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INVESTIGATION OF TETHERED SYSTEM FOR CREATING ARTIFICIAL GRAVITY

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INVESTIGATION OF TETHERED SYSTEM FOR CREATING ARTIFICIAL GRAVITY

A THESIS APPROVED FOR THE
SCHOOL OF AEROSPACE AND MECHANICAL ENGINEERING

BY

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DEDICATION

I dedicate this thesis to my beloved Aai, Baba, Sister, and my late Aaji (who passed away this year) for believing in my dream of becoming an Aerospace Engineer. Their unwavering support and encouragement during the last two years kept me motivated to complete this piece of work.

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A big thanks to my mother Rama for being a constant motivator. With our family going through tough times as we lost my grandmother and aunt, my mother was always there to help me stay positive. My sister Harsha and my father Vijay gave me the courage to keep pushing the boundaries and not lose hope. A big thank you to my wonderful family.

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Abstract

Interplanetary journeys are long; taking anywhere between 6 months to a few years. Studies performed with astronauts in the various space missions have provided insights on adverse effects of microgravity on the human body. Artificial gravity provides a solution to keep humans healthy in such long duration interplanetary journey. Various designs have been studied to create artificial gravity, out of which, a tethered spinning system is the most promising due to its compact structure and ability to vary the radius of rotation. Though theoretically the most promising, little investigation has been done concerning the tethered system for artificial gravity. Speculative studies and some experiments on manned and unmanned missions have been done to analyze the rotating tethered system in Earth's orbit. These studies were performed in the Lower Earth Orbit. Such studies provide an excellent opportunity to speculate about the conditions during a trajectory to Mars.

The primary purpose of this thesis is to investigate the amount of propellant required to spin the tethered system and tether materials, and also to find the deployment velocity on a trajectory to Mars. This system will increase the radius of rotation to reach a distance of 1 km from the center of rotation. To create artificial gravity, the capsules will be spun using thrusters till they reach a distance of 1 km each. This increase in the radius of rotation creates the

need to investigate the amount of propellant to spin-up and spin-down (varying the radius of rotation), as well as the rate of deployment of the tether. Ion thrusters are selected to propel the capsules, because of its low thrust and better controllability.

The propellant requirement is estimated using the rocket equation. Traditionally, the equation is used to determine the propellant required for long-distances. In this thesis, we will use the same concept for a smaller change in velocity for the spin-up procedure. To find the amount of propellant required we have considered three scenarios in which the propellant could be used by incrementing energy, radius, and velocity in steps. The steps are crucial in determining the change in tangential velocities, and by extension mass of propellant required. A balance of deployment velocity and thruster engagement will ensure constant acceleration on the floor.

The results from the simulation indicate that approximately 165 kg of fuel is required for the spin-up procedure when deployed at a gradually increasing rate, never exceeding 3 m/s. The deployment rate will help in ensuring humans in the capsules feel comfortable. This outcome will provide insight into the further investigation in the tethered system for controlled artificial gravity for human factors, tether material, and tether control. With growing interest in manned missions, an economical option needs to be investigated thoroughly. The outcome of this will provide insights on areas of further investigation to make the tethered system a reality.

Chapter 1

Introduction

In 1961 Yuri Gagarin became the first man to travel in space. We have come a long way ever since. We have developed technology to send people to the moon and back successfully. With the continuous improvement in space technology, we have sent rovers and satellites increase the knowledge about the Red Planet and paving a way forward for human exploration. Several missions have been sent to the planets in our solar system to improve our understanding of our solar system. Based on the findings from these missions, manned missions to other planets (especially Mars) has been a topic of interest for decades. Although Rovers have provided us the essential data, human missions are important where human judgment is required. It is speculated that manned missions to the Mars would become a reality in the 2030s[1].

A fuel efficient journey to Mars can take anywhere between 6 to 9 months[2]. Humans undergo physiological deconditioning due to long-term exposure to microgravity. The most prominent problems are muscle and bone density loss, cardiovascular problems, disturbance in ocular pressure due to uneven body fluid distribution[3]. To mitigate this, we need artificial gravity for long-duration space travel. Various studies have conflicting opinions about the need for artificial gravity, but it is a valid option to keep humans healthy.

1.1 Background on Artificial Gravity and Motivation Behind the Study

Konstantin Tsiolkovsky, the influential Russian space visionary, discussed the idea in his manuscript Free Space that he wrote in 1883. This manuscript was first published in English in 1956[3]. In 1928, inspired by the pioneering projections of Hermann Oberth, Hermann Noordung introduced a detailed engineering proposal for a space station that employed artificial gravity which consisted of a wheel-shaped structure for living quarters, a power generating station attached to one end of the central hub, and an astronomical observation station. Later, different designs were proposed in order to create artificial gravity such Flexible I also known as the tethered systems.

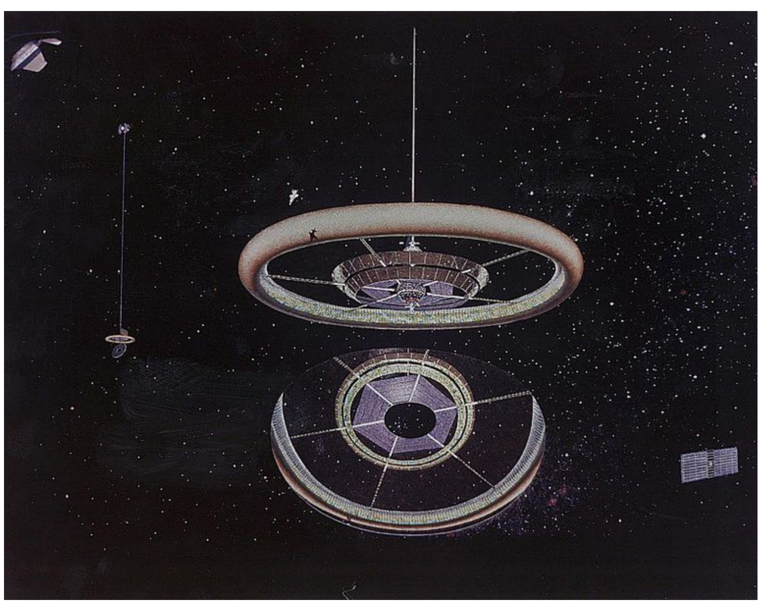


Figure 1.1: Stanford Torus - A torus concept design[4]

One of the teams working on the concept of creating artificial gravity using tethered system is CU Artificial Gravity team[5] at Cornell University. The team is working on conceptualizing the tethered system using cubesats. The team shared their work in the form of reports, in which they have primarily come up with a design for the 3-body tethered system as shown in Figure 1.2.

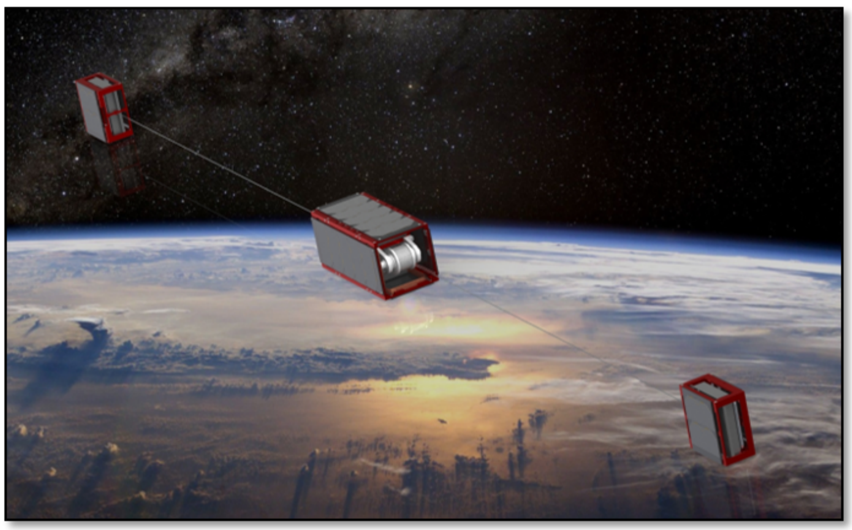


Figure 1.2: Concept design of CU Artificial Gravity Satellite Team[6]

The team has developed the concept with a mindset of testing it in Lower Earth Orbit. This concept has motivated us to investigate that if the same system is used on a journey to Mars, how much fuel would be required and what is required to make the system work in theory?

1.2 Rationale for Investigation and Research Questions

The most significant advantage of the tethered system is that large radius of rotation can be achieved - resulting in low Coriolis effect - without adding much mass to the system. Coriolis effect interferes with human comfort while moving their head. Since the tethered system comprises of 3 objects, it becomes a compact structure which will inevitably reduce the cost. The challenges associated with tether material, geometry, and control also provide an opportunity to investigate further. The lack of fully theory and implemented experiments on this subject provides the perfect conditions for developing a thesis topic.

Based on the rationale provided for investigation, we have identified a gap which leads us to a primary and a secondary research question.

Gap: Investigation of the tethered system for creating artificial gravity for manned missions in the context of Thrusters/fuel and tether material.

Primary Research Question:

How much fuel is required to spin the system to create a constant acceleration and what tether material could be used?

Research Hypothesis:

Analyzing the system under different scenarios viz. radius, velocity, and energy steps to estimate the mass of fuel will provide insights for the amount of fuel to be carried as well as the time required to spin up or down. The characteristics of tether material will be crucial in determining the feasibility of the tethered system to create artificial gravity.

Secondary Research Question:

What is the deployment velocity of the tether to maintain the required acceleration and time required to spin-up?

Research Hypothesis:

As the tether is deployed, the radius of rotation increases which decreases the acceleration. The thrusters will engage (perpendicular to the plane or rotation) to increase the angular velocity to maintain the acceleration. However, if the deployment velocity of the tether exceeds the tension limit, the tether will snap. The deployment velocity should be variable.

The outline of the thesis is discussed in Section 1.3 which is anchored in the research questions and their hypothesis above.

1.3 Outline of the Thesis

In this thesis, we consider a manned mission to Mars with 2 capsules each of 80000 kg[7] connected with a tether in between spinning to create artificial gravity. The main requirement is to create a constant acceleration (Equivalent to Mars' gravity) of 0.3g.

The structure of the thesis is given in Figure 1.3. Chapters 1 and 2 are foundational to address the research questions in terms of providing a rationale for investigation and identifying assumptions from a critical literature review. In chapter 2, we have done a critical literature review of artificial gravity, tethered missions, human factors, and thrusters/fuel. This leads to defining the assumptions and parameters to work with, encompassing human comfort in spinning spacecraft and thrusters to be used.

Chapters 3, 4, and 5 comprise the body of the thesis. Chapter 3, covers the explanation of the physics of the rotating tethered spacecraft which includes angular velocities to keep constant acceleration, the energy required to spin the system and fuel required to keep the system spinning. In this chapter, we describe the system to be investigated bounded by the assumptions discussed in Chapter 3. Chapter 4, comprises of the mathematical framework required to determine the mass of propellant required and the velocity profiles with tether deployment. This chapter is foundational to answering the research questions.

In Chapter 5, we will discuss the results gained from the simulations viz. the velocity profiles, fuel usage, and time required to spin-up and spin-down. As we present the results, we verify the results by seeing if they comply with human comfort parameters from the literature review. Discussion of tethered spacecraft without tethers would be incomplete.

Chapter 6 is a result of the special studies report, which addresses the tether design criteria, potential materials for such application (space environment and loading conditions) and deployment mechanism. Towards the end of the thesis, we summarize the findings from the research and present a way forward by presenting new gaps and research hypotheses.

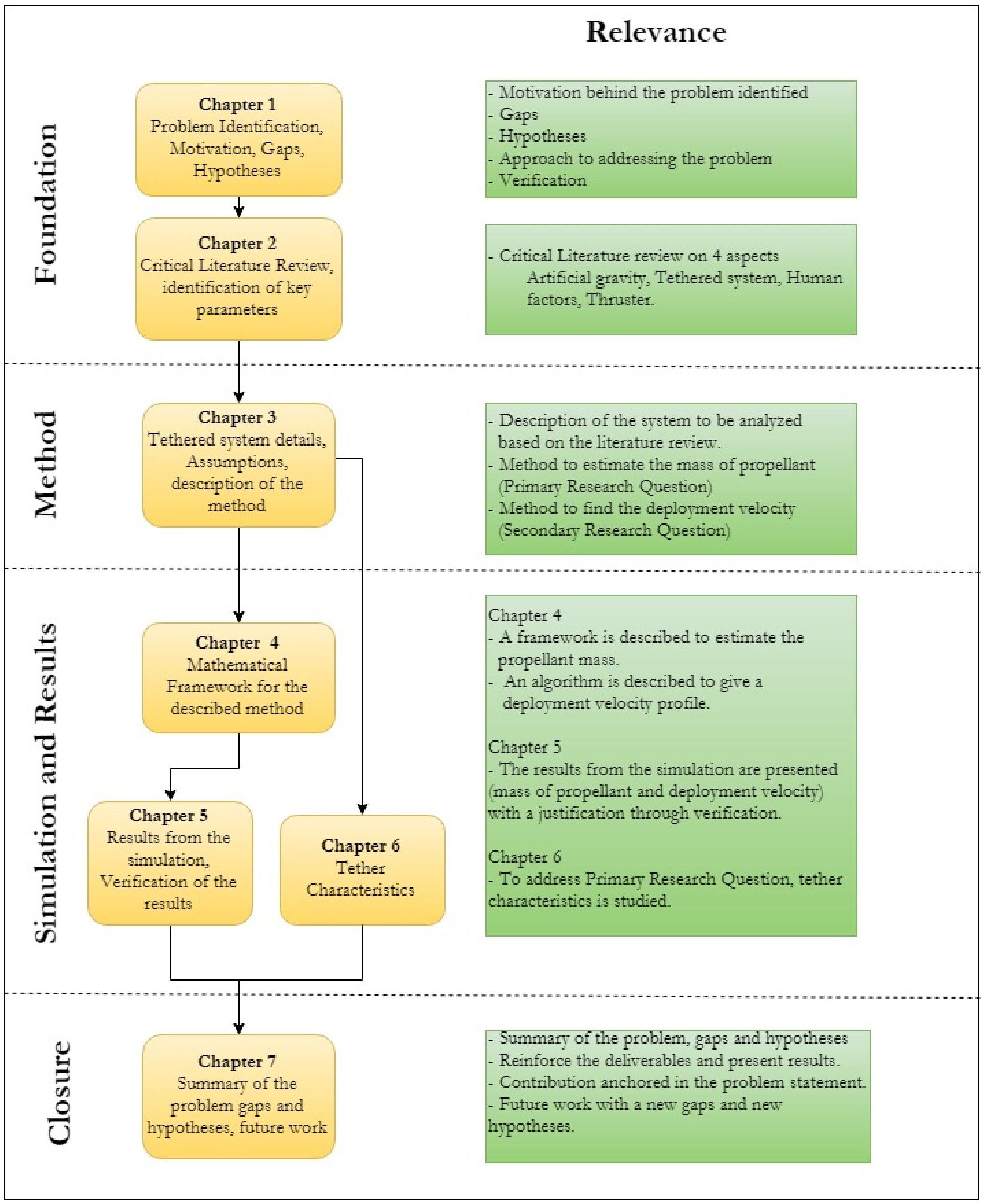


Figure 1.3: Thesis Outline - Connectivity between chapters and relevance to the topic

Chapter 2

Critical Literature Review

The idea of artificial gravity is not novel; its roots are in 19th century in concepts of Konstantin Tsiolkovski and there appeared many paper concepts during the last century. However, very little was actually realized. In this Chapter, literature about the previous artificial gravity concepts, tethered missions, and past experiments for artificial gravity in space is critically evaluated. Further, the literature on tethered system in context of artificial gravity is considered and analyzed.

Our aim with this Chapter is to look at the information from previous studies, concepts, and experiments with respect to tethered system to create artificial gravity, note key information for assumptions, and justify the research question. The review is conducted from 6 major sources published as well as unpublished. By the end of this chapter, we will have identified the current state of artificial gravity using tethered system and methods used to propel such systems and related systems (spacecrafts). We will further discuss the parameters with respect to human comfort, propulsion system used, and the method to calculate amount of propellant required which is elaborated on in Chapters 3 and 4.

2.1 Past Artificial Gravity Experiments in Space

Despite the long-standing interest in artificial gravity, experimental results obtained in space are quite limited. There were a few space missions early on that were devoted to animal studies. Rats were centrifuged continuously at 1g for several days and showed no signs of physiological deconditioning. A 2.5 m radius centrifuge was planned for installation on board the ISS to afford the opportunity to examine the adequacy of various levels of artificial gravity in protecting rodents during spaceflight. However, this project was cancelled. Human experiments with artificial gravity are even more limited. They include anecdotal reports of the crew on the lunar surface, during space missions with tethered and spinning vehicles, during orbital maneuvering systems burn, or when riding eccentric rotating chairs and sleds used by scientists for investigations of the vestibular system in orbit[3].

The first animals to be centrifuged in space were flown on the 20-day Cosmos-782 mission in 1975, when fish and turtles housed in containers were centrifuged at 1g. The center of the containers was placed at 37.5 cm from the center of a platform rotating at 52 rpm. After the flight, the physiology and behavior of the centrifuged animals was indistinguishable from their 1-g ground and 0-g flight controls. Furthermore, turtles centrifuged at 0.3g showed no of the muscle wasting[8].

In the 1966, Gemini-11 [9] tested the tethered spinning formation flight with Agena booster, where the crew experienced acceleration of 0.0005g. Though the acceleration wasn't big enough for crew to feel simulated gravity pull and to study physiological effects, it did provide some insights related to tether dynamics. In 1973, astronauts in Skylab conducted artificial gravity exercise by running in the cushioned ring in the large open space compartment [3]. In the year 1992, the STS-42 SpaceLab Shuttle mission involved linear sled which exposed test subjects to linear accelerations in the range 0.2 - 1g, however constant acceleration was possible only 0.05 g due to the short trajectory [3]. STS-90 NeuroLab mission in 1998[10] then systematically tested short-radius centrifuge, where test subjects were tested in 10 minutes centrifuge runs every other day. Even smaller doses of the acceleration were increasing the resistance against vestibular system malfunctioning and its decreased performance [9]. There were also experiments with animals and plants such as Cosmos-782, Cosmos-936, various experiments aboard Skylab, Salyut, Mir, SpaceLab and ISS [3]. Currently the ISS is equipped with European Modular Cultivation System (ECMS) Rotor providing artificial gravity 0.001g to 2.0g in 600 mm centrifuge [11].

2.2 Studies and Experiments on Tethered Missions

In 1992, one of the primary mission objectives of STS-46 was the deployment of the European Space Agency's EURECA (European Retrievable Carrier). The EURECA carried the apparatus for the TSS (Tethered Satellite System) deployment. During deployment, the satellite reached a maximum distance of only 860 feet from the orbiter instead of the planned 12.5 miles because of a jammed tether line. After numerous attempts over several days to free the tether, TSS operations were curtailed, and the satellite was stowed for return to Earth. It would be re-flown in 1996 on STS-75[12]. The primary objective of STS-75 was to carry the Tethered Satellite System Reflight (TSS-1R) into orbit and to deploy it spaceward on a conducting tether. The mission scientists hoped to deploy the tether to a distance of 20.7 kilometers (12.9 mi). The tether broke after being deployed for over 19 kilometers[13]. Multiple unmanned experiments on tethered systems have been performed such as Tempo3[14], ProSEDS, Yes2[15], and simulation experiments such as CU Artificial Gravity[16]. The findings from CU Artificial Gravity have given insights on controlling the tether and maintaining stability in 2 axes and also about the mode of propulsion being the torque coils.

2.3 Artificial Gravity Concepts

NASA's fascination during 1960s and 1970s to make space colonies is evident in the multiple studies [17][10][18][19]. One of the concepts worked out was the Discovery II spaceship[19] which was used in the movie '2001 - A Space Odyssey'. The spacecraft produced an artificial gravity of 0.2g with a rotation rate of 3.25 rpm and the rotation arm 17 m. This accounted to a gravity gradient of 12 milli-g/m. In contrast to the design of Discovery II, Professor O'Neill and his students at the Stanford university worked out the concept rotating cylinders to create artificial gravity with radius up to 32 km creating 1g. It was designed to be stationed in one of the Lagrange points[19] and powered by solar energy. It was an elaborate description with rigorous calculations, the concept never took shape due to funding constraints and shift in focus to other missions[18].

Table 2.1: Systematic representation of the sources and the parameters taken into consideration for literature review in context of the problem statement

Papers/Books	Tethered Spacecrafts	Human Factors	Propulsion	Reeling/Unreeling Travel Duration	Travel duration	Comments
Space Architecture [20]		x			x	Discussion on Human comfort factors.
Artificial Gravity[9]	x	x	x		x	Discussion on human factors, tethered spacecrafts, propellant use
CU Artificial Gravity [5]	x		x	x		Discussion on propulsion system, extensive analysis of tether dynamics
Schultz [7]	x	x	x	x	x	Duration of mission and corresponding propellant required
Space Vehicle Design[21]			x			Tsiolkovski equation to determine mass of propellant required
Ion Propulsion[22]			x			Discussion about electric propulsion. Information about how thrusters are used.

Table 2.1 represents the synthesis matrix to organize the literature. The matrix has references on the vertical axis and attributes on the horizontal axis. The ‘x’marking represents the presence of a particular attribute in a particular reference (a book or a paper).

The unpublished material, provided by the CU Artificial Gravity team at the

Cornell University[5], considered a tethered satellite system with 2, 3U cubesats with a tether deployment mechanism. The team has done an extensive analysis on determining the shortfalls of torus shaped and a rigid I shaped designs, which provides a rationale for investigating tethered system for artificial gravity. They have considered torque coils to spin-up the cubesats. This is a good consideration when experimenting in Earth's orbit where the magnetic field is strong but might not be applicable for interplanetary missions. In addition, the team discussed only about one orientation, which is rotation after complete deployment, but it is unclear what would happen if the system is slowly deployed after starting the rotation. This aspect is worthy of investigation.

Clement [3] discusses a variety of aspects about human comfort factors in Chapter 3. According to the chapter, humans are most comfortable with rotation speed of 6rpm or less, which CU gravity team and Hall[23][20] agrees with. The gravity gradient is an important consideration for human comfort. Clement and Hall agree that smaller the ratio of acceleration felt from head to toe, better is the comfort which is about 2%. The gradient is more for radii less that 12 m. Hence, in this thesis, we will assume the rate of rotation to never exceed 6rpm and a minimum radius of 12m.

Schultz[7] has data and discussion which is the most relevant to propelling the tethered system for spinning up and down. The author estimated that for a tethered system with modules having mass 80000 kg[7], approximately 14400 kg of cryogenic propellant would be required for 1 cycle and 1 contingency cycle. Schultz[7] has not exclusively provided the calculation, but it is evident that he has used the rocket equation for calculating the amount of propellant required. The rocket equation is described in the book Space Vehicle Design [21]. If any changes are to be made for maneuvers in space, either thrusters are used, or gravity assist is used to change the delta v which can be predetermined based on the mission time. Based on the paper[7] the ratio of mass of propellant and mass of module is 0.18. It is clear that it is better to have this value as close to 0 as possible which will make the mission more cost efficient due to the fact that the propellant is the most expensive parameter in space missions.

2.4 Discussion on Thrusters for Creating Artificial Gravity

Many tethered experiments have been conducted in the lower earth orbits. The thrusters for this application (creating artificial gravity) needs to create a slow thrust which should be easy to control. A gradual increase in thrust will result a gradual increase in acceleration. A sudden increase in acceleration results in jerk. Not only will this make the system difficult to control, but might cause discomfort to the astronauts inside the capsules.

There are different types of thrusters that could be used for this application such as ion thrusters, cold gas thrusters or cryogenic propellant. Cryogenic propellant[7][24] usually comprises of liquid propellant + oxidizer. This is a bulky apparatus. Moreover, the thrust provided is more than cold gas or ion, and hence would create unstable dynamics which will be difficult to control, and uneasiness in astronauts. Ion thrusters have a compact structure, a low thrust but high exhaust velocity. This makes them very effecient and, the spacecraft easy to control, but takes long to spin up or down. Cold gas thrusters are typically used for attitude control, or by astronauts for Extra Vehicular Activity. In case of cold gas thruster, it has a compact structure where thrust produced is nor too high nor too low, but the probability of leakage is high[25], which does not make it a great fit for the application.

Based on the literature, Schultz[7] has estimated that 14400 kg cryogenic propellant would be required for 1 cycle and 1 contingency cycle for a 80,000 kg module. The calculation was anchored in the rocket equation.

$$\begin{aligned} m_p &= m_d[e^{(dv/v_{ex})} - 1] \\ m_p &= m_d[e^{(dv/I_{sp}.g_0)} - 1] \end{aligned} \tag{2.1}$$

Before starting to estimate the propellant required we will discuss the 3 most common thrusters:

Table 2.2: Commonly used thrusters and their parameters

Thruster	I_{sp}	v_{ex}	Thrust
Cryogenic[26]	433	4330 m/s	66.7 x 10^3 N
X3 Ion thruster[27]	4190	30000 m/s	5.4 N
Cold gas (Nitrogen)[28]	80	800 m/s	0.01 N

Schultz [7] has used the rocket equation to find the mass of propellant required. According to this for a module of mass m_d = 80000 kg will require 14400 kg of propellant considering dv = 716 m/s. From this example we know that rocket equation works for smaller change in velocity. In this thesis, we will use an ion thruster instead of the cryogenic thruster mainly because of rapid advancement in ion propulsion [22]. The I_{sp} is high which means we would need less propellant to produce a certain amount of thrust. This will allow us to use a compact structure, which would not make the apparatus too heavy.

Based on the literature review, it is worth investigating the scenario of varying radius of rotation and the amount of propellant required to spin up and down as discussed by Schultz[7]. CU gravity[5] and Schultz[7] have considered fixed radius rotation, hence, it will be interesting to find what steps could be taken to use the propellant efficiently for varying radius or rotation. This will be a critical factor in addressing my main problem statement which is to create artificial gravity to reduce the effects of long duration exposure to micro-gravity and not make them feel sick.

2.5 Synopsis of Chapter 2

In this Chapter, we have critically reviewed past and current studies, concepts and experiments on tethered missions and artificial gravity and identified the key assumptions and parameters crucial for investigation of the research questions. In Chapter 4, we will discuss the requirements for the model to be analyzed in order to answer the questions anchored in the literature review.

Chapter 3

The Physics behind Artificial Gravity using a Tethered System

In Chapter 2, we have briefly discussed on the concepts to generate artificial gravity. The underlying principle is that the system spins to create an outward force which enables a person to stand, similar to that of Earth. Artificial gravity using tethers have a working principle similar to (but not the same as) the example of string and ball. Consider a ball attached at the end of a string as shown in Figure 3.1. When we spin the ball, the angular speed (ω) increases. As a result, the string becomes taut when the angular speed creates enough reaction force - centrifugal force - resulting in radially outward acceleration. Artificial gravity created by spinning a spacecraft works on the same principle.

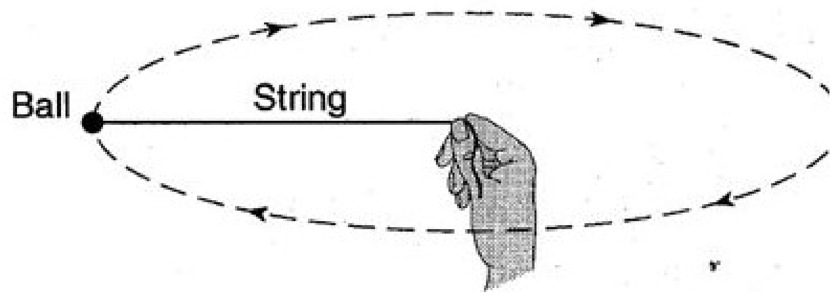


Figure 3.1: Ball spun using a string in horizontal plane

Table 3.1: Parameters and constraints from literature review

Parameters	Values
Angular Velocity (ω)	< 6 rpm
Minimum radius of rotation (r_{min})	12 m
acceleration	0.3g (Mars' gravity)

3.1 System Setup

The summary of the key findings from the literature review is presented in Table 3.1. In addition to these findings, we have assumed the dry mass of the capsule to be 80,000 kg[7] and the maximum radius of rotation of 1000 m, beyond which the Coriolis effect reduces significantly[3]. Based on these parameters, we set up the system to be analyzed. The tethered system would consist of 3 major components - a long tether or pieces of tethers, 2 capsules at each end of the tether, and a center block with deployment mechanism (containing a spool and reel controlling mechanism) as shown in Figure 3.2. The Cornell University Artificial Gravity Team[16] have provided an extensive analysis of why a three-body system works better than a 2-body system in their report.

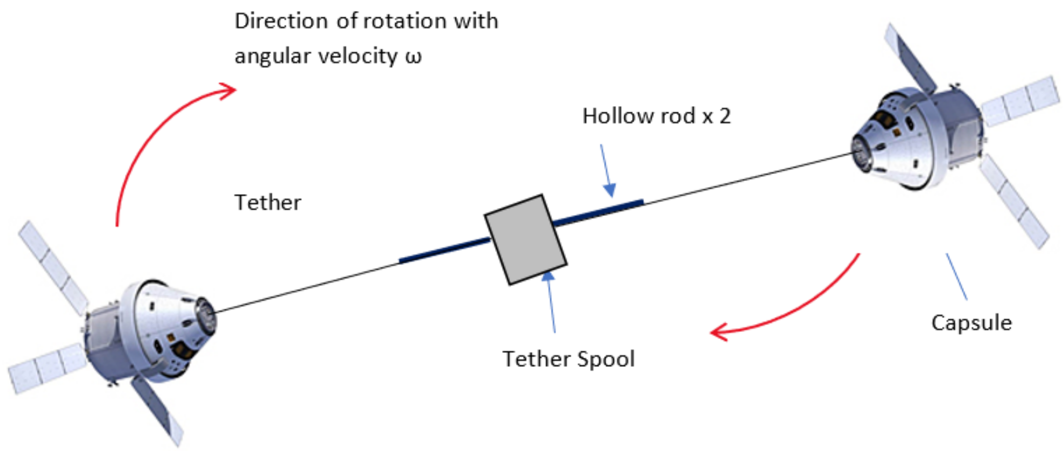


Figure 3.2: Pictorial depiction of the 3 body-system (Not to scale)

In the illustration created in Figure 3.2, the two rods attached to the spool serve as components to keep the capsules at a minimum radius of rotation[1]. The 2 rods will contain tether from the spool. The mass of the two capsules is 80000 kg[7] each. We want to simulate Mars' gravity of 0.3g or 2.94 m/s^2 at the floor of the capsule. Denis Zanutto in the Chapter 8 his PhD Dissertation[29] has done an extensive study on selection of the tether spool based on deployment strategies. Based on his work, a standard spool in the center block is assumed to be of 2x2 m. A habitable module such as Orion capsule has a height of 3.3 m[30]. To satisfy the condition of initial radius to be a stable 12 m, we considered a rod of 9 m on either side.

In order analyze the system, we have considered some assumptions. It is important that the end masses are the same or at least similar to ensure the simulated gravity in both the capsules is the same. The tether dynamics is not taken into consideration for simplicity. Further, it is assumed that the tether will have some tension due to the outward force pulling it and the angular

[1]This is a hypothetical system and the rods serve only as fillers to maintain the minimum radius of rotation. The distance can be maintained by using other components

momentum is conserved.

3.2 Spinning the System

If we were to consider a system as mentioned in Section 3.1, there are 2 ways in which the system could spin: deploy first and then spin the system, or spin first and then deploy the tether.

In the first scenario, if the tether is deployed to its full length and then spun, 2 major problems arise. First, realistically, the tether dynamics makes controlling the spin difficult and second, since the overall angular velocity will not be the same in all the 3 blocks[16], the tether might tangle before the momentum builds up. In addition, if the central block (containing the tether spool) has distinct edges, the tether will get damaged, and even break, if it winds about the central block. If the tether is deployed completely and then spun-up, the tether dynamics remains of unpredictable nature even if a mechanism like torque coils[31] are used.

In the second scenario, we spin-up the system first and then deploy. This serves two purposes. First, the angular velocity is built up with the initial spin. When we spin the system up to 6 rpm all the three bodies have the same rpm, but as the radius increases, the center block will stay constant (6 rpm) while the other 2 modules will become slow. Now, we increase the rpm to keep the acceleration constant. So, if center block is 6 rpm, the system is deployed till 1000 m, the angular velocity needs to be $\sqrt{0.3 * 9.81/1000} = 0.07$ rad/s. Because this is the case, the torque coil [16]. like mechanism is needed to control the rpm of the central block to avoid tether entanglement. Secondly, the pull force created by the spinning system coupled with an outward velocity will create enough tension to spin-up (reducing the uncertainty associated with tether dynamics in reality.)[9]

It is possible to have different ways of spin-up and deployment sequences. In this thesis, having analyzed the 2 scenarios, spinning first and then deploying reduces the problem of tension in the tether along with over-all angular velocity, and hence, is the foundation of the working principle of the spinning tethered system.

In Section 3.2, we will look at the system in two main stages of initial spin-up and deployment.

3.2.1 Stages of the Tethered System to Create Artificial Gravity

Table 3.2: Stages of tethered system to create artificial gravity

Stage 0	**Stage 1: Spin-up**	**Stage 2: Tether Deployment**
r = 12 m w = 0 a = 0	r = 12 m w = 0 to 6 rpm a = 0 to $4m/s^2$ Change in tangential velocity: 0 to 7.4 m/s	r = 12 to 1000 m w = 0.6 to 0.07 rad/s a = 4 to $3.93m/s^2$ Change in tangential velocity: 7.4 to 54.6 m/s

In table 3.2, it is clear that there is a change in velocity in stages 1 and 2. This implies we need to engage thrusters to maintain a constant acceleration. This will give the help us calculate the amount of propellant required for one spin-up procedure. With increasing radius of rotation, the acceleration at the floor would reduce and hence, requires to increase the angular velocity. This process is described in detail in Chapter 4. Throughout the process of unreeling, theoretically, the centripetal force should not exceed the tensile strength of the material of the tether. In practice, interference of different factors such as change in spin rates, wobbling nature of the satellites, etc. would make it difficult to determine (mathematically model) exact forces on the tether.

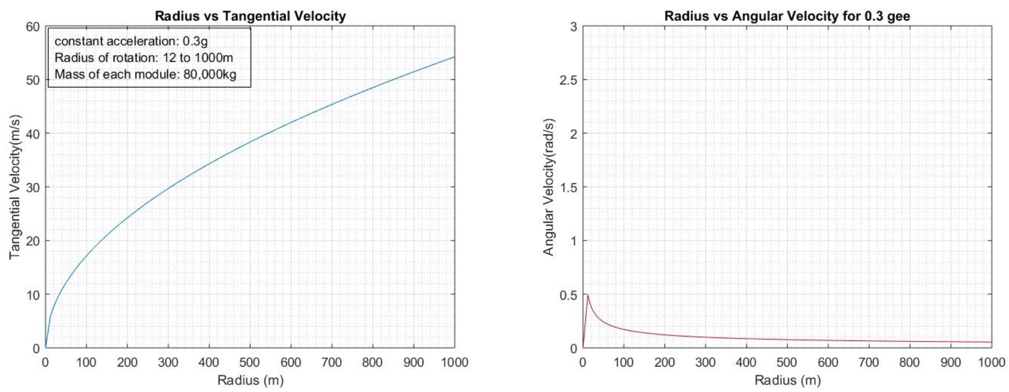
3.2.2 Reeling Procedure

The first step in reeling would be to start reeling the tether first which will increase the angular velocity. The thrusters need to be engaged similar to the unreeling procedure. The tension in the tether is equal to $mr\omega^2$, hence, when we reel the net force is will be equal to force+tension. This can create more stress on the tether. Since the tether is pulling the capsule in, the net force on the tether would be twice as much as the original tension $mr\omega^2$. This is something that needs to be taken into consideration while reeling. Stress = Net Force/Cross-sectional area of the tether. Since the thrusters need to be engages in similar way, it is reasonable to estimate the fuel to be twice as much as unreeling procedure.

Having laid the foundation of the spin up and spin down method, we will focus on: Producing an acceleration of 1g. (Earth's gravity)

3.3 Relations between Radius, Velocities, and Rotational Kinetic Energy

From the literature review, we have chosen the maximum rate of rotation to be 6 rpm (0.6 rad/s). By using the spinning method discussed in Section 3.2, we spin the system to an initial angular velocity of 0.6 rad/s. Then as the radius increases, the rotation speed reduces as shown in Figure 3.3.



(a) Radius vs Tangential Velocity (b) Radius vs Angular Velocity

Figure 3.3: Change in tangential and angular velocity with increasing radius

The Figure 3.3 gives the trend of change in angular and tangential velocities as the radius of rotation increases to 1000 m for creating an acceleration of 0.3g. The tangential velocity increases to approximately 54 m/s while the angular velocity decreases to 0.07 rad/s.

Also, it is important to note how angular momentum increases as the radius increases. The change in angular momentum implies more energy (and by extension more fuel) is required to change the angular velocity at a given radius.

$$E = \frac{1}{2} I \omega^2 = \frac{1}{2} m_d v^2 \tag{3.1}$$

We know that $I = mr^2$ for point mass and acceleration in a circular motion is $a = r\omega^2$. Hence,

$$E = \frac{1}{2}m_d r^2 \omega^2 = \frac{1}{2}m_d a r \tag{3.2}$$

Equation 3.1 indicates the Energy at a given radius is directly proportional for a given acceleration.

$$\begin{aligned} L &= I\omega \\ E &= \frac{1}{2}L\omega \end{aligned} \tag{3.3}$$

Where,

E: Rotational Kinetic Energy

I: Moment of Inertia

ω : Angular Velocity

L: Angular Momentum

r: Radius of Rotation

v: Tangential Velocity

m_d: Dry Mass

From Equation 3.3 it can be inferred that the amount of energy required is proportional to the angular momentum, and hence, larger radius will require more energy to increase the angular velocity due to conservation of angular momentum.

In the next section, we will look at estimating the mass of fuel to spin-up or spin-down the system.

3.4 Mass of Propellant Required

Tsiolvski, the father of rocket science, came up with an equation which helps us find the amount of fuel required to accelerate from initial to final velocity. To find the mass of propellant required to make the human module to rotate is to $3m/s^2$ we use the following equation.[21]

$$v_i - v_f \;=\; dv \;=\; v_{ex} ln \,\frac{m_d}{m_d + m_p} \tag{3.4}$$

Where, m_d: dry mass, m_p: mass of propellant v_{ex}: exit velocity of the propellant Hence, we used the equation to determine the mass of propellant required for every the change in tangential velocity.

$$m_p = m_d[e^{(dv/v_{ex})} - 1] \tag{3.5}$$

In Equation 3.5, the change in velocity is associated to the mass of propellant required. We assume that a constant thrust is being applied to the system, which implies fuel is used until the system is completely deployed. This estimation will help with carrying an appropriate amount of fuel.

For the system under consideration, the assumption is that we are creating an acceleration of 0.3g or 2.94 m/s^2, at the floor of the module. As the radius increases, the tangential velocity increases if we are to keep the acceleration constant. To make corresponding changes in tangential velocity, we need to use some propellant which is governed by the rocket equation.

The deployment velocity depends on the thrust required to change the tangential velocity in order to create constant acceleration. In stage 2, as mentioned in 3.2, the tether needs to be deployed up to 1 km. The results on deployment velocity are discussed in Chapter 5.

3.5 Synopsis of Chapter 3

In Chapter 3, we describe the system under consideration, propose and elaborate the method to answer the research questions. We began by illustrating the tethered system based on the key findings in Chapter 2. Then, based on the details, we discussed and analyzed the spin-up procedure briefly, thereafter establishing stages of spin-up. In Section 3.3, we looked at the relation between radius, velocities, and energy, and their relation with mass of propellant required and deployment velocity. In Chapter 4, we will setup a logic for simulation, important to determine the results.

Chapter 4

Simulation of the Tethered System

Simulating artificial gravity in space has its own limitations. A computer simulation helps us understand the system behaviour and estimate requirements. However, depicting the real system requires accurate mathematical modelling of the tether and its dynamics, capsules, temperature, wobble, and much more. In this Chapter, we will look at the framework required for simulation with a rough mathematical model[2]. This framework aids us to answer the research questions of estimating the mass of propellant required deployment velocity.

4.1 Trapezoidal Rule of Numerical Analysis

In numerical analysis the trapezoidal rule (also known as the trapezoid rule or trapezium rule) is a technique for approximating the definite integral. The trapezoidal rule works by approximating the region under the graph of the

[2]A rough mathematical model is simplifying the complexities by making assumptions in the system to create a rough estimation

function as a trapezoid and calculating its area[32]. It follows that:

$$\int_a^b f(x)dx = \frac{\Delta x}{2}[f(x_0) + 2f(x_1) + 2f(x_2) + ... + 2f(x_{n-1}) + f(x_n)] \quad (4.1)$$

Where, $\Delta x = \frac{b-a}{n}$ and $x_i = a + \Delta x$

In this thesis, we use this principle to find the total mass of propellant required by integrating over small changes in change in velocities (dv). The small intervals provides us an opportunity to look at the deployment velocity profile.

4.2 Mathematical Framework to Simulate Tethered System

4.2.1 Estimating Propellant Mass

In Chapter 3, we have laid out two stages for system spin-up and deployment. It is also established that fuel is required for each of these two stages. The rocket equation 3.5 is dependent on the change in velocity dv. In stage 2, as the radius of rotation gradually increases, the tangential velocity remains the same, which reduces the acceleration at the floor of the capsule due to law of conservation of momentum. Thrusters are required to increase the tangential velocity in order to keep the acceleration constant. In Figure 3.3 it is evident that the tangential velocity increases as the radius of rotation increases. This corresponds of the desired velocity at that radius of rotation, hence, the change in velocity is the difference between the desired velocity and the velocity before thrusters are applied.

In context of this section, the trapezoid rule is modified to be used to calculate the sum and not the area under the curve. For analysis, we have considered a very small step-size (h) for the 3 scenarios,

1. Equal radius steps
2. Equal energy steps
3. Equal velocity steps

In all the three scenarios, the dv is different to keep the acceleration constant.

Equal Radius Steps

To calculate the mass of propellant required, the following steps are carried out.

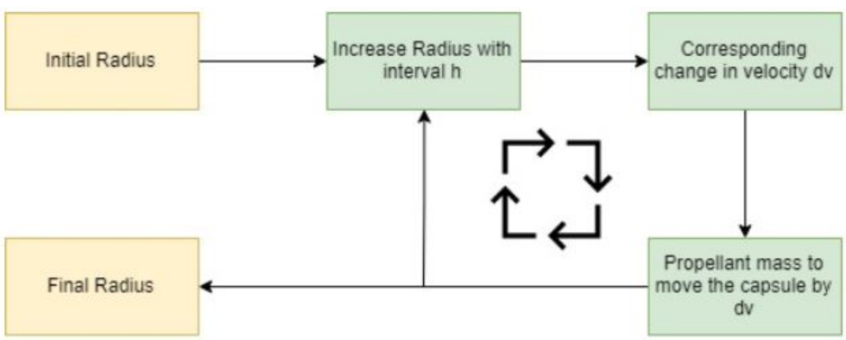


Figure 4.1: Trapezoidal rule to estimate propellant for radius steps

Here,

$$
\begin{aligned}
h_r &= \frac{r_f - r_i}{\text{Number of steps}} \\
dv &= v_2 - v_1 = \sqrt{ar_2} - \sqrt{ar_1} \\
m_p &= m_d(e^{\sqrt{ar_2} - \sqrt{ar_1}/v_{ex}} - 1)
\end{aligned}
\tag{4.2}
$$

Equal Energy Steps

To calculate the mass of propellant required, the following steps are carried out.

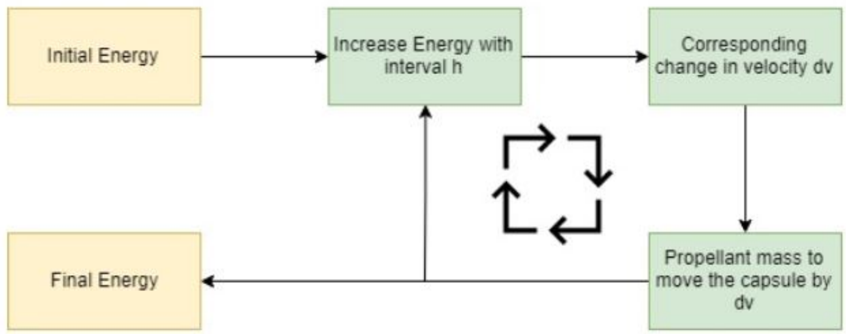


Figure 4.2: Trapezoidal rule to estimate propellant for energy steps

Here, the dv is calculated

$$\begin{aligned} h_e &= \frac{E_f - E_i}{\text{Number of steps}} \\ dv &= v_2 - v_1 = \sqrt{\frac{2E_2}{m_d}} - \sqrt{\frac{2E_1}{m_d}} \\ m_p &= m_d(e^{\sqrt{\frac{2E_2}{m_d}} - \sqrt{\frac{2E_1}{m_d}}/v_{ex}} - 1) \end{aligned} \tag{4.3}$$

Equal Velocity Steps

To calculate the mass of propellant required, the following steps are carried out.

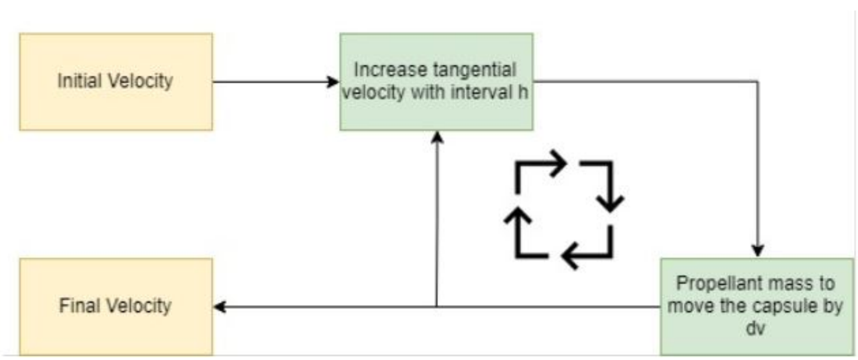


Figure 4.3: Trapezoidal rule to estimate propellant for energy steps

$$
\begin{aligned}
h_v &= \frac{v_f - v_i}{\text{Number of steps}} \\
dv &= v_2 - v_1 \\
m_p &= m_d(e^{v_2 - v_1}/v_{ex} - 1)
\end{aligned}
\tag{4.4}
$$

In the Equations 4.2, 4.3, and 4.4, h_r, h_e, h_v are the intervals for radius steps, energy steps, and velocity steps respectively. The simulation runs for initial and final parameters with an interval of h as shown in Figures 4.3, 4.2, and 4.1. The interval h becomes smaller as the number of steps increases.

We then calculate the change in velocities for those intervals and calculate the mass of propellant required. The simulation is setup in a way that it adds the propellant mass calculated with each step, giving the total mass of propellant in the end. The same principle is true for time required for spin-up and deployment velocity.

4.2.2 Time Required to Spin-up and/or Spin-down

The time required to spin-up or down is given by the equation

$$
dt = \frac{m_d dv}{Thrust} \tag{4.5}
$$

This equation is derived from the Newtons second law of motion $F = ma = m\frac{dv}{dt}$. The thrust provided by the thrusters provides an external force required to change the tangential velocity. The total time required is calculated by integrating the equation and is estimated using numerical approximation.

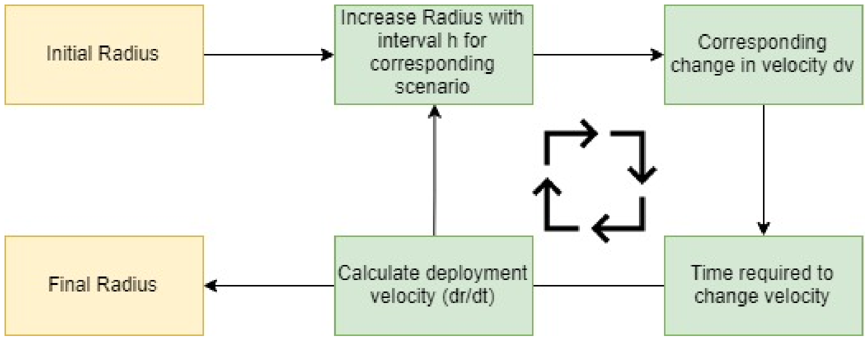


Figure 4.4: Method to calculate time required to spin-up and deployment velocity

Figure 4.4 shows the simulation logic to calculate the time required to spin-up the system. This logic is executed in the same loop as that of the mass of propellant loop in Section 4.2.1. Hence, the plot generated will help us understand how fast or slow the tether needs to be deployed with respect to time.

4.2.3 Deployment Velocity

Expanding on Chapter 3, Section 3.2 the deployment velocity is directed radially outward. Mathematically, deployment velocity = dr/dt. This is also calculated in the same loop as 4.4.

In radius steps, the dr is the same as h and dt is calculated as described in Section 4.2.2. In energy steps, we use the Equation 3.1 $r = aE/m$ to calculate the corresponding radius at that instance, and then calculate dr. Similarly, in velocity steps, the corresponding radius is calculated using Figure 3.3 based on the equation $r = v^2/a$. The plot of dr/dt in Chapter 5 gives us the trend of deployment velocity.

Understanding how fast to deploy the tether is equally important to maintain tension in tether. Mathematically this will be a plot of dr/dt vs time.

Deployment Using Polar Plot

Polar plots are useful to capture the motion of a rotating object; in this case, the tethered capsule. The simulation setup to determine the capsule profile is given below. The simulation runs for 900000 seconds[3]

Stage 1: The initial conditions for the capsule is r=12, w=0, a=0. The thrusters with 5.4 N thrust are engaged and the system starts to spin-up. From Newton's second law of motion,

$$
\begin{aligned}
F &= m_d a \\
Thrust &= m_d \frac{dv}{dt} \\
dv &= \frac{Thrust}{m_d} dt
\end{aligned}
\tag{4.6}
$$

We know that, r = 12 (constant) for Stage 1. Hence,

$$
\begin{aligned}
a &= \frac{v^2}{r} \\
\omega &= \frac{v}{r} \\
\theta &= \omega t
\end{aligned}
\tag{4.7}
$$

With a constant thrust, the tangential velocity of the capsule increases until an acceleration of 0.3g is produced. Then, in Stage 2, the capsules deploy to

[3]900000 seconds is the approximate time required to deploy the system completely using 1 thruster.

maintain constant acceleration on the floor of the capsule. Mathematically,

$$\begin{aligned} dv &= \frac{Thrust}{m_d} dt \\ r &= \frac{v^2}{a} \\ \omega &= \frac{v}{r} \\ \theta &= \omega t \end{aligned} \tag{4.8}$$

The values of θ and radius are then used for polar plot. These results are presented in Section 5.6.

4.3 Synopsis of Chapter 4

Having laid the foundation of the system under consideration to create artificial gravity, in this chapter we have created a mathematical framework to simulate the tethered system described in Section 3.2. This framework aids us to answer the primary research question of estimating the mass of propellant required under the given set of assumptions and secondary research question of deployment velocity. In Section 4.1, trapezoidal rule of numerical approximation is used to estimate the mass of fuel and deployment velocity. This method is useful because it can be used in different scenario such as estimating the fuel requirement for tethered system with cubesats or even torus design for artificial gravity. The next chapter will comprise of results from the simulation with discussion.

Chapter 5

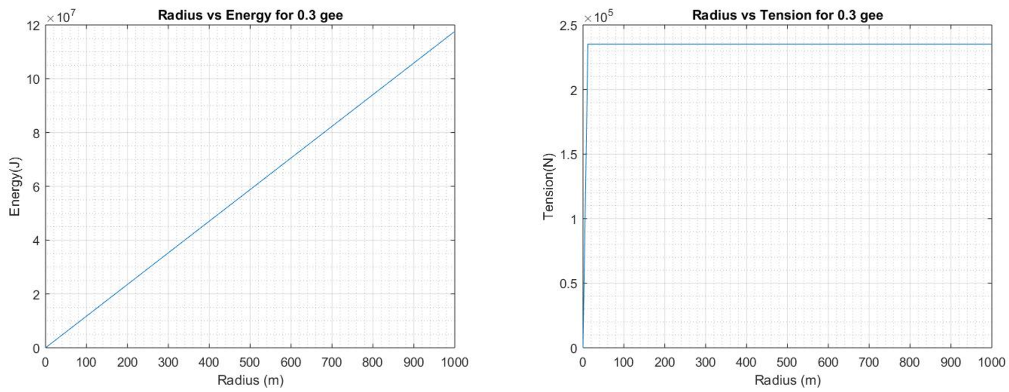
Results and Discussion

We created a mathematical framework in Chapter 4 to address the research questions in Chapter 1. In this chapter, we will look at the results from the simulation. Later, we will verify the results by looking at the human factors. These results also help in developing the future work section of Chapter 7.

In Chapter 3, we have described two stages to simulate gravity, first being the spin-up stage and second being the deployment stage. We will first look at the plots of Tension vs Radius and Energy vs Radius.

5.1 Parameters to Keep Constant Acceleration as Tether Deploys

In order to keep constant acceleration, Kinetic Energy required to reach 1000 m is 1.176×10^8 J and produces a tension of 235.2 kN when fully deployed. The energy and tension gradually increases as the radius of rotation increases. The amount of tension calculated here is useful in determining the tensile stress on the tether in Chapter 6.



(a) Energy vs Radius (b) Tension vs Radius

Figure 5.1: Change in Energy and Tension in the tether as radius of rotation increases

Figure 5.1a represents the kinetic energy corresponding to the radius of rotation. It can be seen that as the radius of rotation increases, the energy required to move the mass increases. This interpretation corresponds with the fact that more tangential velocity (as shown in Figure 3.3) is required at larger radii of rotation which is anchored in the Equation 3.1

In Figure 5.1b, the initial increase in tension corresponds to stage 1, where the centripetal force ($mr\omega^2$) increases with constant radius. Since the simulation is set-up to create a constant acceleration, the tension is constant in stage 2, deployment.

5.2 Results for Spin-up to 6 rpm

Before increasing the radius of rotation gradually, we spin up the system to 6rpm at a radius of 12 m in Stage 1. This step is important from the results gained about behavior of the tether, from the tether experiment from Gemini program as discussed in 2. Fuel required is given by rocket equation:

$$m_p = m_d(e^{dv/v_{ex}} - 1)$$

The change in velocity for initial spin-up is dv = 7.2 m/s at 12 m radius, and the exhaust velocity of ion thruster is 30 km/s[22].

Hence, the fuel required for initial spin-up is 19 kg which takes 29 hours to spin-up with 1 ion thrusters and 2 hours with 10 ion thrusters.

5.3 Preliminary Results

In the scenarios below, we have discussed how the dv changes, which will give mass of propellant required.

5.3.1 Equal Radius Steps

In this scenario, the thrusters are engaged at radius of rotation increasing at equal intervals.

In Table 5.1, m_p is the mass of propellant for radius steps and i corresponds to the number of steps. The number of steps could be increased to gain more accurate results. dv is the change in tangential velocity corresponding to the radius. (See Equation 4.2)

Table 5.1: Mass of propellant per capsule for scenario 1

i	r(m)	dv(m/s)	m_p(kg)
1	12 100	10.12051	26.99257
2	100 200	7.174389	19.13399
3	200 300	5.505103	14.68162
4	300 400	4.641016	12.377
5	400 500	4.088817	10.90426
6	500 600	3.696573	9.858136
7	600 700	3.39935	9.065447
8	700 800	3.164038	8.437879
9	800 900	2.971729	7.925004
10	900 1000	2.810732	7.495635
		Total	146.0739

5.3.2 Equal Energy Steps

Similar to the equal radius steps scenario, the energy required to move the capsule is given by equation 3.1 To spin up the system from 12 to 1000 m, which corresponds to 1.411x10^6 J to 12x10^7 J. Equation 4.3 captures the way in which the mass of propellant is calculated using equal energy steps.

Table 5.2: Mass of propellant per capsule for scenario 2

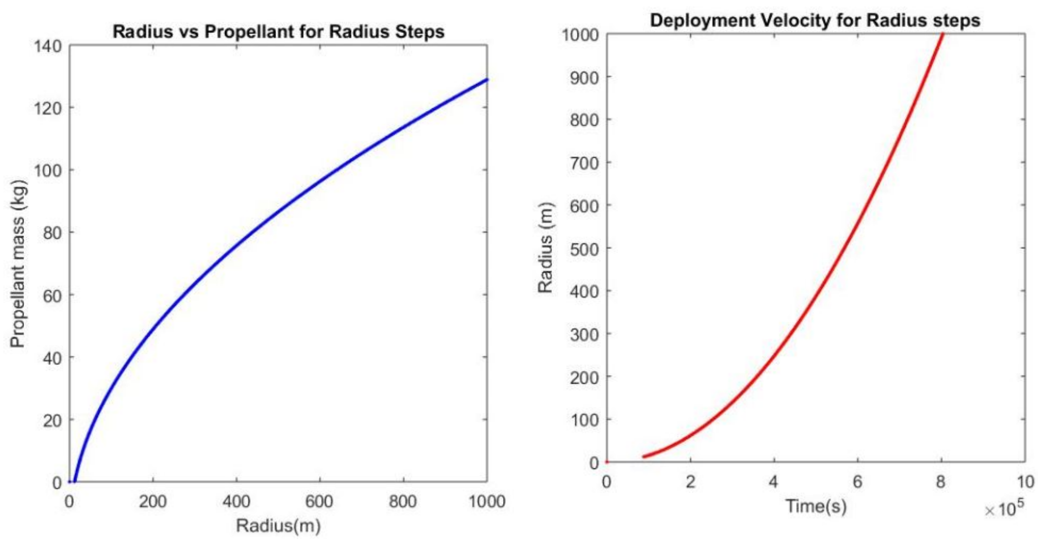
i	*Energy*(J)	dv(m/s)	m_p(kg)
1	1.411x10^6 - 1x10^7	8.611388	22.967
2	1x10^7- 2x10^7	6.549291	17.46668
3	2 x10^7 - 3x10^7	5.025448	13.40232
4	3 x10^7- 4x10^7	4.236649	11.29853
5	4 x10^7 - 5x10^7	3.732562	9.954119
6	5 x10^7 - 6x10^7	3.374494	8.999158
7	6 x10^7 - 7x10^7	3.103168	8.275542
8	7 x10^7 - 8x10^7	2.888358	7.702659
9	8 x10^7 - 9 x10^7	2.712805	7.234475
10	9 x10^7 - 10x10^7	2.565835	6.84252
11	10 x10^7 - 11x10^7	2.440442	6.508111
12	11 x10^7 - 12x10^7	2.331813	6.218411
		Total	146.0718

5.3.3 Equal Velocity Steps

If we consider the velocity changes by 4 m/s till it reaches the final velocity of 54 m/s (see Figure 3), the mass of propellant required is given by substituting $dv = 4$ for 12 steps in Equation 4.4 which results in 144.01 kg.

5.4 Estimation using Trapezoidal Rule of Numerical Analysis

In Section 5.3 the propellant required is estimated using large steps. This gives us a rough estimation. As discussed in Chapter 4, we can estimate the propellant required more accurately using trapezoidal rule of numerical analysis. For the analysis, we selected 10,000 steps for each scenario. The results are presented based on the scenarios discussed in Chapter 4.

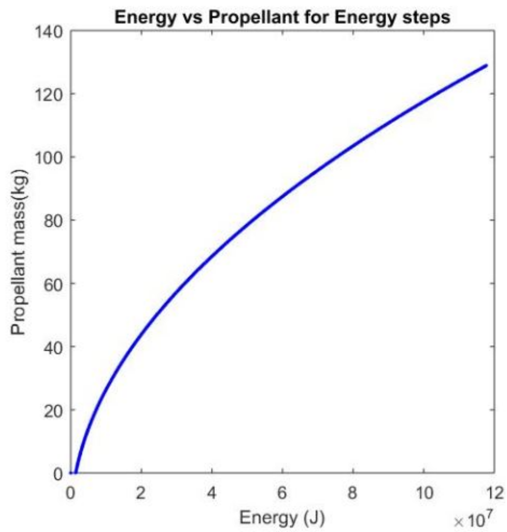


(a) Fuel required to spin-up to 1000 m in radius steps

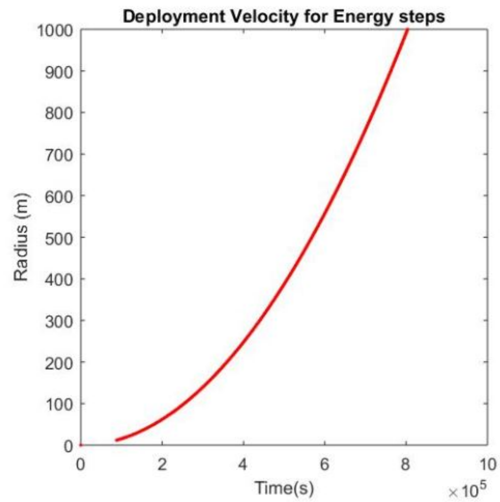
(b) Deployment velocity using radius steps

Figure 5.2: Results using radius steps

In Figure 5.2, the plot represents the fuel requirement, deployment velocity, and time required for radius steps. Here h = 0.0988. The fuel required to spin-up the system is 128.88 kg with a gradually increasing deployment rate.



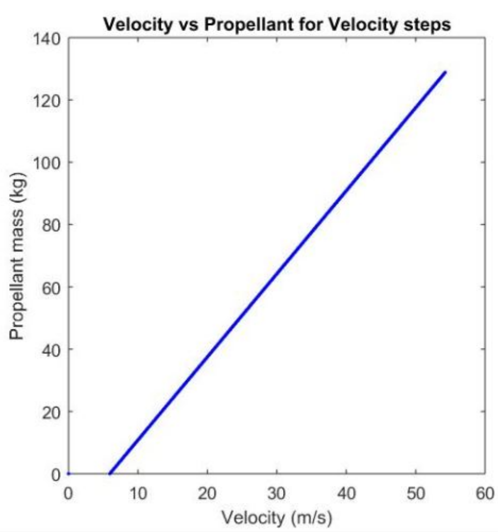
(a) Fuel required to spin-up to 1000 m in energy steps



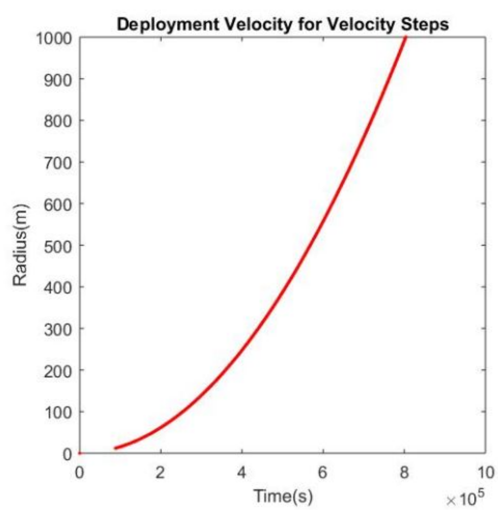
(b) Deployment velocity using energy steps

Figure 5.3: Results using energy steps

In Figure 5.3, the plot represents the fuel requirement, deployment velocity, and time required for energy steps. Here, h = 11630.736. The fuel required to spin-up the system is 128.87 kg with a gradually increasing deployment rate.



(a) Fuel required to spin-up to 1000 m in velocity steps



(b) Deployment velocity using velocity steps

Figure 5.4: Results using velocity steps

In Figure 5.4, the plot represents the fuel requirement, deployment velocity, and time required for velocity steps. Here, h = 0.0048. The fuel required to spin-up the system is 128.83 kg with a gradually increasing deployment rate.

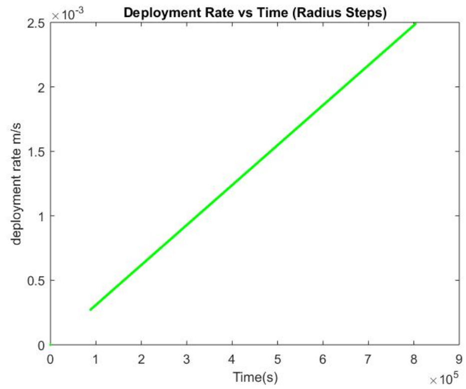
Since we are using numerical analysis for estimation, the accuracy of the results increases as the number of steps increase. A large number of steps also provide an opportunity to view the system as a continuum.

5.5 Rate of Deployment Velocity

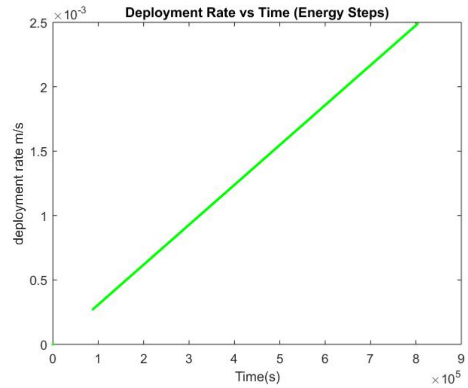
Deployment velocity is essentially the velocity at which the tether should unreel as we increase the radius. The deployment velocity should be just enough to keep the tether tense while not snapping it.

As shown in Figure 5.5, the deployment velocity increases gradually with time never exceeding 2.5x$10^{-3}(m/s)/s$. Since we are simulating Mars' gravity of 0.3g or 3 m/s^2, it is important to note the deployment velocity is not only crucial for human comfort, but also for maintaining the tension in tether[4] .

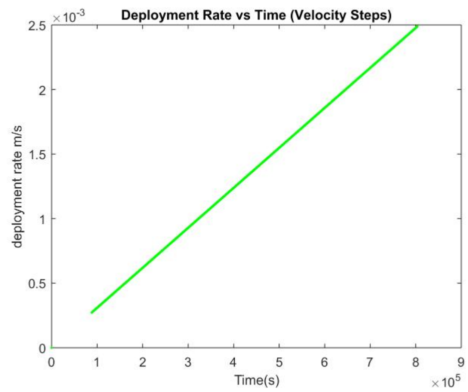
[4] We are creating an acceleration of 3 m/s^2. This implies that if the deployment velocity is any more than 3 m/s, the tether is being deployed at a rate beyond which acceleration is not enough to keep a proper tension in the tether. A slack in tether could lead to undesired tether dynamic, which may be difficult to control



(a) Deployment velocity vs t for radius steps



(b) Deployment velocity vs t for energy steps



(c) Deployment rate vs time for velocity steps

Figure 5.5: Rate of deployment for the three cases.

We know from the Equation 4.2, time for spin-up depends on the thrust. Hence, if we hypothetically increase the number of ion thrusters, they will produce a higher thrust. Table 5.3 helps us understand that if we increase the thrust by 1000, it will take only 800 s to spin-up while maintaining the tension in the tether.

Table 5.3: Change in spin-up time and deployment rate with number of thrusters

No. of Thrusters	Rate of Deployment(m/s)/s	Time (s)	Number of Turns
1	0.0025	800000	33
10	0.025	80000	3
100	0.25	8000	0
1000	2.5	800	0

This result is also helpful in determining the thruster for spin-up procedure. A cryogenic propellant system itself creates a thrust of 66.7 kN (see Table 2.2) of thrust, which is undesirable. Having said that, if the goal was to simulate 1g which is 9.81 m/s^2, cryogenic propulsion system could suit well. However, a proper trade-off analysis needs to be done to determine the feasibility.

5.6 Deployment Using Polar Plot

So far, we have determined that the number of thrusters reduce the deployment time. A better way to visualize the deployment velocity is by using polar plot (r,θ). This will help us understand the profile the capsule will trace in 2-D space. The simulation is setup to align with the Stage 1 and Stage 2 as described in Chapter 3. Figures 5.6, 5.7, 5.8, 5.9 represent the deployment profiles for 1, 10, 100, and 1000 thrusters respectively. In the plots below, the numbers around the circle are the angles (θ) while the numbers inside the plot from 100 to 1000 represent the radius(r).

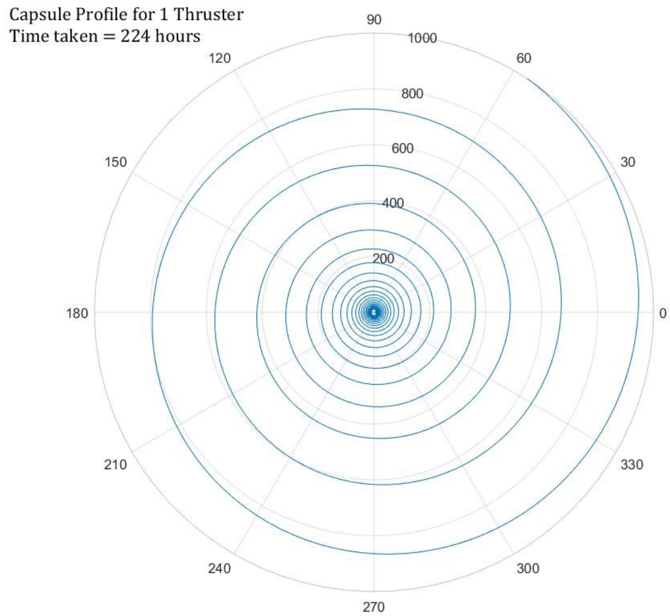


Figure 5.6: Deployment profiles for 1 thruster

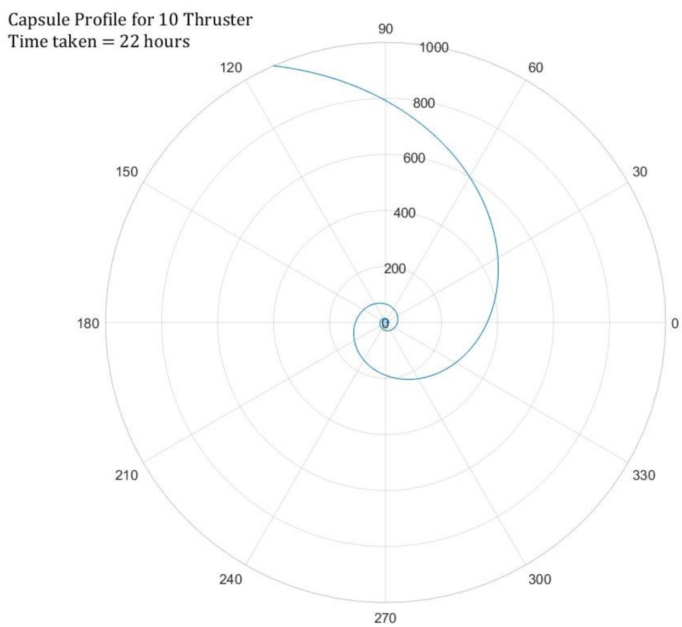


Figure 5.7: Deployment profiles for 10 thrusters

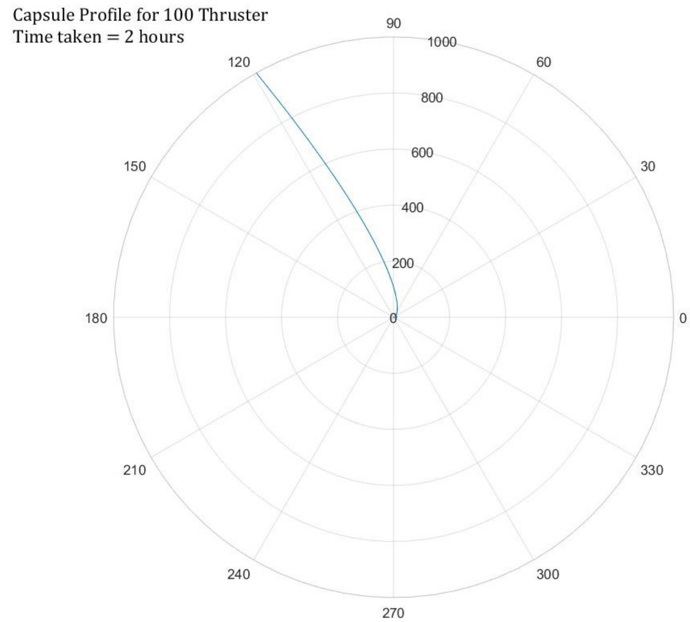


Figure 5.8: Deployment profiles for 100 thrusters

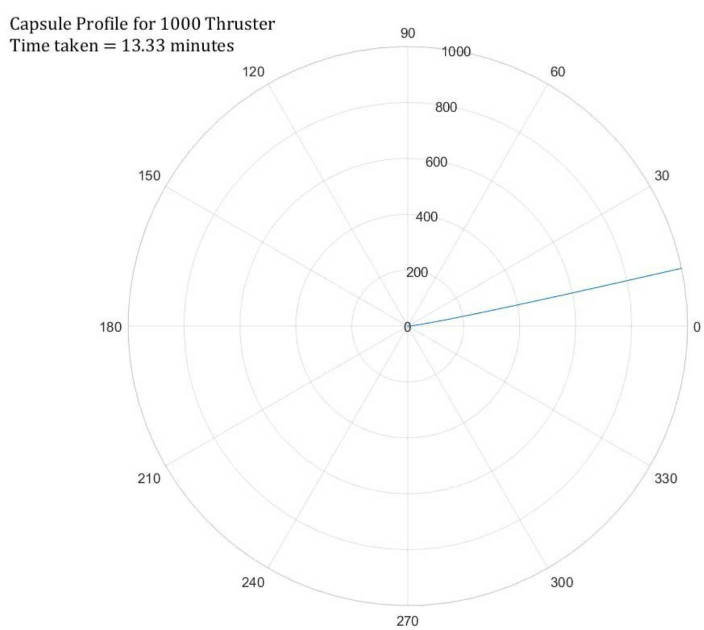


Figure 5.9: Deployment profiles for 1000 thrusters

Recalling the figures for deployment velocity from Figure 5.5, it is clear that the deployment of the tether needs to gradually increase with time, in order to maintain a constant acceleration. This trend can be clearly seen in Figure 5.6.

In addition to the deployment profile, it can be noted in Table 5.3 that the number of turns each capsule makes decrease with increased thrust. With 1000 thrusters it takes 800 seconds to deploy and intuitively, will take a less turns to reach 1000 m. Similarly, 1 thruster requires approx. 9 days, which takes more turns than 1000 thrusters. Although, a 1000 thrusters may deploy the system faster, the deployment may not be smooth. Further analysis based on these results would be helpful in understanding the optimal thrust value to avoid jerky movements.

5.7 Verification: Effect of the Results on Humans

The first research question is pertinent to human safety and comfort, and hence, it is critical to verify that the forces on the human inside the tethered system are safe. One of the factors to look at is the 'pull force'should not exceed the human tolerance limit. According to the findings from the paper in a journal pertinent to the human survivability [33], the compression of the vertebrae, can occur with +Gz (vertical axis) decelerations of 20 to 25 gee and accelerations up to 15 gee. From Figures 5.5a, 5.5c, and 5.5b deployment velocity will create slight changes in the net acceleration of 0.3g, the astronauts will be safe and comfortable.

5.7.1 Human Comfort and Safety

Because the gravity level varies along the radius of the centrifuge, an astronaut lying in a centrifuge along a radius with her feet positioned at the rim will have her head closer to the axis or rotation than her feet. The head will have a smaller radius of rotation. Consequently, the gravity level at her head will have a lesser magnitude than the gravity level at her feet. The variation in artificial gravity level as a function of distance from the center of rotation is referred to as the gravity gradient. Hence, gravity gradient is related to the posture felt by the astronaut. The mathematical relation is given by:

According to Clement[3], for an astronaut of height h = 2 m in a rotating environment with a radius of 100 m, this ratio is 98%, which corresponds to a gravity gradient of 2%. An individual would not likely perceive a difference of only 2%. However, for radii of rotation less than 10 m, the gravity gradient ranges from 20 to 100%, which may be perceived as a bent posture.

Having identified the initial radius of rotation to be 12 m, the gravity gradient is approximately 17% at initial spin-up which resembles partially bent posture. The gravity gradient decreases and becomes negligible in effect after 100 m, which takes about 63 hours to spin-up as per the results from Figure 5.2. Using thrust equivalent to that of 10 thrusters, the time reduces to 6 hours.

5.7.2 Nausea (Coriolis Effect)

Although subjects at rest in a rotating system feel only the sensation of weight, that is, the gravity level generated by the centrifugal force, when they move, another force, called Coriolis force, is felt. The Coriolis acceleration is a direct result of any linear movement within the rotating reference frame and is equal

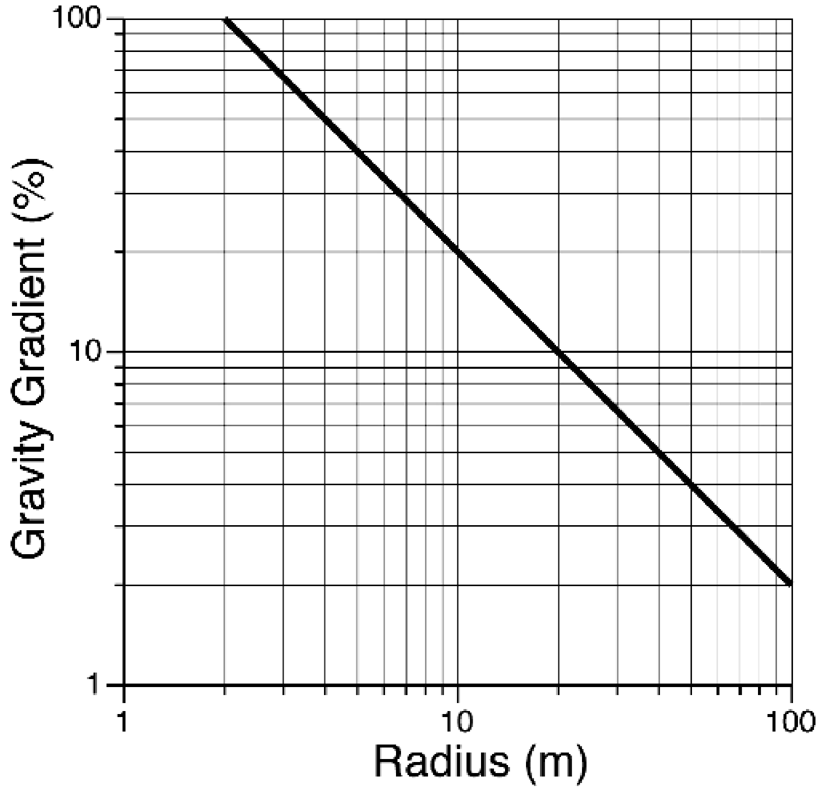


Figure 5.10: Gravity Gradient a function of radius of rotation for an astronaut height of 2 m standing on the floor of a spinning vehicle or lying on an internal centrifuge with their feet pointing outward towards the rim along a radius.[3]

to twice the cross product of the angular velocity vector and the linear velocity vector v of the moving object, person, or body part. The direction of the Coriolis acceleration is perpendicular to the plane formed by ω and v in a right-hand-rule sense in accordance with vector calculus. Of course, the resulting force is obtained by multiplying the mass of the moving object or person by the acceleration, so the magnitude of the Coriolis force is as shown in the following equation[3].

For instance, if individuals in a spacecraft climb and descend ladders, they would feel the effects of the Coriolis acceleration in the form of a force that would tend to push them to one side or the other as illustrated in figure 5.11. If

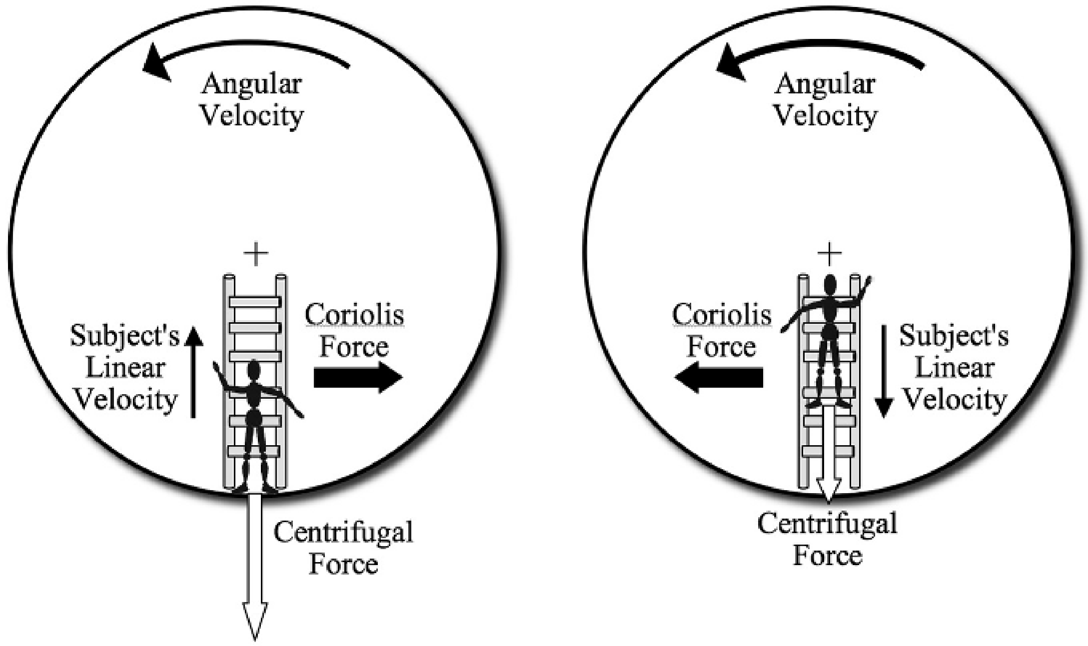


Figure 5.11: Coriolis effect in a rotating frame of reference[3]

the spacecraft was rotating in the counter-clockwise direction and the astronaut was climbing a ladder towards the center of the vehicle in the manner shown in the figure, he or she would feel a force pushing to the right. When descending the ladder, the force would seem to be pushing them to the left.

With this understanding of Coriolis effect in rotating systems, it is important to note that the Coriolis force is independent of the radius of centrifugation. But it is also evident that the Coriolis force will reduce with decreased angular velocity ω. In the case of the system under consideration for this thesis, the angular velocity decreases to 0.06 rad/s as the radius of rotation reaches 1000 m. This implies that if a person moves at a certain velocity, the Coriolis force will be less and hence, will feel less sick (this is not considering the sickness induced due to head movement).

5.8 Synopsis of Chapter 5

Chapter 5 comprises of the results from the simulation and a discussion of their significance with respect to determining the feasibility of the mission followed by a discussion of additional parameters. In Section 5.4, we found that the simulation results are:

1. Approximately 165 kg of fuel for spin-up.
2. The deployment velocity gradually decreases with increase in radius, never exceeding 3 m/s.
3. Time required for spin-up procedure depends on the thrust produced. Thrust more than 1000 times that of thrust produced by ion thruster may create a slack in the tether during deployment.

These results are then verified using the information pertinent to human factors gathered in Chapter 2. The forces as a result of the deployment velocity are within the comfort zone as discussed by Clement[9] based on figure 5.11. The tension in the tether is equivalent to the centripetal force. This result is used in Chapter 6 for determining the tensile stress.

Chapter 6

Characteristics of the Tether for Artificial Gravity

Discussion about tethered spacecraft without a discussion of tethers would be incomplete. We will discuss the consideration that needs to be taken to design the tether viz material, external factors etc. with concentration on artificial gravity.

6.1 Material Selection Criteria

Before looking into the discussion of materials, it is important to understand important characteristics a tether should possess. The NASAs Space Tether: Design Criteria [34] provide a systematic process for the selection of tethers for space applications. Enlisted are some common criteria:

1. The strength should not be a driving parameter in tether design, i.e., they should possess enough inherent durability and robustness to support a normal amount of mishandling and damage.[34]

2. To achieve maximum performance and low cost, tethers need to be made of materials with high strength to mass ratio.

3. Space tethers would be exposed to temperatures up to -270° C on the journey to Mars. However, the temperature will fluctuate between -13° C to -100° C [35].

4. It is desirable that the tether can be wound and unwound without significant bending and torsional stiffness or shape memory. This affects the deployment performance and predictability of the dynamics of the tether.

5. The material should ideally display low friction levels and little abrasion.[15]

6.2 Materials

Some current tether designs use crystalline plastics such as Ultra-High Molecular Weight Polyethylene (Dyneema Spectra), Aramid (Kevlar) or carbon fiber. A possible future material would be Carbon NanoTubes, which have an estimated tensile strength between 140 and 177 GPa (20.3-25.6 million psi), and a proven tensile strength in the range 50-60 GPa for some individual nanotubes. The members of the Cornell University - Artificial Gravity team have done their analysis by considering a tether made of Dyneema, of the diameter 0.5mm. In the following subsections, we will discuss the three materials and their characteristics.

6.2.1 Kevlar

Polyaramid is a classic candidate for space tether material also known for bullet vests. It has high strength and can withstand temperatures up to 500° C. It has a rough surface and high yarn to yarn friction ratio. It tends to crack and flake when bent repeatedly around a small radius. Detectable strength loss occurs after 1000 bucklings and severe strength loss after 20,000[36] which is a lot more that 1 buckling as is considered in this thesis.

6.2.2 Dyneema

Ultra-High Molecular Polyethylene is another promising candidate for space tether material. It can withstand temperatures up to 144 to 152 °C. It has a smooth surface and low yarn to yarn friction ratio. Dyneema is subject to creep under continuous load but is UV resistant. It has high resistance to elasticity.

6.2.3 CNT yarn

Carbon Nano Tubes (CNT) are a topic of interest in the past few decades considering its strength and other properties[37]. It has a high melting point up to 1000° C. CNT yarn is considered to resistant to creep and can withstand huge loads, but tests need to be performed in order to determine other characteristics such as working temperatures, effect of radiation, etc. for diameters more than 5 mm.

Table 1 displays a comparison of properties between Kevlar, Dyneema and CNT yarn. This comparison gives an insight to which would be a good choice for artificial gravity.

The tether is exposed to a load of 240,000 N for a duration of approximately

Table 6.1: Comparison of material properties

Parameters	Kevlar[36]	Dyneema[38]	CNT yarn [39]
Specific Strength (kNm/kg)	2514	3711	46268
Breaking Length (km)	256	378	4716
Density (kg/m^3)	1440	970	1600
Tensile Strength (GPa)	3.7	3.5	60
Diameter (μm)	12	12	12
UV resistance	UV resistant	UV resistant	Reduces strength over a long period
Creep	Under continuous load	Under continuous load	Resistant to creep
Temperature	Kevlar shows essentially no embrittlement or degradation at temperatures as low as -196°C.	Brittle below -150°C	Not tested.

6 to 9 months. We know that the $\sigma = F/A$ where $A = \frac{\pi}{4}D^2$. Based on the calculations presented in Chapter 4, F = 240 kN.

In Table 6.2, we have calculated the diameter required to withstand the tensile force of 240 kN. by using the equation $d = \sqrt{\frac{4F}{\pi\sigma}}$. Although the diameter may not be uniform based on the geometry, it is a reasonable assumption to consider the tether with uniform diameter. Based on the diameter of the tether, we calculate the number of strands that would make up the tether using the equation $N = D/d$ where N is the number of strands, D is the diameter of the tether and d is the diameter of the individual strand.

From the calculations the tension on the tether would be 235000 N and hence, a tether with diameter 5 mm Dyneema seems the most promising. It should be taken into consideration that CNTs and their yarns are still in the developmental

Table 6.2: Number of fibers required for a particular diameter of the tether (The diameter corresponds to the tensile strength of a particular material. More the diameter, more are the number of fibers required)

Parameters	Kevlar[36]	Dyneema[38]	CNT yarn [39]
Diameter required to bear the load of 240 kN (mm)	9.21	5.13	2.25
Number of fibers required	768	428	188
Mass of 3km tether (kg)	287.8	60.14	19.08

stages and conclusions cannot be made due to the lack of experimentation on characteristics such as resistance to creep, fatigue, and radiation.

6.2.4 Discussion

To create artificial gravity for a human capsule, there are a variety of criteria we need to consider as discussed in Section 6.1. Three materials are selected for the study Kevlar, Dyneema, and CNT - from a perspective of the mentioned criteria. Tables 6.1 and 6.2 lay a comparison between the three materials.

In Table 6.1, we begin by comparing the specific strength (strength - weight ratio) which indicates the higher specific strength is, the higher strength and lighter weight the material is. Carbon Nano Tubes have the highest specific strength indicating its capability to withstand high stresses well suited for the application of artificial gravity. Then we look at the breaking length or self-support length. Though this concept is pertinent to vertical column of material, it is important to note that while creating artificial gravity, the tether will be stretched and needs to have high breaking length. Based on the first criteria mentioned in Section 6.1, CNT seems promising.

Further, we compare the temperatures and radiations the materials can withstand, and its response to creep. These parameters tie to Criteria 2 (temperature), Criteria 3 (physical characteristics such as creep) and Criteria 6 (space environment). Kevlar and Dyneema are resistant to UV radiations but prolonged exposure reduces its strength. Additionally, they decrease their strength under continuous load. CNT has not been extensively tested for radiation creep or for temperatures, but it is theorized that it is resistant to creep, radiations and can withstand a large range of temperatures.

In Table 6.2, we calculate the diameter of the tether, and the number of strands in the tether, of those respective materials. From the calculations in Appendix B, Dyneema can pull a 240 kN force with a 5 mm tether, whereas Kevlar and CNT needs a smaller diameter up to 2.25 mm. It is also important to note that CNT has a higher specific strength and a larger breaking length compared to Kevlar and Dyneema.

6.3 Effects of External Factors

6.3.1 Micro-meteoroid

All space tethers are susceptible to space debris or micro-meteoroids. Therefore, mission designers need to decide whether or not a protective coating is needed. It is also important to take into consideration that longer the tether, larger is the probability of micro meteor impact. The meteoroid environment consists of particles of natural origin, and most are generated by comets and asteroids. The average mass density for a meteoroid is 0.5 g/cm3. There are approximately 200 kg (440 lb) of meteoroids within the 2,000 km (1,080 nm) altitude. The average impact velocity of a meteoroid relative to an orbiting spacecraft is estimated to be 19 km/sec. The probability of tether impact with a micro-meteoroid of mass greater than 0.1 gram was calculated as 0.1% for a mission of 420 days.[3] In case of severed tether, the result could be loss of mission, loss of satellite, and end-body entanglement due to recoil of the tether remnant. This is especially critical for missions where the safety of end-bodies is of paramount importance, such as those involving manned spacecraft like the space shuttle or space station.

For applications that exert high tensile forces on the tether like creating artificial gravity, the tether should withstand high tensile stress and be light weight. Light weight tethers are desirable as they provide high strength to mass ratio. Considering these aspects, we will now look into the materials that could be used.

6.3.2 Impact of Radiation on Materials

The journey to Mars may take from 6 to 9 months. This means long term exposure to radiation. The potential material should be able to retain its strength with a long-term exposure. Below, we have discussed the effect of UV on Dyneema and Kevlar in form of a literature review.

Dyneema

HMPE is one of the most UV resistant high modulus fibers. The line strength drops relatively rapidly during the first in approximately 18 months of UV exposure and then much more slowly after the surface of the fibers has been burned. How much strength is lost will vary depending on the lines specific construction (diameter, braiding angle and tightness, type and amount of coatings) and the location (UV intensity). The graph below shows the results from two different tests (two different locations with two different lines, but both 8 mm diameter), which bracket the likely strength loss (e.g. all the other empirical evidence falls between these two tests). This shows that HMPE single braid will lose about 20 to 35 % of their tensile strength (leaving 65 to 80 % of the original tensile strength) within 20 months of continuous exposure and at five years will retain about 50 to 75 % of its tensile strength, and 40 to 70% at 10 years. Single braid line size (or double braid with the core exposed at the splices) should be selected to compensate for this UV reduction in tensile strength. 3/16 inch stainless wire has a tensile strength around 3800 lbs, while 3/16-inch HMPE single braid has tensile strength around 5,800 lbs. So, picking the same size HMPE as wire will roughly allow for equal strength after five years of intense UV.

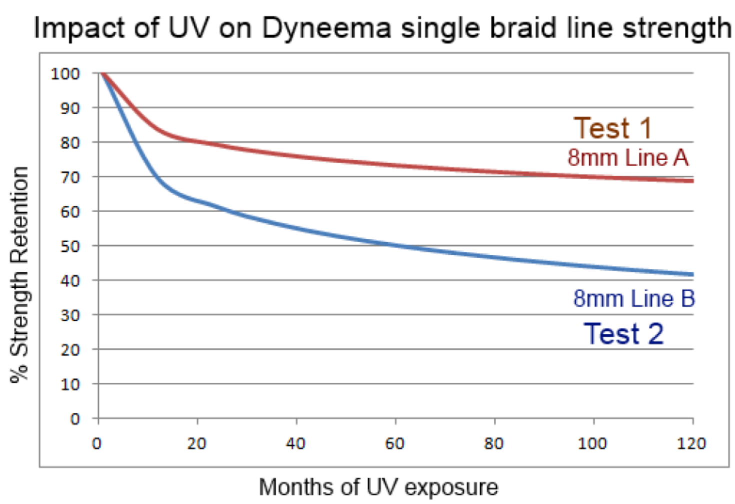


Figure 6.1: Effect of UV radiation on strength of Dyneema [40]

Kevlar

Like other polymeric materials, Kevlar is sensitive to UV (ultraviolet) light. Unprotected yarn tends to discolor from yellow to brown after prolonged exposure. Extended exposure to UV can also cause loss of mechanical properties, depending on wavelength, exposure time, radiation intensity and product geometry. Discoloration of fresh yarn after exposure to ordinary room light is normal and is not indicative of degradation. Figure 6.2 shows the absorption spectrum of Kevlar, along with that of sunlight. The overlap region of these two curvesespecially between 300 nm to 450 nm should be considered when specifying outdoor use of unprotected Kevlar. This range includes the near UV and part of the visible region. For effective protection of Kevlar from UV degradation, this kind of light must be excluded.

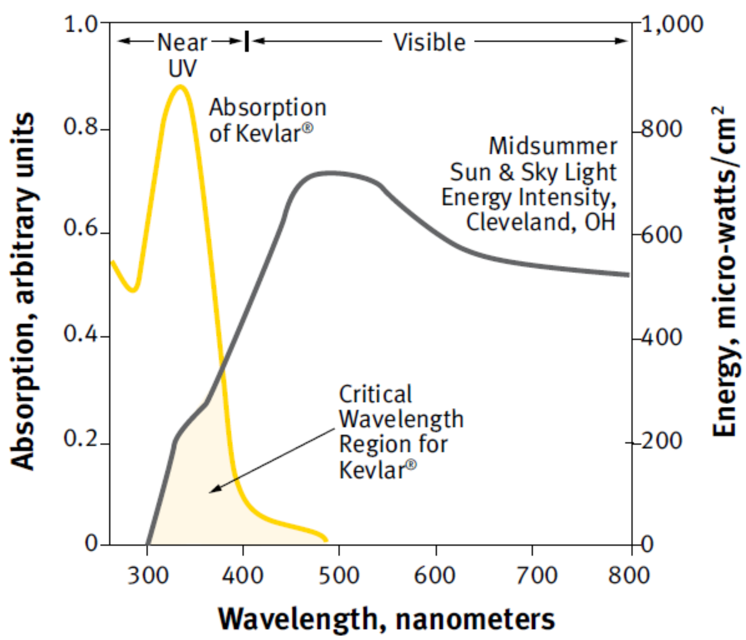


Figure 6.2: Overlap of the absorption spectrum of Kevlar with the solar spectrum.[36]

Having established the single fiber characteristics, Kevlar is intrinsically self-screening. External fibers form a protective barrier that shields interior fibers in a filament bundle or fabric. UV stability increases with size the denier of a yarn, the thickness of the fabric or the diameter of a rope. Extra UV protection can be provided by encapsulation:

1. By over-braiding with other fibers or,
2. By applying an extruded jacket over ropes and cables.

6.3.3 Degradation due to Space Environment

The potential causes of the inadvertent tether severing include manufacturing defects, system malfunctions, material degradation, and collision with space-borne matter. Material degradation could be caused by space radiation environments, which are Galactic Cosmic Radiation, Geomagnetically Trapped Radiation, and Solar Proton Events (solar flares). Due to the tether being exposed to radiation and varying stresses and friction, heat might get trapped in the tether with no way to dissipate the heat, creating undesirable changes in the material.

As mentioned earlier in Section 6.1 space between Earth and Mars can be extremely cold. However, the tether can be kept under working temperatures by absorbing the heat from the sun. In the Tethers in Space Handbook[35] it is discussed that the tether in lower earth orbit (altitude $<$ 140 km) the temperature can vary drastically between day and night cycles. The calculation is as follows:
Heat transfer through radiation:

$$T_{eq} = \sqrt[4]{\frac{\Sigma Q_{eq}}{A\epsilon\sigma}} \tag{6.1}$$

$\Sigma Q_{eq} = Q_{in} - Q_{emitted}$

$Q_{in} = Q_{solar} + Q_{internal} + Q_{aerodynamic} + Q_{albedo} + Q_{Earth}$

$Q_{emitted} = A\epsilon\sigma T^4$

Where,

T: Temperature (K)

Q_{in}: Total Heat

A: Cross-sectional Area

ϵ: Emmisivity = 0.9 for non-metals

σ: Stephan-Boltzman Constant = 5.73 x $10^{-8}(Wb/m^2K)$

Based on their calculations, the temperature varied between -13° C to -93° C over one orbit around earth.

The same principle can be used to calculate the temperature of the tether during the interplanetary travel. The equation would ideally reduce to $Q_{in} = Q_{solar} + Q_{internal}$, since, there would be no heat from aerodynamic, albedo, or Earth/Mars unless the tether is near the planets. It is also worth noting that the tether is rotating and hence will have incident radiation at different angles. This increases the complexity of calculating the temperature of the tether. Nevertheless, based on observation, the we can consider only the solar and internal heat for an interplanetary journey, unless the system is close to any planet that adds to the tether heat.

6.4 Discussion on Desired Characteristics in any Material

6.4.1 Fatigue

Fatigue is the property where the material weakens due to repeated change in loading conditions. It affects the tensile stress adversely. It is important to note that in application such as creating artificial gravity, the loading change is complex in nature. As discussed in Chapter 3, the system spins up first and then starts the spin-up procedure. As the radius increases and the angular velocity is changed to keep the acceleration constant, the load on the tether changes continuously. Similarly, during the spin down procedure, the tension changes. Due to this, the material chosen should be tested for its fatigue. Higher the number of cycles, better it is for the material.

6.4.2 Creep

With increasing static load and temperature, the fiber elongates irreversibly. This is called creep. To create artificial gravity, the material needs to have resistance to creep. It is important to consider that the creep characteristic changes with temperature and hence the tether material should be tested for a static load in a constant low temperature.

6.4.3 Torsional and Bend Radius

The tether is wound over a spool. The bend radius should not decrease strength. Also the system spins about the center. Hence, it should withstand torsion. A pre-twist can be provided to decrease the torsional stress on the tether[29].

6.5 Remarks

There is no better way to study a space tether accurately than to experiment with them. Since it is difficult to create space-like environment on earth, and mathematically modelling the tether is very complex, this study only serves as a ballpark. Tethers have been widely used for experiments in lower earth orbit, which has a different space environment than an interplanetary journey. The primary assumption in this study is that the pull force is uniform throughout and has a rod like geometry. More accurate results can be generated using specific geometry. Also, because this study is based on a lot of assumptions, no solid conclusion can be drawn in terms of selection of a particular material.

Future work is anchored in the Section 6.2 where we have presented a comparison and discussion of the three tether materials selected. Given the limitations identified above and ongoing research on CNT, it opens research avenues to investigate the characteristics of CNT yarn for high tensile stress applications such as creating artificial gravity. Moreover, experiments on the desired characteristics mentioned in Section 6.4 would help making a working model of tethers to create artificial gravity.

Chapter 7

Closure and Future Work

Creating artificial gravity in reality poses challenges of its own. Till then, the best we can do is study and investigate as much as possible in order to make it a reality. The motivation behind this thesis is to try and add to what is already known about tethered system for creating artificial gravity.

7.1 Summary of the Thesis

The primary goal achieved in this thesis is to estimate the mass of propellant required to spin-up and down for 2 cycles, and the deployment velocity required during this maneuver, which is a crucial factor in checking the feasibility of the tethered system for controlled artificial gravity. A large part of this was justifying the gaps identified through critical literature review, formulating a simulation model anchored in the key findings from the literature, and interpreting the results with regards to feasibility of the system for controlled AG. This will provide an avenue to investigate the system further and provide a path toward experimental missions.

In Chapter 1, the foundation for the thesis is laid. We began with an introduction to artificial gravity and methods to create it. A review of these methods leads to a motivation section where we provide the rationale for investigation. From this process, two research questions are defined and the connectivity to the overall theme of the thesis is identified in Section 1.2. Once the questions are posed and a strategy for their solution is created, significant engineering and scientific contributions of the work are discussed in Section 1.3.

In Chapter 2, a critical review of the literature is presented, in context of Artificial Gravity using tethered system from Sections 2.1 through 2.3. In Section 2.3 the review of the literature is summarized and connectivity between the gaps and review established. This chapter is foundational for Chapters 3 through 6.

In Chapter 3, we described the system under consideration, and propose and elaborate the method to answer the research gaps. We began by illustrating the tethered system based on the key findings in Section 3.1. Then, based on the details, we discussed the method proposed as hypothesis in Section 3.2 to answer the research questions. The proposed methods are tested in Chapters 4 and 5.

In Chapter 4, having laid the foundation of the system under consideration to create artificial gravity. In this chapter we have created a mathematical framework to simulate the tethered system described in Section 3.1 and 3.2. This framework aids us to answer the primary research question of estimating the mass of propellant required under the given set of assumptions and the secondary research question of deployment velocity. In Section 4.1 and 4.2, trapezoidal rule of numerical approximation is used to estimate the mass of fuel and deployment velocity. This method is useful because it can be used in different scenario such as estimating the fuel requirement for tethered system with cubesats or even torus design for artificial gravity.

In Chapter 5, we presented the results from the simulation and a discussion of their significance with respect to determining the feasibility of the mission followed by a discussion of additional parameters. In Section 5.2, we found that 144 kg of fuel is required for one spin-up procedure, with a gradually decreasing deployment velocity. This spin-up procedure takes 9 days using 1 ion thruster and 22 hours using 10 ion thrusters. These results are then verified in Section 5.7 using the information pertinent to human factors gathered in Chapter 2.

In Chapter 6, we have looked at the tether materials and its selection criteria. In Section 6.1 we looked at the considerations that need to be taken into account for its application in creating artificial gravity (AG). In later sections, we discussed three potential tether materials - Kevlar, Dyneema, and CNT - for creating AG which are selected from the literature review. In Section 6.3, we discuss the effects of space environment which was helpful to gain insight to find a way forward (elaborated in this chapter).

7.2 Answering the Research Questions

Primary Research Question

How much fuel is required to spin the system to create a constant acceleration and what tether material could be used?

To answer this question, one of the first things to determine was the type of thruster to be used. The propulsion system should provide adequate control and smooth transition (no jerks) while thrusting which is achieved using an ion thruster. The ion propulsion also has an advantage of using less fuel which indicates lower mass of propellant as discussed in the Chapter 3.

Using ion thrusters, we estimate the fuel required for spin-up per capsule is approximately 165 kg. Considering the spin-down procedure utilizes approximately the same amount of fuel, the total fuel required will be 660 kg for one cycle for both the capsules. In addition to the mass of propellant, we found that the deployment rate gradually increases to keep a constant acceleration.

Determining the tether material for a particular application is difficult without experimental data. However, in Chapter 6, we have discussed the criteria of selection of tether for high tensile stress application such as creating artificial gravity. The characteristics of Kevlar, Dyneema, and Carbon Nano Tubes are compared to determine a plausible material. We came to a conclusion that, although, Kevlar and Dyneema have been experimented on, CNT yarn is a promising candidate for artificial gravity missions due to its high strength to mass ratio, and high tensile strength.

Secondary Research Question

What is the deployment velocity of the tether to maintain the required acceleration and time required to spin-up?

Deployment velocity is the increase in radius of rotation over time. In Chapters 4 and 5, we have discussed the method used to investigate the propellant mass which are radius steps and energy steps. With these steps, an approximate radius vs time profile is generated using trapezoidal rule of numerical solution.

The results indicate that, the time required to spin-up does not vary if deployed using different scenarios, but will depend on the thrust[5]. We found that it takes 9 days to spin-up completely using 1 ion thruster producing 5.4

[5]The time required to produce required acceleration also depends in which method to produce the acceleration. For instance, the time required to simulate 0.3g will differ if we deploy the tether first and then spin the system3.2

N thrust, 22 hours for 10 ion thrusters, and 2 hours for 100 ion thrusters, but with a 1000 ion thrusters the system can be deployed faster which takes 13.33 minutes.

This thesis is based on speculation. This provides a lot of prospects for future research work, some of which are discussed in the next section.

7.3 Future work

The analysis in this thesis is based on assumptions. In order to progress towards execution, aspects such as tether control, accurate mathematical modelling, transition, need to be investigated. In a paper about tether control[41], the author discusses that the tether can remain stable with slight change in forces in the end mass. Such a control system for tether could be investigated further. From the results in Chapter 5, we know that the deployment rate is sufficient for human comfort and tether tension. A further study could be ensure a smooth transition from deployment to constant radius at fully deployed radius. One way to do this would be to gradually start reeling the tether as the desired radius of rotation approaches.

Since we are dealing with tethered system, the most important aspect is to investigate and test more tether materials. The discussion is limited to three materials and a theoretical approximation is made to give an insight for which material is best suited for the application of artificial gravity. A further study inclined towards experimentation would be helpful to provide an insight on the tether material for such application. This can be addressed in two ways. First way to do so is to look at upcoming (promising) materials such as graphene and investigate its characteristics in space conditions (vacuum, cold temperatures, etc.). Second way will be to look into coatings - and their reaction with the material - which protect the tether material from radiation and temperature variation.

The next thing would be to ensure human safety for such missions. In any spinning system, a human body reacts to the Coriolis effect and varying forces. From Chapter 2, we know that spinning in a system with large radius of rotation will be safe enough not to cause physical damage. But, since the system under investigation is an ideal one, it opens an avenue to detailed analysis of its effect on the human body, especially while reeling and unreeling the tether. Bioastronautics is a field of study for humans in space. From the results, researchers could either simulate these conditions in laboratories or on a computer. Scrutinizing this aspect of the problem would eventually help in the mission design and decisions pertinent with safe-guarding the travelers.

We are living in an exciting era for space exploration. This is all the more reason to keep researching on artificial gravity and human factors in space.

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