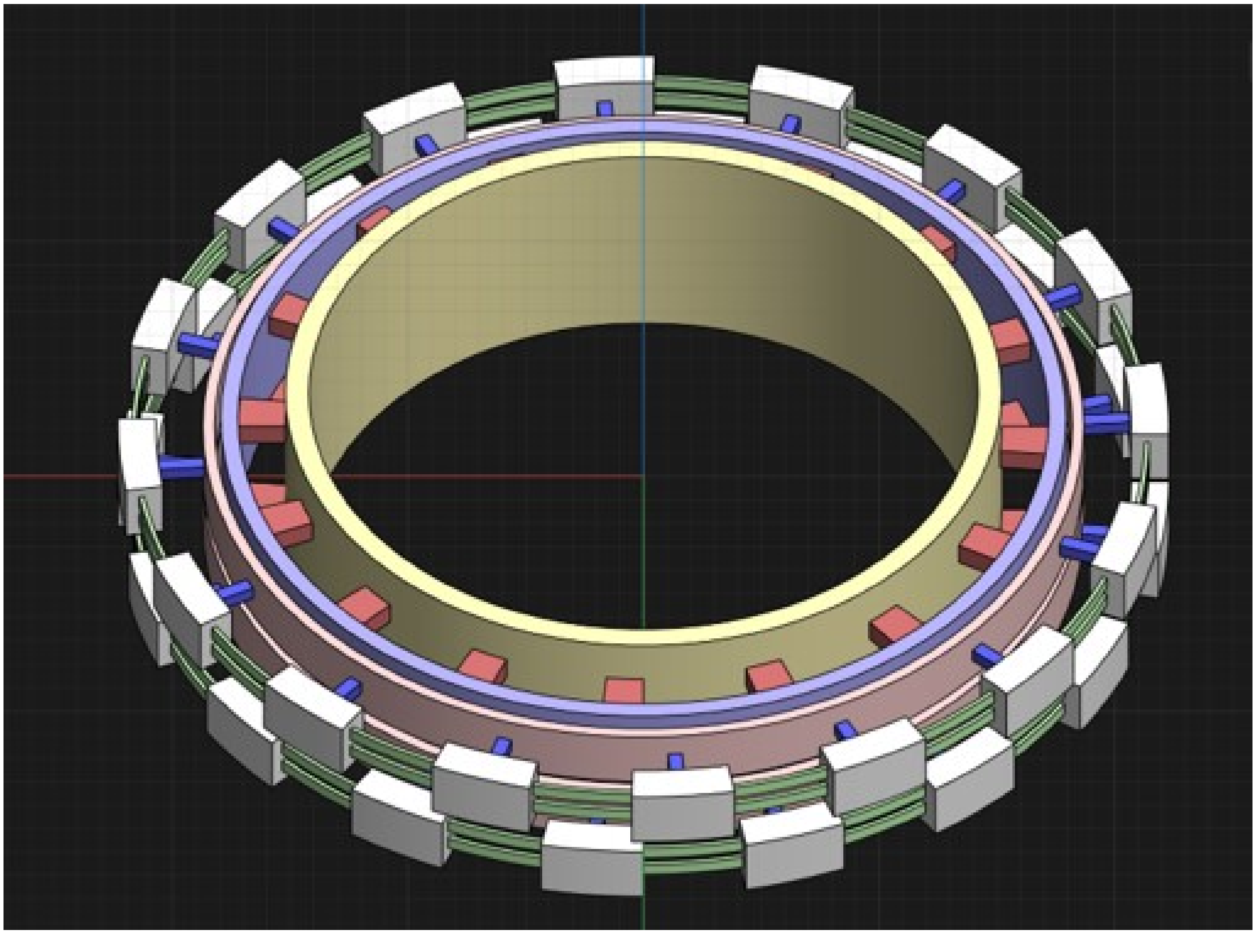

FIGURE 1.1. Rotating space station conceptual Design

1.3 Aims and Work streams

The Project aims to develop through research, 5 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

1.4 The Attitude and Orbital Control System of a Rotating Space Station

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.

Table 1.2. 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).	Research and Design of Existing Life Support technologies that can be integrated into the gravity conditions on a rotating space station.	Ilanthiraiyan. Sivagnanamoorthy
Electrical and Power System (EPS).	Research and Design of existing and new power generation and distribution technologies that can be integrated on a rotating space station.	Yesung Baek. (YAM)

The reference frames used in orbit determination are the ECI, ECEF, and Orbital frames, as shown in Figure 1.2. 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.[3] 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.[4] 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.[5] Its perception from the rotating frame is often why it is considered a fictitious force, similar to centrifugal acceleration.[6] From an inertial reference frame - an observer outside the rotating body - the object's path continues in the direction of the tangential velocity.

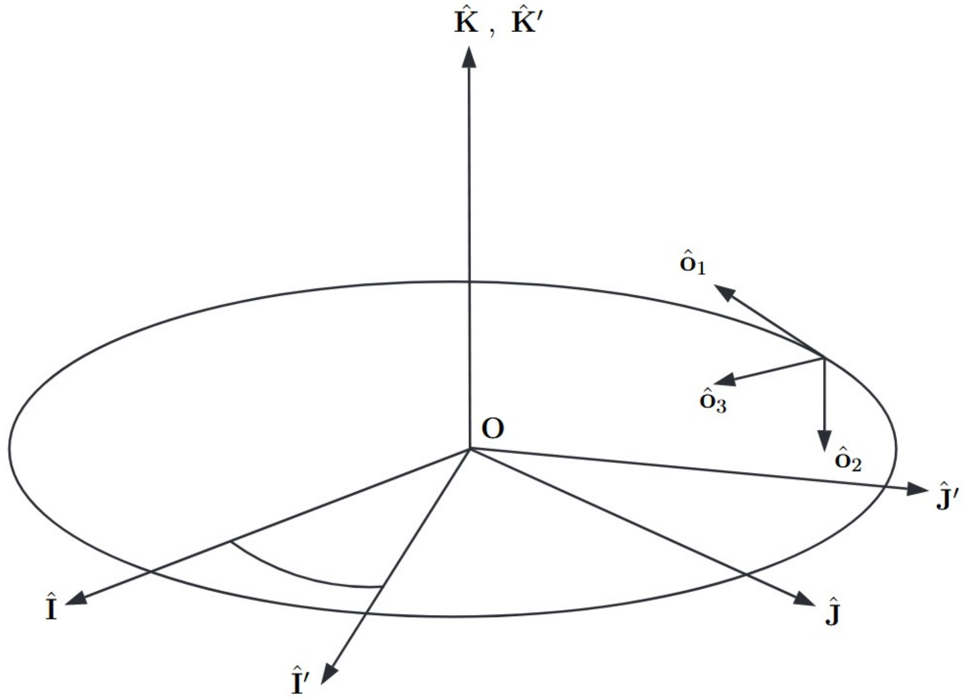

FIGURE 1.2. Earth-Centered Inertial, Earth-Centered Earth-Fixed, and Orbital Reference Frames for an Equatorial Orbit[7]

The AOCS is responsible for station keeping. 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;[8] atmospheric drag due to its altitude; J_2 perturbation, which arises due to the oblateness of the earth; solar pressure;[9] 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.

Chapter 2

Research and Design process

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,[10] the optimum Revolution Per Minute on the human body without added training to adapt to high rotation rates is 2 RPM.[11] 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.

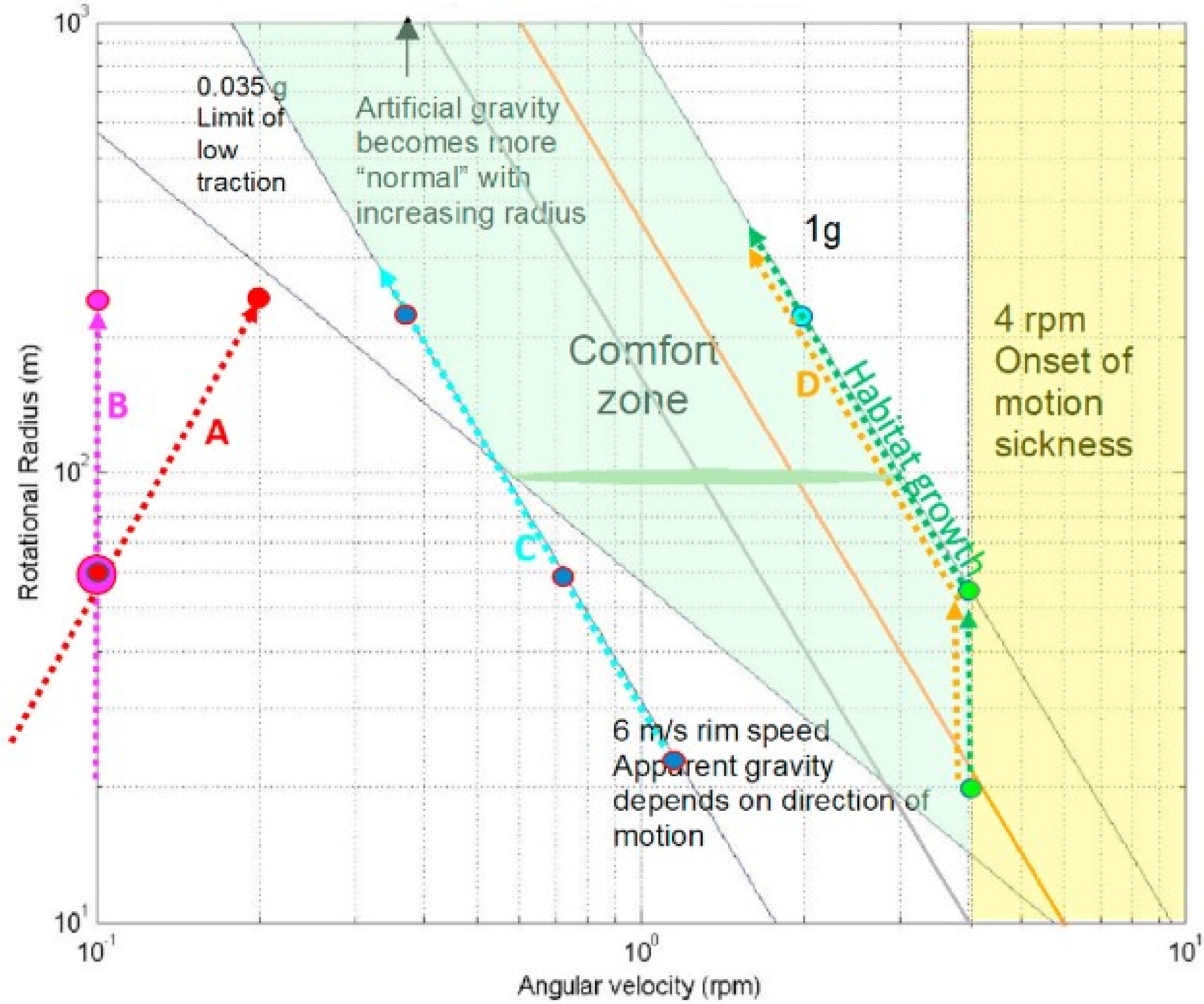

FIGURE 2.1. The Comfort Zone for artificial gravity.[12]

2.1.2 Gravity Gradient

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.

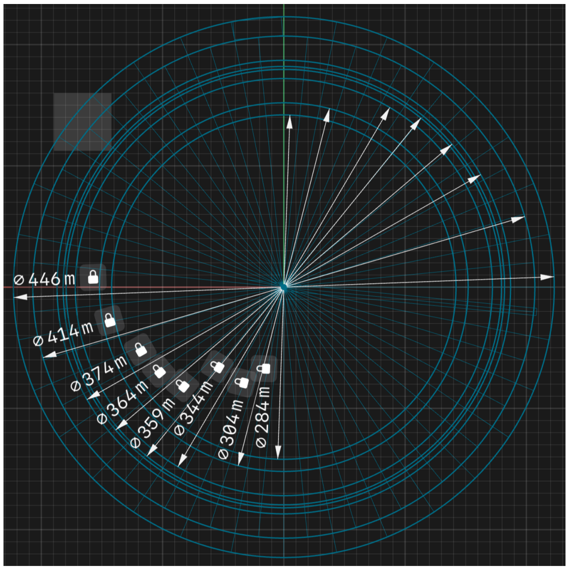

FIGURE 2.2. Diameter Distribution

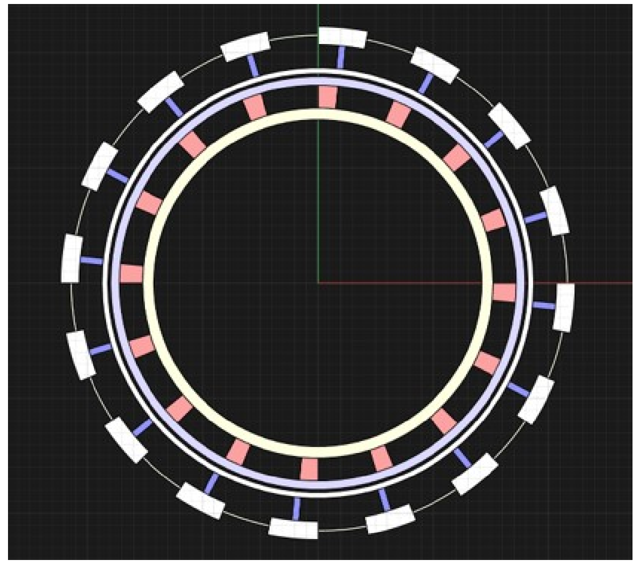

FIGURE 2.3. Top View of Station

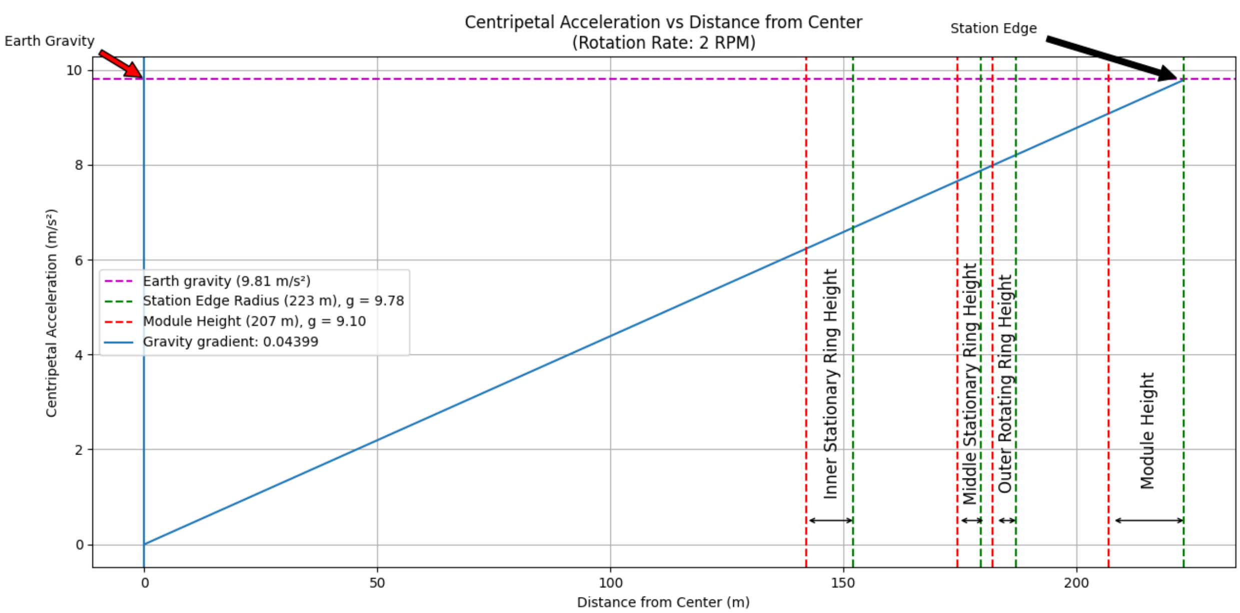

FIGURE 2.4. Graph of centripetal acceleration against radius of the station.

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[13] 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[5] 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.

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

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.[13]

Based on a study,[10] 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.[5]

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

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

Assuming an average crew mass of 82 kg,[14] 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.[13]

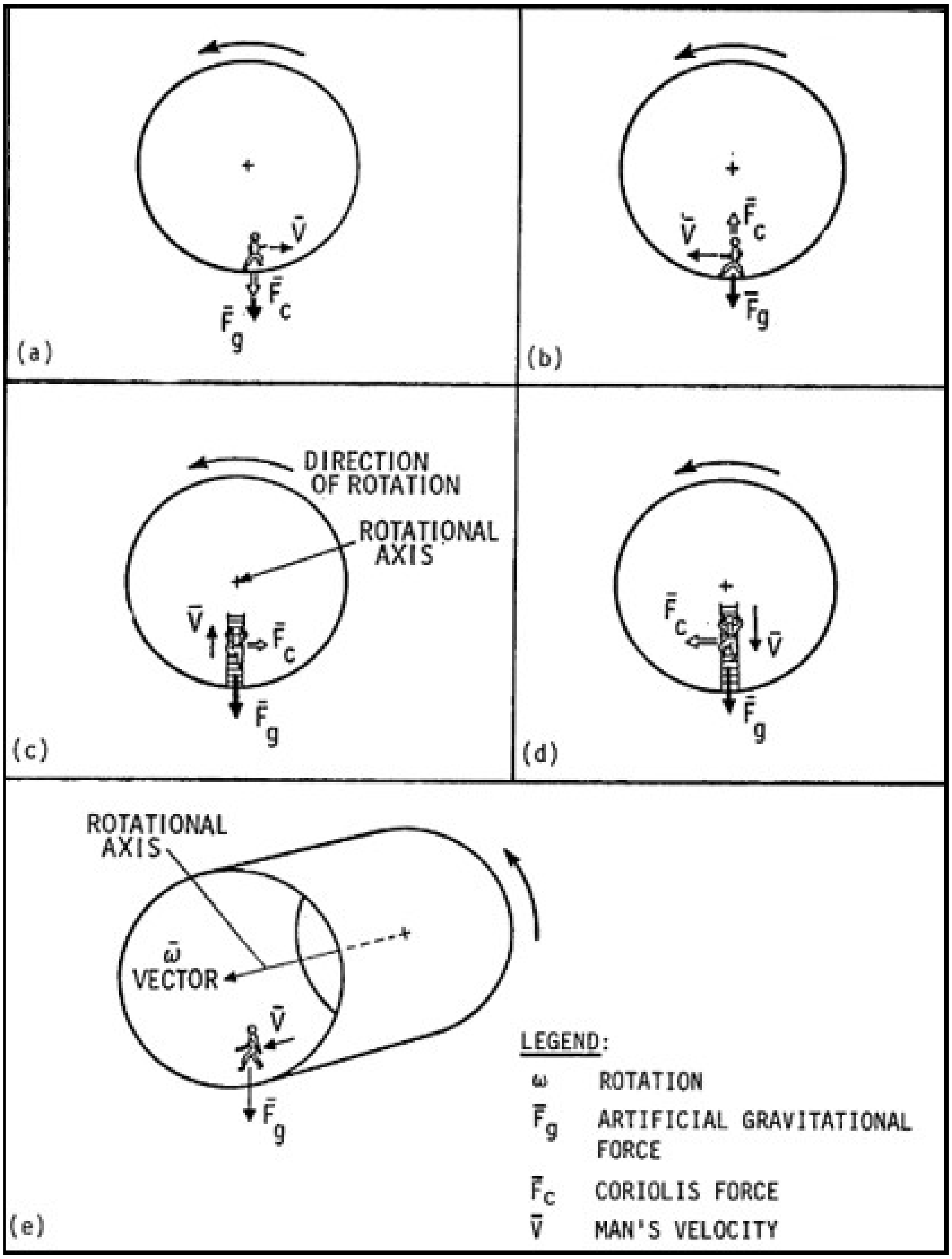

FIGURE 2.5. The Coriolis force F_c experienced when moving in a rotating body.[10]

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

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[1] 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.[15] This is a Sun-synchronous orbit, and the station processes once every year.

2.2.1 Types of Orbits

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.

Table 2.3. Literature comparison of the ISS SSO, LEO and GEO[16]

	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.[17]

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

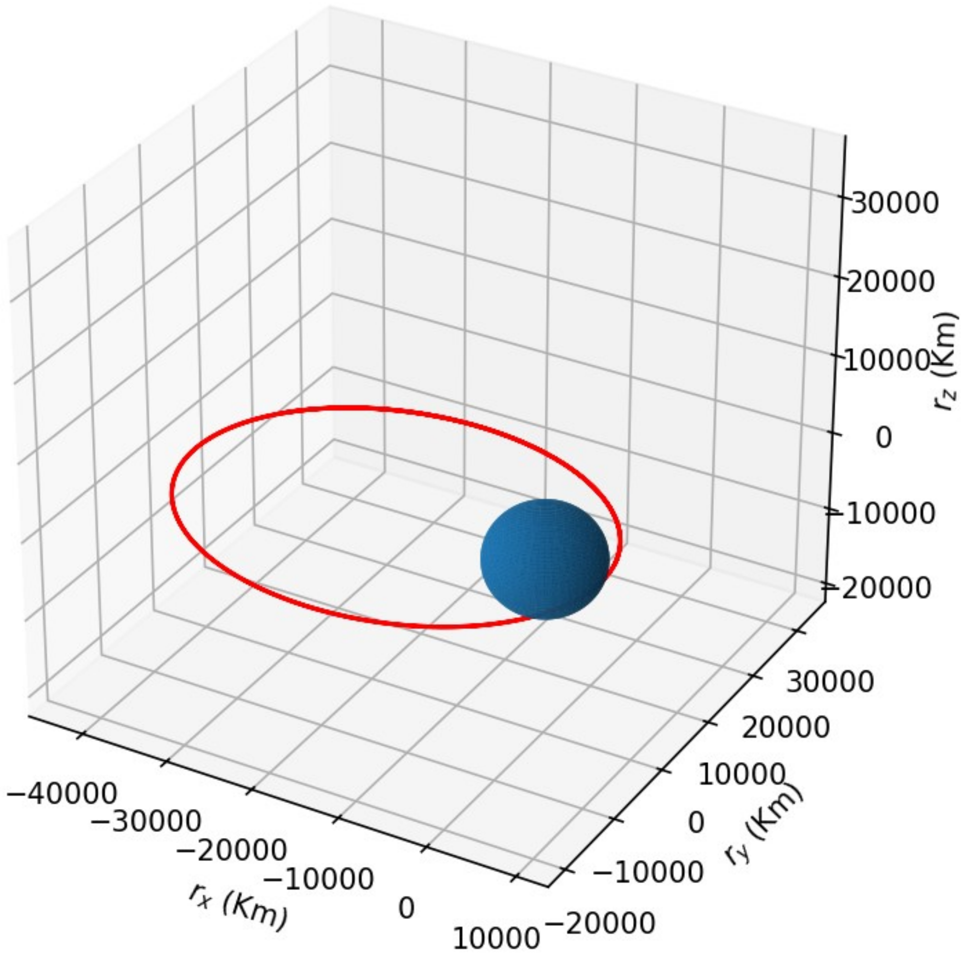

FIGURE 2.6. An Example of a 3D plot of an elliptical orbit around the earth.[18]

TABLE 2.4. The Conceptual rotating space station design orbital parameters[15]

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

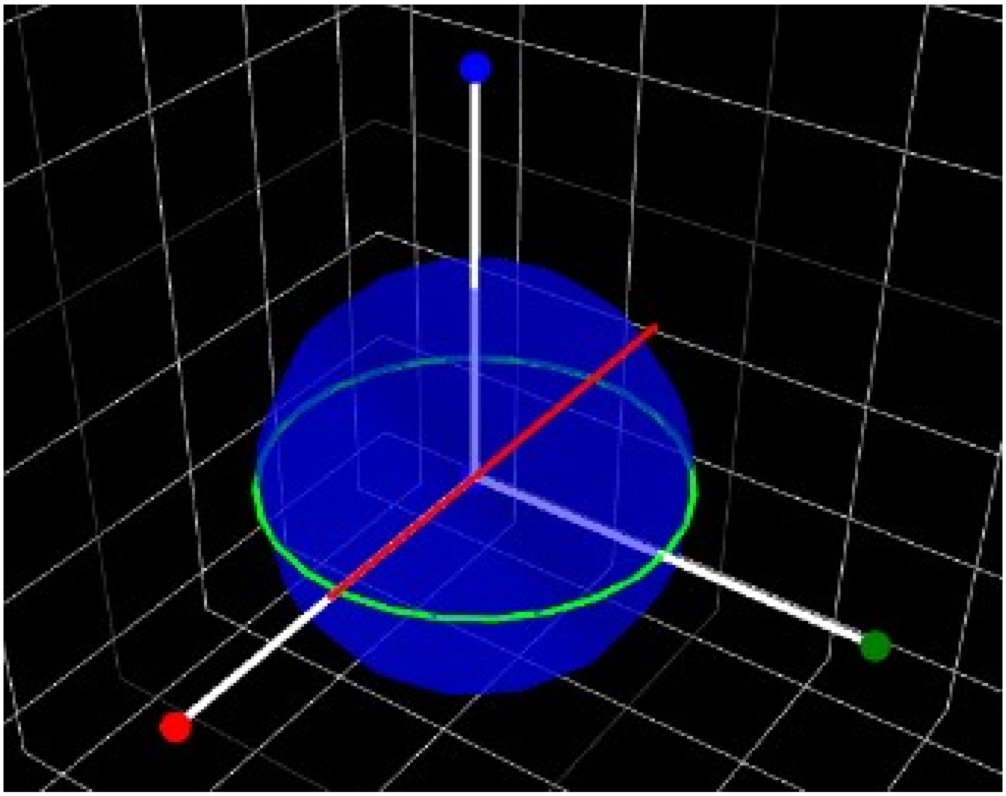

FIGURE 2.7. 3D orbit propagation from Table 2.4 for the Space station around the Earth[19]

2.3 Attitude and Orbital Spin stabilisation

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.[20] This is known as the tennis racket effect.[21] 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.

2.4 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 2.5. Decision matrix for comparing thruster systems for LEO space station applications

2.4.1 Updated Criteria Explanation with Reference Insights

(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 maneuvers (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 maneuvers. (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 (Use the Technology readiness levels on zotero as reference too.)

2.4.2 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.

2.4.3 Recommendation for the station

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 maneuvers

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 maneuvers
(3) Implement an integrated control system that can seamlessly transition between primary and secondary systems based on required response time

2.5 Drag and Debris Avoidance

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

2.6 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 3

Future Work

3.0.1 Station Keeping (include in the intro too)

- Orbit degradation: J2 perturbations, Atmospheric drag, momentum loss, solar winds, radiation, Debris contact (sample calculations and simulations (future)) - Thrusters for station keeping.

Further parameters such as the distribution of Inertia, Mass and Control systems will be determined in future works.

3.0.2 Hardware (Introduction)

- Sensors - Actuators - Control Systems - CAD of station + mass distribution being symmetrical + more calculations later - Ion Thrusters: Power requirements

3.0.3 Software (introduction)

- Python - Matlab for CS - Orbital simulators: DRAMA and Master program.

Chapter 4

Conclusions

The integration of an AOCS system has been investigated and results are presented in this report. The fundamental concepts, such as the coriolis force, which is meant to affect the crew during daily life and mission activities within the module is calculated in equation 2.11. Further research into the effect of having a low force and acceleration on the crew would need to be presented in future works. The gravity gradient calculations assist in the structural design of the station, ensuring that the materials used are strong enough to withstand the centripetal forces, tangential forces and Station spin.

Maximising safety in the rotating station is crucial to its operation as a habitat for long-term accommodation. In space, everything is a risk if not properly designed. One of the factors for safety taken into account was the orbit positioning. The chosen orbit is modelled after the orbit of the ISS,[15] which is the SSO, with a low probability of debris contact and mimics the outer planet conditions of the ISS, which has been in operation for 24 years[22] so far. the limitations to deciding based on debris probability is that the amount of debris in LEO is constantly changing. The ESA DRAMA software can help in bridging this limitation and will be used to provide more analysis of orbits.

$$T = -V_{ex} \times \dot{m} \tag{4.1}$$

Tangential thrusters will aid in rotating the station, during spin-up and spin-down operations, including keeping the station spinning. Values for the spin speed and accelerations have been calculated for the design and presented in tables 2.2 and 2.4. From the low acceleration required to spin up and keep the station stable, calculations can be done using equation 4.1 to find the thrust needed to be generated during the spin-up and spin-down operations. Where V_{ex} is the Ejection velocity and the $\dot{m}$ is the mass of propellant emitted per time interval.[23]

Comparisons between; Ion thrusters with low thrust, high specific impulse, and a lower plume/waste production; and chemical thrusters, with high thrust, low specific impulse and large fuel usage can be made and designed around specific mission parameters in the future.

The Control System aspect of AOCS will be covered in future reports, which will explore the software by using MATLAB SIMULINK to design attitude feedback and response systems. The hardware components, that will integrate with the Station structure, such as sensors and actuators that create a gyroscopic spin stability effect will also be covered in future reports.

Chapter A

Research Catalouge

Appendix is here

Bibliography

[1] C. A. Jorgensen and J. Antol, “International space station evolution data book,” NTRS Research Center: Langley Research Center (LaRC), Tech. Rep., 2000.

[2] S. Torney, “Human-research-program-overview,” NASA, Tech. Rep., 2017. [Online]. Available: https://ntrs.nasa.gov/api/citations/20170003808/downloads/20170003808.pdf

[3] “Centripetal force and centrifugal force - definition, examples, differences between centripetal force and centrifugal force and faqs.” [Online]. Available: https://byjus.com/physics/centripetal-and-centrifugal-force/

[4] N. D. Katopodes, *Chapter 10 - Geophysical Effects.* Butterworth-Heinemann, Jan. 2019, p. 710–779. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128154892000101

[5] A. Persson, “Back to basics: Coriolis: Part 1 — what is the coriolis force?” *Weather*, vol. 55, no. 5, pp. 165–170, 2000. [Online]. Available: https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/j.1477-8696.2000.tb04052.x

[6] ——, “How do we understand the coriolis force?” *Bulletin of the American Meteorological Society*, vol. 79, no. 7, pp. 1373–1386, 1998.

[7] C. D. Hall, “Spacecraft attitude dynamics and control,” *Lecture Notes posted on Handouts page [online]*, vol. 12, no. 2003, 2003.

[8] J. D. LAFONTAINE and S. C. GARG, “A review of satellite lifetime and orbit decay prediction,” *Indian Acad. Sci. (Engg. Sci.)*, vol. Vol 5, p. 62, 1982. [Online]. Available: https://www.ias.ac.in/public/Volumes/sadh/005/03/0197-0258.pdf

[9] D. P. Rubincam, “Lageos orbit decay due to infrared radiation from earth,” *Journal of Geophysical Research: Solid Earth*, vol. 92, no. B2, pp. 1287–1294, 1987.

[10] M. Queijo, A. Butterfield, W. Cuddihy, C. King, R. Stone, and P. Garn, “Analysis of a rotating advanced-technology space station for the year 2025,” The Bionetics Corporation Hampton, VA 23666, Tech. Rep., 1988.

[11] K. N. Bretl, A. T. McCusker, S. O. Sherman, T. R. Mitchell, J. B. Dixon, and T. K. Clark, “Tolerable acclimation to the cross-coupled illusion through a 10-day, incremental, personalized protocol,” *Journal of Vestibular Research*, vol. 29, no. 2-3, pp. 97–110, 2019.

[12] M. Chen, R. Goyal, M. Majji, and R. E. Skelton, “Review of space habitat designs for long-term space explorations,” *Progress in Aerospace Sciences*, vol. 122, p. 100692, Apr. 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0376042120301044

[13] “Future work to be completed by the author.”

[14] M. K. Ewert and C. Stromgren, “Astronaut mass balance for long duration missions,” in *International Conference on Environmental Systems (ICES 2019)*, no. ICES-2019-126, 2019.

[15] [Online]. Available: https://heavens-above.com/orbit.aspx?satid=25544

[16] [Online]. Available: https://www.esa.int/Enabling_Support/Space_Transportation/Types_of_orbits#LEO

[17] P. Goldreich, “Inclination of satellite orbits about an oblate precessing planet,” *Astronomical Journal, Vol. 70, p. 5*, vol. 70, p. 5, 1965.

[18] “This result has been generated by the author.”

[19] [Online]. Available: https://alfonsogonzalez.github.io/AWP/#

[20] H. Murakami, O. Rios, and T. J. Impelluso, “A theoretical and numerical study of the dzhanibekov and tennis racket phenomena,” *Journal of applied mechanics*, vol. 83, no. 11, p. 111006, 2016.

[21] P. Mardešić, G. G. Guillen, L. Van Damme, and D. Sugny, “Geometric origin of the tennis racket effect,” *Physical Review Letters*, vol. 125, no. 6, Aug. 2020. [Online]. Available: http://dx.doi.org/10.1103/PhysRevLett.125.064301

[22] L. DeLucas, “international space station,” *Acta Astronautica*, 1996. [Online]. Available: https://www.sciencedirect.com/science/article/pii/0094576596000562

[23] K. Holste, P. Dietz, S. Scharmann, K. Keil, T. Henning, D. Zschätzsch, M. Reitemeyer, B. Nauschütt, F. Kiefer, F. Kunze *et al.*, "Ion thrusters for electric propulsion: Scientific issues developing a niche technology into a game changer," *Review of Scientific Instruments*, vol. 91, no. 6, 2020.