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SPINNING TETHERED SYSTEM FOR THE GENERATION
OF AN ARTIFICIAL-GRAVITY ENVIRONMENT IN SPACE

SISTEMA SPINNANTE A FILO PER LA GENERAZIONE DI
GRAVITA' ARTIFICIALE NELLO SPAZIO

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Abstract

This thesis is focused on human space flight. In particular are studied the solutions to solve the dangerous effects on the human body caused by prolonged permanence in a weightless environment.

This is one of the main problems related to long manned exploration missions that are planned for the future.

Chapters 1 and 2 present a general overview of issues related to “artificial gravity” and describe the physical problems that occur in the absence of gravity. Until now few experiments on artificial gravity have been carried out in space and a definitive solution to solve the problem still has to be found.

The thesis presents some solutions for countering the physical deterioration that astronauts have to face, in particular the possibility of using centrifuges or spinning spacecrafts.

Specifically, the thesis focuses on a particular design of a spacecraft for generating artificial gravity composed by two modules connected by a tether. The peculiar characteristics of the system are described and analysed, with particular attention to the tether characteristics, the deployer, the deployment manoeuvre, and the habitat design.

The dynamic of the system is simulated for a particular deployment strategy and the behaviour as a function of the mass of its components is analysed.

The thesis is not focused on a single topic, but it presents an overview of the system in the attempt to relate together different aspects of artificial gravity in space.

The thesis can be considered an introduction to the problem while the reader is referred to other sources for the details of the different topics.

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Nomenclature

ESA = European Space Agency

NASA = National Aeronautics and Space Association

ISS = International Space Station

ΔV = change of velocity to perform a space manoeuvre

Ω = velocity of rotation

G = gravitational acceleration on Earth

l = length of the tether

\dot{l} = velocity of deployment of the tether

T = tension of the tether

$\dot{\theta}$ = velocity of rotation

A, a = acceleration

n = mean motion around Earth

μ = standard gravitational parameter of Earth

m_r = reduced mass

v_{rim} = rim speed

CM = centre of mass

I_{sp} = specific impulse

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Introduction

Space environment presents some critical aspects for human survival. One of them is for sure the weightlessness. Human body evolved for millions of years in an environment with a peculiar gravitational field provided by Earth and developed with characteristics dependent on it. Lack of gravity influences negatively human beings both psychologically and physiologically. These aspects have been quite underestimated so far, as they manifest in the long period, and only few experiences were carried in the past years about this topic. Prolonged absence of gravity will be a challenge for long exploration missions that will probably be scheduled in the near future.

Aim of this thesis is presenting feasible solutions to solve problems on human body related to a microgravity environment.

Even adding complexity in the design of the spacecraft, providing artificial gravity is the only solution to solve at root all the problems related to weightlessness. The alternative is unattractive: continual vigilance and research for countermeasures. Thus, this is the first step for the development of manned interplanetary missions.

Solutions are presented in two categories: generation of partial artificial gravity and generation of continuous artificial gravity. The option of continuous gravity is more attractive for long mission and can be achieved with particular configurations of the spacecraft.

The strategy for generating artificial continuous gravity in space is spinning the spacecraft and creating a consequent centripetal acceleration. The module of this acceleration is dependent on the radius and velocity of rotation. Choosing the right combination of them would provide a level of acceleration equal to the gravitational acceleration present on the surface of the Earth.

Particular interest in the thesis is given to the design of a spinning tethered system. The possibility to use tethers in space is already demonstrated in several missions, but their usage for generating artificial gravity has never been tested properly. By the way, the advantages of a tethered configuration, which is lighter and more flexible, can make tethers the perfect candidates for the task.

In the thesis is proven how a tethered spinning system is completely achievable with the modern technologies and could provide a reliable solution for generating artificial gravity.

Chapter 1

Overview on artificial gravity

This chapter describes the characteristics of an artificial gravity field. It is explained its scientific basis and are shown the ideal features for providing comfort to human body. Past experiments and missions are described to provide general information about the topic.

1.1 History of artificial gravity

The idea of providing artificial gravity through centrifugation was introduced early in the conception of human space travel.

At the beginning of the nineties (1911) the Russian space visionary Tsiolkovsky presented his idea of rotating spacecraft and later von Braun (1953) did the same.

Science fiction popularized the idea with movies. For example, “2001: A Space Odyssey” (Kubrick 1968) presented a huge torus rotating spacecraft, and later the idea of rotating structures has been reused several times.

From the sixties, scientific experiments begun in this sector. In particular the Russian developed a large number of ground tests in rotating chambers or using short-radius centrifuges [1].

Experience with artificial gravity in space has been quite limited, with most of the investigations using only animals. Can be mentioned several experiments where rats were centrifuged continuously at 1 G for several days, while specific human experiments have not been conducted to date. In 1967 took place the Gemini 8 mission, with two spacecrafts connected by a tether and put in rotation, but the results were inconclusive and the experiment was nearly a disaster when the two vehicles went into an uncontrollable spin.

A 2.5-meter radius centrifuge was originally planned for the International Space Station (ISS) but unfortunately the project was later cancelled. It was a pity because that

machine could have provided important documentation on practical effects of artificial gravity in the human body.

In the last few years, with the growing attention in long exploration missions, such as for example a mission to Mars, an increasing interest in this sector is found in the scientific community. But practical tests are still lately to arrive.

In conclusion, several studies on the argument were made on Earth, but a space system able to provide continuous artificial gravity has still to be developed.

1.2 Continuous and intermittent gravity

Artificial gravity through structural rotation is the most direct method to prevent human body against problems caused by microgravity environment. The artificial gravity generated by rotating structures may be divided in two groups, depending on its duration: continuous and intermittent. [1]

The continuous artificial gravity option generates a field constant in the time, with the result that the environment would be totally similar to the Earth's one. It is achieved putting into rotation the entire spacecraft or at least the part of it where the astronauts would live.

Intermittent gravity provides a gravity field only during a specific amount of time, for example with usage of centrifugal machines on board. From a physiologic countermeasure perspective, this solution would likely provide periodic artificial gravity exposures.

Comparing the two options, it is clearly how the surest artificial gravity solution is the one that would produce an environment similar to that on Earth, such as the continuous solution.

General opinion could be sceptic about it, as this requires a long-radius rotating vehicle, with cost and size that would be excessive and prohibitive, while the alternative approach with intermittent artificial gravity (likely combined with exercise) seems easier and less risky.

On the other hand, intermittent gravity would be just a partial solution of the problem. Manned exploration of planets is probably the next milestone in human space development, and it requires spacecrafts designed for accomplish the goal in the best way possible. And clearly, recreating an environment similar to Earth is the best possible solution.

For this reason, even taking into account concerns related with the difficulties associated to the development of a big rotating spacecraft, this thesis is clearly focused

on the study of a system that can provide a continuous level of gravity force. Apart of a clear advantage from the psychological point of view, having a continuous gravity can help in the design of a spacecraft structured to support human life for long time. For instance, it will be possible to grow plants and develop every kind of liquid cycles necessary to the success of the mission with a design similar to the ones used on Earth. As explained in the chapter 2, the absence of gravity leads both to medical and psychological consequences. These are important factors that must be taken into account and tried to be solved.

1.3 Scientific basis

In nature exist four fundamental forces and every interaction in the physical universe is reducible to them: strong nuclear, weak nuclear, electromagnetic and gravitational. [2] Concerning about gravity, there are different theories that explain its essence. One is the Theory of Everything, which predicts the existence of gravitons that create gravity. Another is the General Theory of Relativity of Einstein. It states that gravity and acceleration are equivalent and interchangeable according to the frame of reference, and the apparent gravitational force is a consequence of the curvature of four-dimensional space-time.

In any case, gravity results important because it draws atoms close enough together for electromagnetic interaction, as electromagnetic force is the cause for all mechanical and chemical phenomena, and its origin is irrelevant to human health.

The presence of a gravity field provides a constant acceleration and the acceleration is what is necessary to provide weight to an object. The source of the acceleration is irrelevant for humans. In fact, human body cannot distinguish between the effects generated by gravitation or by centrifugation. This concept is the explanation of the usage of the term “artificial” in the description of the gravity field produced by structures, as the acceleration is provided in an artificial way.

Acceleration is divided in two categories: linear and centripetal.

Linear acceleration, parallel to the velocity, modifies velocity magnitude and requires an ever-increasing energy input, which is practically impossible to provide.

Centripetal acceleration, perpendicular to velocity, modifies the velocity direction but not the magnitude. The rotation is self-sustained through the conservation of energy and momentum and this makes centripetal acceleration the only viable way of providing weight in space.

This mathematical conclusion drives the design of a spacecraft spinning around a

central axis. The mathematical model that describes the environment internal to the spacecraft is an inertial frame of reference inside a rotating frame of reference. This situation causes particular resultant forces with not intuitive effects.

Actions in a rotating environment origin an acceleration that is a sum of different terms, expressed as:

$$\bar{A} = \bar{\Omega} \times (\bar{\Omega} \times \bar{R}) + 2 \cdot \bar{\Omega} \times \bar{v} + \bar{a} \quad (1.1)$$

where the different terms are respectively:

$\bar{\Omega} \times (\bar{\Omega} \times \bar{R}) =$ centripetal acceleration

$2 \cdot \bar{\Omega} \times \bar{v} =$ Coriolis acceleration

$\bar{a} =$ acceleration of the object relative to the rotating system. For a circumferential motion is another centripetal acceleration.

The result of the cross-product of the Coriolis acceleration generates an acceleration that is manifested in a plane perpendicular to the axis of application of the movements. This leads to unpredictable effects that normally are present on Earth just in such irrelevant quantities that can be neglected. Practically this produces an instantaneous stimulus about the third axis that can be both disorienting and disturbing. This is called Coriolis or cross-coupled effect. [3]

The magnitude of this effect is predictable from the analysis of the combined vehicular angular velocity (Ω) and the relative velocity of the moving object (v).

Due to this aspect, it is necessary to design parameters of velocity and radius of rotation of the spacecraft for achieving an optimal comfort for the astronauts. These parameters characterize the comfort zone.

1.4 Comfort zone

The comfort zone is a combination of choices of different factors, in particular maximum angular velocity, maximum speed rim and maximum acceleration, which create an environment comfortable for human life.

The constrains related with the design have been studied since 1960 by several authors [2] [4] [5]. The results can be summarized in Figure 1.1 and in the Table 1.1.

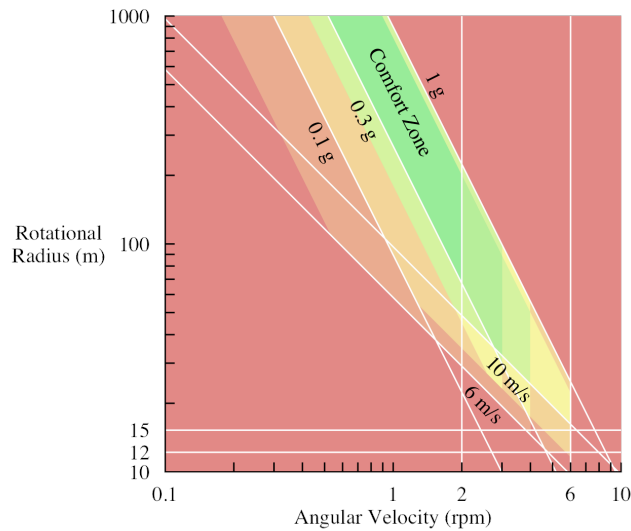


Figure 1.1. Composite comfort chart (Hill *et al.*) The green central zone depicts conditions that all agreed are comfortable; the red periphery depicts conditions that all agreed are uncomfortable; the hues ranging through yellow and orange depict regions of disagreements and conditions that probably require some adaptation to achieve comfort [2].

Author	Target	Min.	Min.	Max.
	A	V	R	$\frac{30\Omega}{\pi}$
	9.81			
	(g)	(m/s)	(m)	(rpm)
Hill & Schnitzer [1962]	1.00	23.4	55.9	4.0
Gilruth [1969]	0.90	14.0	22.4	6.0
Gilruth "optimum" [1969]	0.90	42.1	201.2	2.0
Gordon & Gervais [1969]	1.00	15.6	24.8	6.0
Stone [1973]	1.00	14.7	22.1	6.4
Cramer [1985]	1.00	31.2	99.4	3.0

Table 1.1. Target centripetal acceleration, minimum tangential velocity and radius and maximum angular velocity for comfortable rotation. (T. Hall, [2])

Design drivers for the comfort zone are the maximum angular velocity, the maximum speed rim and the maximum acceleration. These values are chosen to minimize Coriolis acceleration and gravity gradient between head and feet, avoiding headaches, dizzying and orientation problems. It turns out from the graph that rotational radius required is in the order of magnitude of hundreds of meters. This can be practically done with the usage of a huge spacecraft or with the use of tethers to separate two different rotating structures.

Rim speed turns out to be the main driver as it influences the change of gravity felt by astronauts when they are walking. It is necessary to explain the choice of this parameter. The level of artificial gravity (centripetal acceleration) is given by:

$$g_a = \frac{v_{rim}^2}{r} \quad (1.2)$$

with v_{rim} the magnitude of the rotational velocity and r the radius of rotation.

Studies suggest 6 m/s as a sufficient value for the v_{rim} but further investigations discovered that the presented comfort zone in reality has to be considered just acceptable. It can be useful to clarify this point.

Now let's assume for example an astronaut walking in the same direction of the rotational velocity with a velocity v_w . The level of the artificial gravity felt in this case by the astronaut is changed:

$$g = \frac{(v_{rim} + v_w)^2}{r} = g_a + \frac{v_w^2 + 2v_w v_{rim}}{r} \quad (1.3)$$

Then the relative change of artificial gravity compared to the original one is calculated as:

$$\Delta g = \frac{g - g_a}{g_a} = \frac{v_w^2 + 2v_w v_{rim}}{v_{rim}^2} \quad (1.4)$$

From an analysis of the change of the values of v_{rim} , angular velocity and radius (all of them are linked) it is found that substituting the classical value of 6 m/s in the equation is not enough to achieve a small Δg . For a comparison, an elevator provides a Δg of 8% and it is designed to be just comfortable, so values superior to this should be avoided.

Thus, the level of the speed rim needs to be increased. Unfortunately, larger radiuses are needed for sufficient comfort. The result due to this constrain is represented by the green area in the Figure 1.1.

High values of angular velocity cause the creation of cross-coupled rotations, described mathematically with the Euler's equations [2]. It happens when it is performed a rotation about an axis that is not aligned with the axis of rotation. In this situation the semi-circular canals of the inner ear are stimulated as there would be a rotation about a third that is mutually perpendicular to the other two previously described.

The sensation felt is similar to sailing in wavy water.

From the choice of the rim speed and the rotational velocity is derived the consequent length of the rotational radius.

As it is shown in the figure and table there is not a unique combination of these values to achieve an optimal comfort zone. Thus, the design is a little bit flexible and the choice would be done to optimise the comfort zone in dependence on the characteristic of the chosen system. For example, it can be chosen to minimize the mass of the spacecraft choosing a smaller value for the radius and a higher value for the rotational velocity.

1.5 Previous studies

Until now, a full test concerning artificial gravity in space has never been developed. The reason is connected to the cost and the complexity of such an experiment, which has to be performed in space to achieve the maximum of the result.

Develop a full space experiment is clearly a tough challenge. Thus, other kinds of experiments were performed so far: animal studies, ground centrifuges and only few space missions. From these experiments derive the knowledge of effects of microgravity in living beings that is presented in the second chapter.

What it really lacks is an operative test for structures specifically designed to provide artificial gravity.

1.5.1 *Animal experiments*

The Soviet space research community expressed an early and intense interest in artificial gravity [1]. In 1961, they began testing rats and mice in the 25-second weightless periods of parabolic flight. If they were centrifuged at least 0.3 G, their locomotion appeared normal so that this value was suggested as the minimum G-level requirement for avoiding locomotion problems (Yuganov 1964).

Other studies were conducted with monkeys, which physiology is quite similar to humans'.

The first animals (fishes and turtles) to be centrifuged in space were on the Cosmos 782 mission in 1975. The centrifugation was at 1 G, and the animals were found indistinguishable from their ground controls. Furthermore, turtles centrifuged at levels as low as 0.3 G showed none of the muscle wasting typical of weightless, valorising the hypothesis formulated some years before.

In 1977 during the Cosmos 936 mission, rats were centrifuged for 20 days.

These animals, housed in a small-radius (32 cm), high-speed (53.5 rpm), 1 G centrifuge,

showed deficits in equilibrium, visual, vestibular and postural control post flight. But these deficits may have been results of the high rotation rate and the large magnitude of the gravity gradient.

Experiments in space were set only using short-radius centrifuges, and nothing has never been conducted in a spinning spacecraft.

Ground-based animal experiments were carried through years, using centrifugation but also studying animals in partial weight-bearing activities. It was discovered that limb bone mineral density, loss of muscles mass and bones volume were all linearly related to the degree of unloading. These results confirm what was discovered in the space tests.

1.5.2 Human space missions

There are very few examples of manned missions designed to study artificial gravity generation. None of them was specifically designed to study the phenomenon but this subject was a secondary goal for more than one mission.

One of the goals of Gemini program was to prove the possibility to utilize a tethered spinning system to provide artificial gravity [1] [52].

Gemini 11 was a manned mission performed by NASA in 1966. The goal of the mission was to perform a rendezvous between two spacecrafts and then stabilize them with a tether. The expected stability wasn't reached but still was possible to create a small level of artificial gravity (0,00015 G) by spinning the two spacecrafts. This level of acceleration was too small to be felt by the astronauts but proves that artificial gravity performed by a tethered spacecraft is possible.

It was planned also another similar mission, Gemini 8, to achieve an artificial gravitational force. However, due to problems on the rotational control, the mission was aborted.

There were made other experiments, but none of them concerning the use of a tethered system.

The use of centrifugation for other purposes has produced useful measures of centripetal acceleration and its effects on astronauts. One example is a large rotating chamber during the Skylab missions [1] [53] in the American space station active from 1973 to 1979, where the crew could run inside it and produce self-generated gravity.

Later other tests were set inside the laboratory of the Space Shuttle, the Spacelab [1] [54]. Basically, the crew was spun inside centrifuges to study the effects. It was proven that 20 minutes per day of centrifugation reduced the cardiovascular deconditioning in

the 16 days space mission selected. This demonstrate how short radius centrifuges can mitigate the effects of weightlessness.

1.5.3 Centrifugation experiments

Despite the absence of numerous flight-test opportunities, several ground-based studies have been carried focusing on the efficacy and acceptability of human horizontal centrifugation. Obviously, on Earth the investigations are affected by the presence of the gravity field. Thus, the resultant forces are a combination of gravitational and centrifugal forces. Even with this limitation, from the outcomes of the tests with centrifuges took origin the considerations for the comfort zone described previously.

The earliest of the extensive tests of sustained rotation were conducted in 1958. Was created a “slow rotating room” permitting subjects to adapt to rotation during several days. After that, other experiments with different methods and techniques were conducted. The list is long and would be quite useless to mention all of them. More information can be found in [1] [6].

Several experiments were also carried for studying the effects of Coriolis cross-coupled rotation. The results are useful to determine the parameters (in particular the velocity of rotation) for avoiding disorienting effects on humans.

One of the methods currently used for evaluating the efficiency of the centrifugation is to verify if the physiological response of the subjects can overcome the deconditioning due to long bed rest. Studies in this sense have been carried by Clément et al. [7]. Results are partial and sometimes contradictory because of the different method of evaluations. In any case, they can be summarized affirming that centrifugation is promising at least in decreasing the negative effects connected to the microgravity environment. Other studies have to be done to achieve a complete response.

Other authors suggest that results related to centrifugation on Earth are inconsistent with artificial gravity generated in space. Quoting Carrol [4]: *“data from ground-based rotating room tests may not be relevant for estimating maximum allowable spin-rates of orbiting artificial-gravity facilities, since the rotation axis is parallel to gravity, rather than normal to it as in an artificial-gravity facility.”*

Rotation causes two different effects: rotation itself and Coriolis acceleration. These two effects are felt in a different way in ground centrifuges and space centrifuges. Speaking of space centrifuges in comparison with ground ones: *“there the sensed rotation in body coordinates is about a different axis, and depends on which way you are facing at the time. Turning around reverses the felt rotation immediately. Turning*

around even has an azimuth-specific effect: one turn causes a shift in sensed rotation one way, and the next causes an opposite shift in sensed rotation. This is a key difference between ground-based rotating-room tests and orbiting artificial-gravity facilities.”

And about Coriolis acceleration: *“To a person sitting or standing anywhere in a room rotating about a vertical axis, purely vertical motion causes no Coriolis effects (this is what happens in the ground centrifuge). Horizontal motion can cause substantial Coriolis accelerations. In a room rotating clockwise (when you are looking down), the acceleration is to the left of the motion. It is equal to twice the room rotation rate times the horizontal velocity...”* On the other hand, in a space centrifuge: *“Both vertical and horizontal motions cause perturbations, and in body coordinates, both vary with azimuth.”*

The argument is controversial and probably only experiments on orbit can provide a definitive answer.

1.5.3.1 Short radius centrifuges

Short radius centrifuges can be an option for obtaining artificial gravity in a spacecraft. They produce intermitted gravity and can be autonomously or human powered.

The maximum rotation rate of a centrifuge is limited by the Coriolis (linear) and cross-coupled (angular) accelerations encountered when moving an object within a rotating environment. For low centrifugal ratio, Coriolis effects can be neglected, but for high ratio can become a primary problem that leads to nausea, difficulties to move limbs and visual problems. Coriolis force is only proportional to the mass of the rotating object, its linear velocity and the rotation velocity of the environment. Thus, it does not depend on the radius of the centrifuge.

Different designs for centrifuges have been proposed in the past years, for example the “Twin Bike” (Udine), the “Space Cycle” (Caiozzo 2004) and human powered centrifuge by NASA [7].

Normally in a short- radius centrifuge the subjects lay supine with the head near the axis of rotation. This creates a difference in the magnitude of the force between head and feet.

Apart of centrifuges, there are also other methods to simulate partial gravity for studying the effects on human body. It is worth to mention them: tilting the body of subjects or suspend part of it, or walking on the wall of a rotating platform.

Different kind of centrifuges where used for the tests but it has not still found an ideal solution with the best combination of design, time of usage, frequency and acceleration provided.

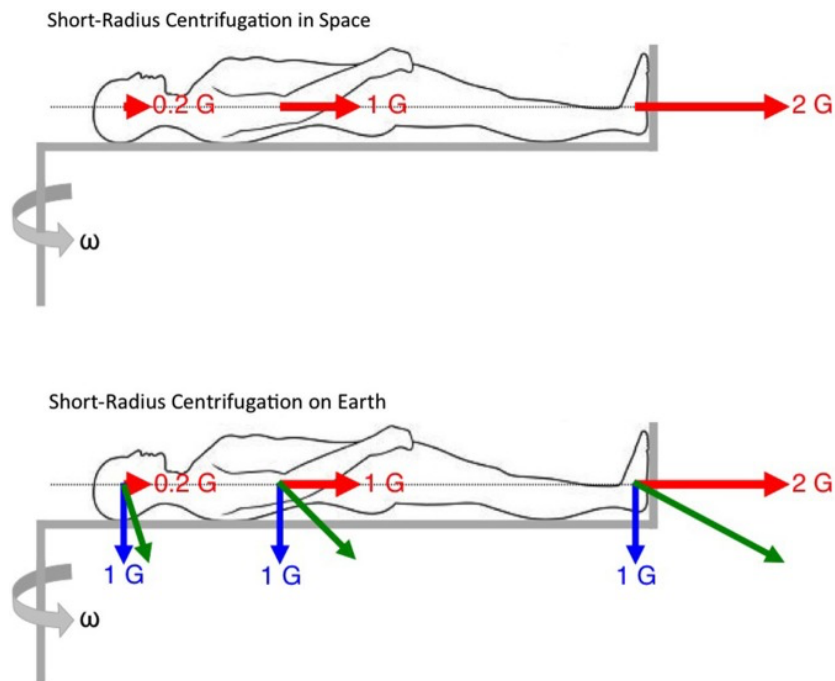


Figure 1.2. Difference between the artificial gravity level felt in space and on Earth using a short radius centrifuge, Clément et al. [7]

Chapter 2

Effects of the lack of gravity

This chapter describes the effects on organisms caused by the absence of gravity. Information are given for humans, which problems can be applied on animals in general as well, and for plants.

Problems on humans are studied both under a physical and psychological point of view.

2.1 Medical problems on humans

The following paragraphs describe all the problems, both physical and psychological, that humans have to face in absence of gravity. It is possible to take precautions, provide useful training to the astronauts, perform physical exercises and so on, but nothing apart a source of continuous artificial gravity can solve them at the root.

2.1.1 *Physical problems*

Extended periods of absence of gravity can be a serious problem for human body, being both physical and psychological.

The principal physiologic deconditioning risks are related to physical and functional deterioration of the musculoskeletal systems, loss of regulation of the blood circulation, decreased aerobic capacity, and altered sensory-motor system performance.

The presence of high radiations is one of the most dangerous things astronauts have to deal with in space but, while radiations are independent to the microgravity environment, they are not studied in this thesis. However, their effect cannot be neglected, and precautions must be taken into account to deal with this problem. Thus, a shield in the spacecraft must be present.

Human body is able to adapt to some problems after some time in space. Other problems will instead continue their growth during time. The following graph shows the time-adaptation for some medical problems. An adaptation point can be set after 6 weeks of permanence in space, while some problems like the loss of calcium in the bones cannot ever be solved.

It is important to explain that even if some problems reach an adaptation after time, their value still exceed the normal threshold present on Earth, so that the physical condition of astronauts' body will be affected by their presence.

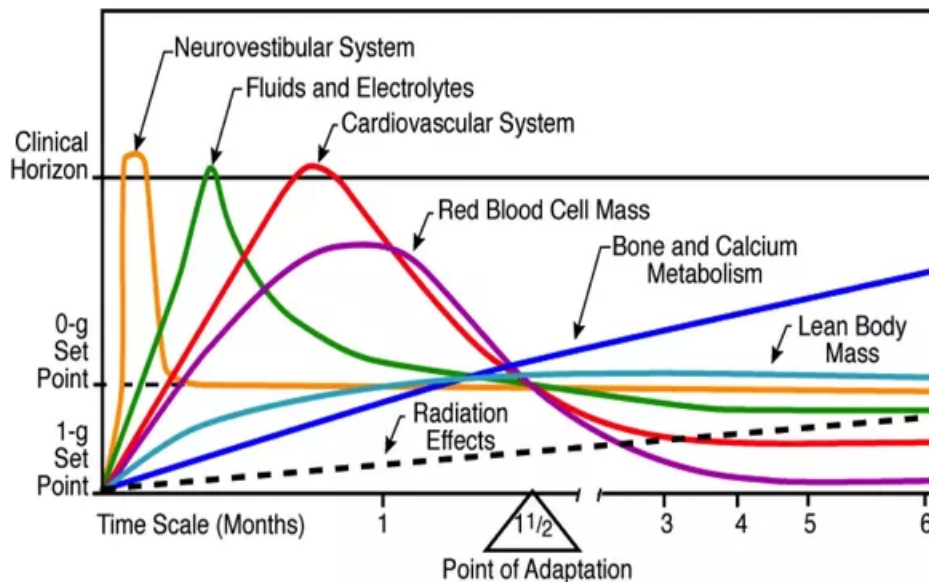


Figure 2.1. A schematic presentation of the main changes occurring in a human body in the near weightlessness environment of space. The 1-g set point represents physiological status on Earth, 0-g set point denotes a complete physiological adaptation level in space which probably can only be achieved by individuals born in space. Point of adaptation is the average time of 6 weeks for a visitor to space to exhibit partial adaptation to the environment. [55]

It is easy to understand how the absence of gravity along time can be dangerous for humans. The image of the astronauts returning from the ISS, who need support as soon they arrive on Earth, even not being able to go out autonomously from the re-entry pods, is something that leaves astonished. Astronauts need months of rehabilitation and exercises to recover completely. And normally the duration on board of the ISS is up to six months, a time that is considered be safe because the problems to the organism are not permanent. Studies say that longer periods can cause irreversible damages.

Following paragraphs are a brief summarize of the principal medical problems that affect astronauts. For more details, all the information can be found in [5] [6] [7] [8] [9] [10] [56] [57].

2.1.1.1 Musculoskeletal problems

Musculoskeletal system is composed by bones, muscles and articulations and permits the movements of the body. As the actions of bones, muscles and articulations are combined and related they can be considered part of the same apparatus. In fact, the behaviour of bones and muscles is similar in a microgravity environment, and they both suffer of similar dangerous effects.

Bones are living tissue, constantly being remodelled. Osteoblasts use calcium absorbed from the blood for strengthen them and simultaneously osteoclasts return calcium to the blood.

Loads along the axis of the bone are necessary to maintain bones healthy. During a spaceflight, the bones that support body weight begin to deteriorate because of the absence of loads and a loss of body calcium quantity occurs, independent of the amount taken in with food or supplements. Calcium is lost at a rate of about 1.0% to 1.5% per month, and the losses are reflected in the density and size of weight-bearing bones. This loss is greatest in the upper thighs and pelvis. For an example, astronauts that spend six months on the ISS lose on average 11% of the bone mass in their hips. For a mission with a duration of two years, such as a mission to Mars, a 40% decrease in bone size might occur (unless the process reaches a plateau), consequently increasing the risk of fractures and the bone's ability to mend.

Muscles begin to weaken with disuse. This clearly happens in a weightless environment, where the body does not need to apply forces to contrast loads that are inexistent. The result is a loss both in strength and in endurance as a function of time in flight. In fact, when muscles are not used for a certain amount of time they can go into “hibernation” mode and begin to waste away.

2.1.1.2 Cardiovascular problems

Cardiovascular system is formed by organs with the function of transporting fluids through the organism to deliver nutrition to the cells.

The fluids are deeply affected to the presence of gravity, so the system is programmed for taking into account this phenomenon. For example, blood is normally shifted to the lower part of the body, ordinarily leaving the brain only with the correct amount needed.

Without the external influence of gravity the entire apparatus is destabilized.

In weightlessness, the shifting of fluid from the legs and lower trunk to the head and chest leads to a sensation of fullness of the head and to a general discomfort.

“Space anemia” is a phenomenon that consists in a loss of body fluid, including blood

plasma, with a consequent excess of red blood cells. The body restores the internal balance of fluids stopping the production of red blood cells in the bone marrow and additionally by destroying the youngest cells.

In absence of weight, the system that acts to maintain adequate blood pressure when we stand up is no longer needed and it shows signs of deterioration.

In addition, cardiovascular fitness is compromised during flights, so the capability of oxygen consumption during exercise is diminished.

Problems related to the cardiovascular system are not risky while flying but become dangerous after the re-entry on Earth with the new exposure to gravity.

2.1.1.3 Sensory-motor problems

Sensory-motor system provides to the body the inputs for the orientation and movements. It is composed by different sensors, in particular the inner ear (otolith), the skin, and the body sense (proprioceptor) receptors. It has also the purpose of keeping the body in balance.

The loss of gravitational stimulation due to weightlessness affects negatively the sensory-motor system and, as linear acceleration is the only stimulus that the organs can feel, a considerable reinterpretation of vestibular signals may take place, and new sensory-motor strategies must be developed. The consequence is the occurrence of space sickness early in flight, and postural disturbances and vertigo after return.

2.1.1.4 Other problems

Apart of the problems just described that affect different systems of the body other general problems may take place.

For example, the immune system function also may be compromised by spaceflight, reducing the ability to fight infections. The degree to which weightlessness plays a role in this is currently unknown.

A series of scientific studies have shown that certain bacteria, including known human pathogens *Pseudomonas aeruginosa* and *Staphylococcus aureus*, seem to become more hardier and more virulent and at the same time weightlessness can suppress certain immune functions, leaving astronauts more vulnerable to disease.

Vision Impairment and Intracranial Pressure (VIIP) syndrome is another effect of the exposition to a microgravity environment. This syndrome is not still fully understood, but the leading hypothesis is that the weightlessness of fluids induces impairment in cerebrospinal fluid resorption and central nervous system venous drainage [11].

Practically, some excess fluids are drifted inside the head. This leads to problems in the sight. After the return on Earth, 48 % of astronauts suffer of problems in the eyes and in some cases they do not end with the return of the astronauts on Earth and continue for several years after.

Countermeasures as interventions like venous limb occlusion and lower body negative pressure could play a preventing role, but the most useful countermeasure can be providing artificial gravity to completely avoid the problem.

Weightless environment is also cause of other human-factor complications: need for handholds or footholds, waste management, fluid handling, food preparation, and hygiene. However, sometimes the absence of gravity could also help the astronauts: they can move heavy objects and use completely the three-dimensional space that they have at disposition inside the spacecraft. Moreover, movements require no efforts.

2.1.2 Countermeasures

Fighting the degeneration of the body in space is something that is currently done during all long permanence missions.

Countermeasures are basically divided into two groups: exercises and alimentations.

Astronauts must perform daily exercises to contrast musculoskeletal losses and preserve the cardiovascular system [11] [12] [13]. These exercises are time demanding, request a high degree of individual discipline and are often difficult to implement. ISS astronauts for example are scheduled for a total of 2.5 hours of exercise each day (including prep time). Practical experiments suggest that short, dynamic, high-intensity workouts are most effective. Extending the duration of workouts has a diminishing effect on further bone adaptation and bones cells appear to be less responsive to routine loading signals. Special machines are needed for a weightless environment. Running inside a spacecraft is impossible for example. Astronauts must be bound to the machines during the practise. Machines clearly occupy volume and weight and are subject to the possibility of break. In the ISS there is a treadmill and a resistive device that allows astronauts to simulate both running and weight-lifting.



Figure 2.2. Examples of training exercise on board the ISS, (a) and (b). Credit: NASA

Usage of centrifuges can be a countermeasure, but experiments suggest that passive centrifugation on a short-radius centrifuge will not be effective in maintaining skeletal muscles mass and bone density during long exposure to microgravity.

On the other way, the use of centrifuges, coupled with other shrewdness, for example resistive and aerobic exercise, extra dietary calcium, and other pharmaceuticals can be enough to mitigate physiological adaptations to weightlessness.

Specific sessions of exercises were studied in order to maximize the effect of the centrifuges.

For all these reasons exercises are a good compromise, but not a complete solution.

Alimentation of the astronauts is controlled. First of all, the food occupies volume and mass, and its quantity has to be minimize. Most of the food is served as gel or pills so meals are completely different from what we are used on Earth. Secondly, the diet should be as more balanced as possible, so a large use of dietary supplements and pills is required.

There are several medications that could help to preserve the health of the astronauts [9]. For example, commonly used medications like Erythropoietin (used in dialysis for cancer patients) and fludrocortisones (used to treat orthostatic hypotension) can increase red cell mass and blood volume.

On the other hand, medications and medicines can alleviate the symptoms of weightlessness, not the root cause, and run the risk of unintended side effects. For example, adding calcium to the diet to avert bone demineralisation increases the risk of developing urinary stones. This happens because bones lose calcium, and this calcium circulates inside the organism increasing its normal level. But bones are unable to fix even the extra calcium provided by the diet, so that it will increase furthermore the level of calcium already present in the organism. This is a useful example to explain that solving health problems using dietary supplements is not always a solution.

2.2 Psychological problems

Psychological problems are probably less evident than the physical ones but can be even more problematic. Human behaviour and psychology is difficult to predict, in particular under circumstances of high stresses as a space mission can be.

Humans are so used to the presence of gravity that living without it is something difficult to imagine. Its absence is for sure the first thing every astronaut can feel after reaching the space.

Living in a spacecraft presents a lot of differences compared to a normal life on Earth: living in a closed space and surrounded by few people, with the continuous idea that after few centimetres of material there is the absolute void and certain death. It is clear that all of this deeply affects the mental stability of the crew.

Astronauts are tested and trained with specific programs [9] to deal with these problems.

There are typical countermeasures adopted in space. Keeping the astronauts busy with daily tasks, psychological support, productive use of the free time and physical workouts can help to reduce the stress caused by this anomalous situation.

In the past years many and many space missions took places, and absence of gravity has never been an insurmountable problem. On the other hand, missions were generally quite short and life in space for long time has never been tested. The typical duration of a period for an astronaut in space is around three-six months, a short duration that cannot influence deeply a human being, both physically and psychologically. The Russian Valerij Vladimirovic Poljakov detains the record for the longest permanence in space, with 437 days in a row in the Mir in 1994. In 2015 started the “One year mission” by NASA, with the goal to spend one year in space studying physical and psychological consequences in order to collect information for a future mission to Mars. These are the longest tests of permanence in space. A mission to Mars can last on average two years, so a duration that has never been performed before and will carry additional difficulties. For example, it is not possibly to supply fresh food or have replacements in the crew. Due to the distance from Earth, communication becomes slower and a message sent in the proximity of Mars needs around 20 minutes to reach the home [14]. This makes way difficult the contacts with family and friends and increases the sensation of loneliness.

Studies on Earth about psychological responses in difficult environments have been carried. Basically, some people are confined into a close environment for a long time without the possibility to interact with the external world. Some examples are missions in the artic or inside submarines [15] [16]. Results show how quarrels and discussions between people become ordinary.

These kinds of examples are not enough to achieve a complete understanding of the consequences of long flights and additional researches have still to be done in the sector.

By the way, it is obvious that the design of any manned missions should try to help as much as possible the life of the crew. A constant artificial gravity is for sure the first goal to achieve in this sense. Its presence can make the astronauts feel like to be at home, decreasing the stress due to environment they are living in.

It is also important to underline that in the future is possible that even normal people could achieve the space. For example, could be developed space tourism and even colonization of other planets. People are not selected and trained as the astronauts are, so making the permanence in space more easy and comfortable as possible providing artificial gravity is a priority for the development of such enterprises.

In conclusion, psychological aspects in space missions cannot be ignored, as they can be a cause of mission failure as well as any other problems related to the technical aspects.

2.4 Plants

Growing plants in space can help space missions in different ways. The principal advantages can be summarized in the following:

- Food production
- Oxygen production
- Recycling of water and organic wastes
- Psychological benefit

Growing food in space helps to solve one of the biggest issues of space travel: the price of eating [58]. With the enormous cost of sending tools in space even bringing food can be a prohibitive factor. Cultivation on board can help to partially solve the problem. Moreover, eating fresh food instead of packaged food is something that astronauts can really appreciate, making their trip more satisfying.

In addition, plants can provide a service now performed by sophisticated equipment to scrub the carbon dioxide expelled in the environment when the crew breathes. At present, the oxygen necessary for breathing has to be replaced by on board supplies carried from the Earth. Plants that use carbon dioxide in their metabolism and expel oxygen as a waste product can potentially take on the task of regenerating the atmosphere and eliminating excess humidity from the environment.

In addition, plants can also be used for exploiting dirty water and organic wastes, which can be turned into fertilizers instead of being thrown away.

And, not to be underestimated, there is the up-lifting psychological effect of caring for and nurturing a garden, so far away from the greenery of the Earth. According to the Horticultural Society of New York [59]: *“plants also act as a form of emotional sustenance called horticultural therapy. It’s based on the simple idea that plant care is a balm for the human psyche. The list of gains is long: stress reduction, mood improvement, alleviation of depression, social growth, physical and mental rehabilitation and general wellness”*.

Clearly, cultivation of plants presents interesting advantages and should be developed.

Different studies, tested both on ground and in space, were performed to understand the behaviour of plants in a spacecraft.

It was found that microgravity highly influences the growth of plants.

Two main differences are present in space plants in comparison with ground plants: the rigidity of the body and the growth velocity.

2.4.1 Previous studies

Studies in space were carried using both plants and protoplasts, which are the undifferentiated plant cells normally used in experiments.

The earliest experiments using protoplast cells started on a satellite launched from the Soviet Union in 1989. Were used rapeseed and carrots protoplasts and exposed to microgravity conditions for 14 days on Biokosmos 9 [17] [18].

The major result of this experiment was a significant decrease in the content of cellulose and hemicellulose, with a resulting decrease on the thickness of cellular walls and in the total peroxidase activity, which is one of the procedures that the plants use for depuration. These two effects decrease the resistance of the plants against illnesses and cancers. The callus cultures established during the two-week-long flight also showed a retarded growth and division compared to the ground control.

The Biokosmos 9 experiment was followed by an American experiment called “PROTO” which was flown on the Space Shuttle in 1992 and four years later a new mission (S/MM-03, Shuttle Mission to Mir-03) was launched.

Both missions confirmed the result obtained in Biokosmos 9: the regeneration of the protoplasts was retarded. It was also used a centrifuge on board the vehicle which provided a 1 G level of gravity. Other protoplasts were used inside it, providing a comparison for the results obtained in the absence of gravity.

Another family of experiments, SVET, were set on board of MIR (the Russian space station) from 1980 [19]. They lasted for 680 days and the purpose was to study the seed-to-seed cycle in microgravity. The conclusions were that seed-to-seed cycle is achievable in space, proving that space auto-sustained agriculture is possible. However, SVET experiment showed also that plant growth in microgravity was retarded, plants were smaller and seeds were mostly sterile.

In ISS the Veggie experiment [20] was developed in 2014, with the goal of studying future hardware modifications and provide information on food crop growth and development in a microgravity environment.

In the meantime, also ground-based experiments were carried simulating the production of plants in a close environment, such for example the Biosphere 2 experiment in Arizona [60].

2.4.2 Cultivation techniques

Plants can be cultivated with three different techniques: in soil, with hydroponic or aeroponic strategy [21] [61].

Cultivation with soil, as is normally made on Earth, results to be difficult to implement in space because of the massive quantity of volume and mass that the soil requires.

Hydroponic consists in cultivate plants directly into water and adding the right amount of nutrients that the specific plant requires. The save in mass and volume united with the possibility to have a controlled production make this option the best for space agriculture. Experiments in ISS proved that this solution is possible.



Figure 2.3. Aeroponic culture on board the ISS in a microgravity environment. Credit: NASA



Figure 2.4. Astronaut Steve Swanson harvesting thirty three day-old Veggie-grown lettuce on the ISS on June 10, 2014. Credit: NASA

Aeroponic technique can be presented as a particular case of hydroponic. Plants are grown in absence of both soil and water, and sprays of water on the leaves or on the roots give the nutrition required. The environment needed for aeroponic is highly controlled and must be separated from external environment.

Both hydroponic and aeroponic show an increase in the production in comparison to standard soil agriculture.

Even if is possible to develop hydroponic and aeroponic cultivations in lack of gravity, their implementation is more difficult and less efficient. For example, water cannot be used and must be used gel solutions, with consequential problems in increase of volume, necessity to use a machine to produce the gel in situ and a decrease in the growth performance.

On the contrary, the presence of gravity can facilitate the implementation of this solution, allowing for example to use water in the liquid state and to utilize liquid cycles without the necessity to use pumps, saving mass and energy.

2.4.3 Effects on plants

Lack of gravity influences negatively all living beings. In the paragraph 2.1, the principal problems that affect human bodies were explained. Similar effects are shown in the plants [22] [23] [24].

The main consequences are the following:

- Slowly growth
- Decrease in resistance against diseases
- Difficulty in the growth connected to the absence of gravitropism
- Decrease in rigidity

Throughout evolution, plants have utilized gravity as the most stable and reliable signal for their survival. The immediate effect of gravity enables plants to orient their leaves towards sunlight and to develop a root system to anchor and absorb water and minerals. Plant gravitropism is the most typical response when a plant is turned onto its side.

In lack of gravity plants have difficulties to develop roots and leaves in the correct direction. From the experiments in space it has been demonstrated that the presence of light in one direction is enough to help the plant to understand in which direction grow. But it is also important to point out that the experiments on orbit were always carried around Earth, where is still present a small gravity gradient that is irrelevant for humans but can be felt by plants. No experiments were studied in the outer space in total absence of gravity, so it is not possible to predict if the only light could be sufficient to make plants grow in the correct direction.

The plant cell wall is the major source of mechanical strength and form and despite its rigidity it permits and facilitates growth. The network of cell walls in a plant can be compared to both skin and bones in humans and animals, and it reacts in a way that is comparable to the reaction of the musculoskeletal human system. In fact, the cell wall thickness decreases in the microgravity environment, due to a lower level of cellulose and mass of matrix polysaccharides per unit length. Same results were supported by ground-based experiments.

This effect can be easily linked to effects in the human body, as the lack of gravity causes a decrease in bone volume with the result of a decrease in body strength.

The decrease in cell wall thickness and rigidity causes negative consequences in the plants. They are clearly weaker and even a small touch can break their structure. And secondly, they are less protected from illnesses and infections in general, because their primary defence against pathogens is the thickness of the cell walls.

It is important to clarify that the results from the performed space experiments, including the few focusing on cell walls, are difficult to interpret and often inconclusive due to the use of various flight hardware, growth conditions, preservations, the small number of experiments, and few replicates.

By the way, it is clear how microgravity impacts negatively in plants growth, with effects comparable to effects on human body.

As it was previously explained, experiments carried until now were performed with at least a small level of gravity, while experiments in total gravity lack has never been performed. For solving this deficit, it is important to develop systems capable of generating artificial gravity, avoiding problems related to plants growth that for sure would manifest.

In any case, further investigations have to be performed in order to obtain satisfying and completed results, and the installation of a system providing artificial gravity can be useful also to accomplish them.

Chapter 3

Technical solutions

In this section are examined the technical solutions that can be used for generating artificial gravity. It is done a fast analysis of pros and cons of every solution and finally is given an opinion on the best choice.

Basically, three options are taken into account: the use of only centrifuges and exercises, with the generation of intermittent gravity; the use of a spinning spacecraft with a fixed geometry; the use of a spinning tethered system.

From the comparison, the last one results to be the best option.

3.1 Centrifuges and exercises

As it was explained in paragraph 1.2, artificial gravity can be divided in two categories: continuous and intermittent. Centrifuges can provide intermittent gravity and it has been demonstrated that they can be a partial solution for decrease the negative effects due to the lack of gravity.

Centrifuges present the advantage of the cost and complexity. Additionally, they were tested long enough in the past so their technology is reliable. They can be used alongside with the practise of exercises for maximizing the effects. The practice of daily exercises is the current countermeasure adopted in the ISS.

Probably centrifuges can be considered the best solution for short flights. But what about longer ones? For long journeys the disadvantages of this solution overcome the advantages.

For example, the failure of the machine causes the complete failure of the system. This is a problem that can be solved if a mission is orbiting around Earth, as the astronauts can be sent back on the planet before their physical problems become irreversible or fixing tools can be sent from Earth. Clearly this cannot be done in a mission in the outer space.

The mass, volume and power consumption of a centrifuge are limited, but on the other hand probably can be compared to the values obtained for creating a system capable of generating continuous artificial gravity, as can be a rotating spacecraft. In fact, in the following paragraphs will be demonstrated that this solution is more simple and reliable than is normally imagined.

But the very weakness of the usage of centrifuges is the creation of intermitted gravity, which is still a partial solution, as it can be performed only during a limited time and in a limited space. It can help to reduce the physical problems but not solving them and nothing can do against the psychological ones. Life inside the spacecraft is substantially unchanged outside the period of exercises.

In conclusion, for long time missions, is necessary to develop a system completely efficient and capable of providing the maximum comfort.

3.2 Spinning spacecraft

Paragraph 1.3 explained the mathematical concept of the artificial gravity. The key is developing a rotating environment that produces a centripetal force. This force is not compensated by any other external forces so that the final result is the generation of a constant acceleration along the radius of rotation.

Theoretically the task is simple, as from the parameters obtained from the comfort zone is possible to calculate the dimensions required. The shape of the spacecraft can be for example a large torus rotating around a central axis. The spinning up manoeuvre can be performed with lateral secondary thrusters.

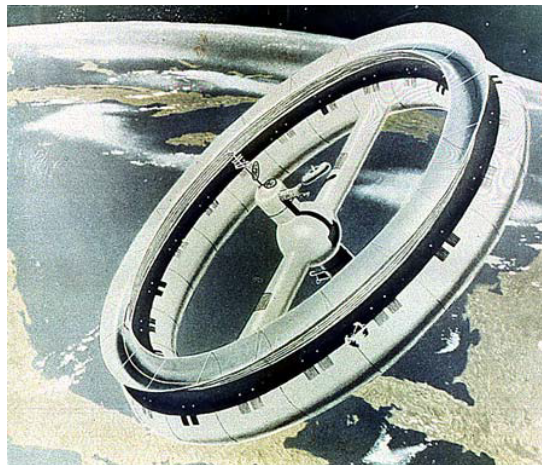


Figure 3.1. An example spacecraft with a torus design presented by Wernher von Braun (concept art, 1952).

The image presents the concept design of a torus spinning spacecraft. The scheme is quite simple: the crew would live in the external ring, in particular in the wall because the direction of the acceleration would be perpendicular to it. The rotation is around the centre of mass that would be in the middle of the circle as the structure is symmetrical. Practically this solution can be impossible to perform due to the giant dimensions required. In the figure 1.1 representing the comfort zone, it is shown that the operational radius would be more than 200 metres.

It is impossible to launch directly such a spacecraft in orbit, so it must be assembled in space after multiple launches of its components. Costs of the deployment and assembly are probably prohibitive.

On the other hand, smarter geometries of spacecraft can be chosen.

In fact, it is not necessary for the structure to be as solid and rigid as the example of the previous image.

Following images show two different examples of spacecraft presented by NASA as possible future transports for human exploration.

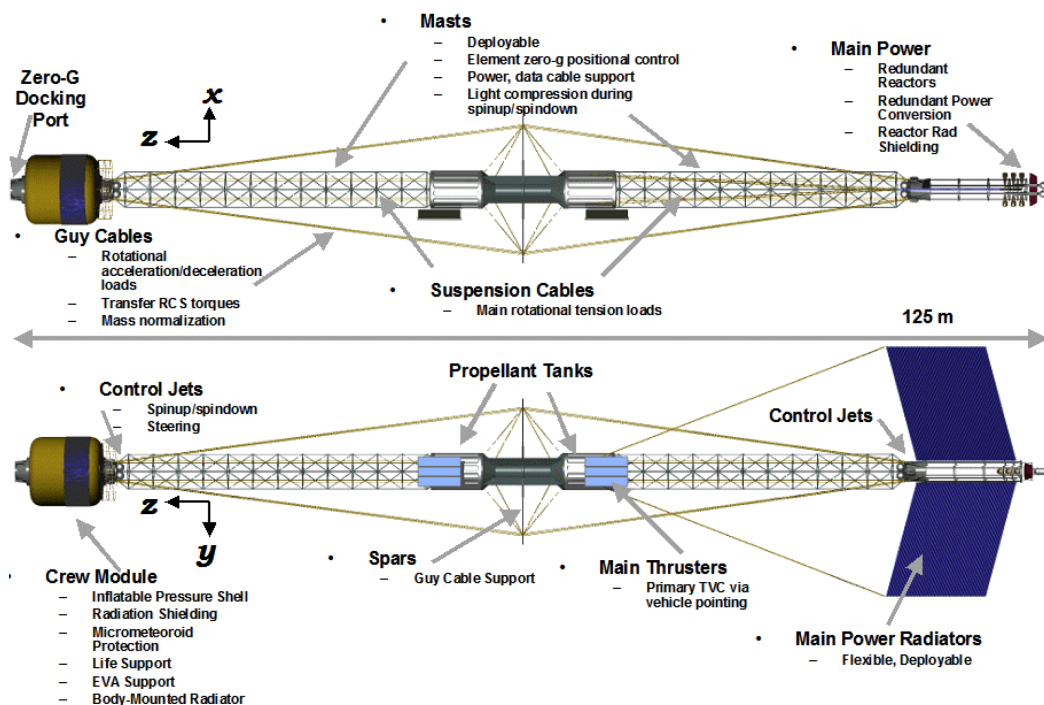


Figure 3.2 Spacecraft configuration proposed by the NASA, *Preliminary Assessment of Artificial Gravity Impacts to Deep-Space Vehicle Design* (Joosten ,2007) [25].

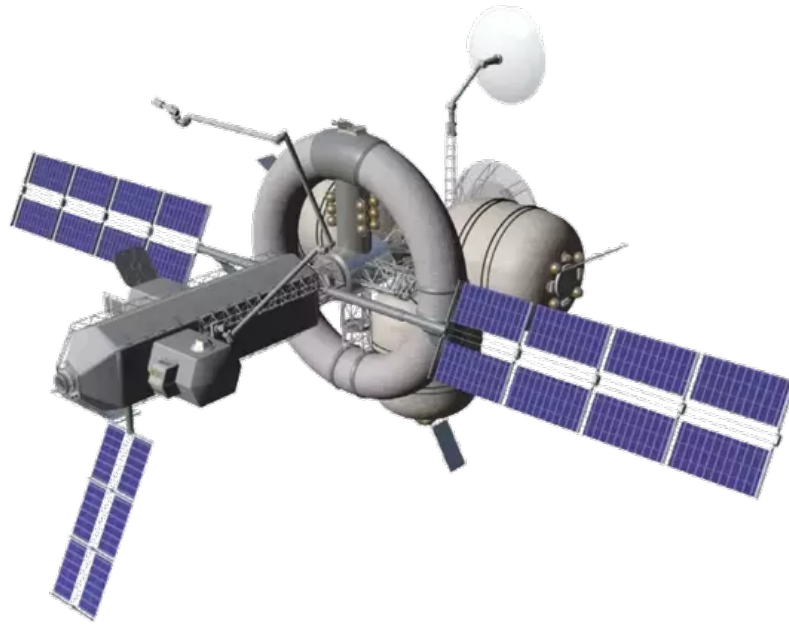


Figure 3.3. Nautilus-X (Non-Atmospheric Universal Transport Intended for Lengthy United States Exploration). Design of a multi-mission space exploration vehicle, NASA, 2011

The usage of tethers, cables, bars and inflatable structures provide lightness and a more customizable geometry to the spacecraft [4].

Several studies have been done to estimate the technical aspects related to this kind of spacecrafts.

In 1989 NASA summarized a study for an artificial-gravity crew transport vehicle as a part of a mission to Mars. The result shows that there would be only a 26% increase of mass and 10% increase of cost versus a zero-gravity vehicle in the same mission scenario. There were used values for the rotation rate and rotational radius of 2 rpm and 224 m respectively [2].

Fifteen years later the mass increase was estimated with a value of 20%.

These results are promising for a future practical development. The important idea for designing such a system is choosing the constrain of the generation of artificial gravity as the primary requirement. Secondly, the design of the other subsystems would follow. With this scheme of procedure is possibly to achieve feasible results. On the contrary, trying to readapt an existing system adding the characteristics for generating artificial gravity would lead to expensive and difficult solutions, with a not practical result in the end.

A study in 2007 started with artificial gravity as the prime requirement and then proceeded with the choice of a low-thrust nuclear electric propulsion system. According

to the author Joosten [25] [26], very little (5%) additional structural or propellant mass was identified above that required for zero-gravity transfer.

Other studies tried to optimize the system using already proven technology.

The first (Jevtovic, [27]), relies on the use of the technology derived from magnetic-levitation trains. This can be used for creating a contactless and frictionless contact point between the central axis and the spinning part. The electromagnetic system works without propellant and is powered by solar collectors.

Solar power is also used in the concept that Sullivan [28] [29] has developed. It consists in an asymmetric spacecraft in which the power generation and motor assembly serves as the counter mass for the habitat. The rotation of the uninhabited counter mass isn't constrained by issues of human comfort and can be much faster than the habitat module's rotation. The centre of mass and rotation axis of the system lies between the spinning counter mass and the habitat.

In conclusion several studies show how in reality an artificial gravity rotating spacecraft is a feasible solution. By the way a smartest design choice can be done, consisting in the use of cables and tethers to further reduce the mass requirements.

3.3 Tethered spinning system

A tethered spacecraft is composed by two different parts united by a tether with the two parts rotating around their centre of mass.



Figure 3.4. Concept art of a tethered spinning spacecraft for the generation of artificial gravity (Landsdorp *et al.* [5])

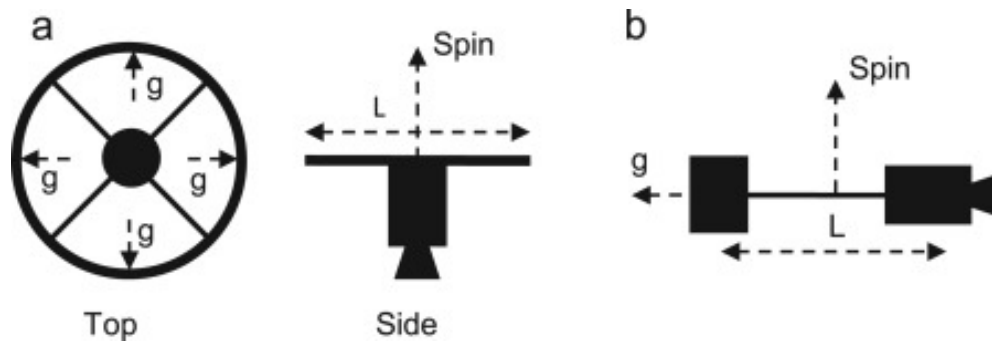


Figure 3.5. Schematic concept of the design spinning spacecraft for the generation of artificial gravity. First configuration (a) is spacecraft spinning around its centre of mass, the second (b) is a tethered system. (Landau, 2008, [30])

The main advantage of this solution in comparison with a normal rotating spacecraft consists in an important decrease in the total mass of the system.

A second advantage consists in the mobility of the structure. In fact, the length of the tether can vary, as it can be just partially deployed. This leads to an important fact: changing the distance between the rotating body and the rotation centre influences the value of the artificial gravity obtained. Thus, is possible to optimise the level of artificial gravity in function of the mission scenario. Taking into account a mission to Mars for example, it is possible to start with a gravity value of 1 G and smoothly decrease it during the time until reaching the 0.38 G level of Mars. The same can be done for the Moon. Astronauts have time to adapt slowly to the new condition without a sudden and harmful change. This advantage is something that can be provided only by a tethered system. Because of this aspect, a tethered structure can be also become a sort of space facility capable of training the astronauts at different levels of gravity, in dependence of the mission they have to accomplish.

Another advantage is the possibility to use a tethered system as a rescue plan in case of abort of the mission [31]. Cutting the tether in the correct moment can provide sufficient acceleration to the habitat module to return on Earth. This solution can be used in case of failure of the principal thrusters for example.

The disadvantages are connected with the tether, in particular with the deploying manoeuvre and the risk and consequences of a breaking. Secondly, it suffers from a perceived incompatibility with vehicle thrust and manoeuvrability. To address those concerns, Landau [30] has performed a detailed mathematical analysis of the dynamics for a tethered artificial-gravity Mars transit vehicle. His proposal allows for high-thrust propulsion and manoeuvring without the need to halt the rotation or reconfigure the vehicle. After this brief overview is already clear how a tethered system presents a series of advantages which cannot be underestimated, and the following work is focused on a deep analysis of this system.

Chapter 4

Tethered spinning system

This chapter is focused on the description of the main topic of the thesis: the usage of a spinning tethered system to provide artificial gravity.

It includes the description of the principal subsystems that characterise this solution, in particular the tether. Moreover, it is presented a list of the advantages and general considerations of this system.

4.1 Tether design

The tether is one of the most critical objects in the design. It must both provide sufficient strength and survive the inevitable impacts of debris.

As explained later on, the best shape for it is a tape. The material must have a high strength/density ratio. As the system is only mechanic, characteristics concerning the electrical proprieties of the material can be neglected.

4.1.1 Hypervelocity impacts

Possible impacts of debris or small meteorites against the tether happen at high speed, with an order of magnitude of several km/s. At these values the impacts are defined hypervelocity impacts.

If the speed of the impact exceeds the speed of the resultant compression waves in both target and projectile, the result is a highly compressed interface between the projectile and target. In this case, the consequent hypervelocity impact formed a shockwave that propagates in the two fronts, one in the direction of the motion of the projectile and the other in its opposite. The shockwave creates an adiabatic propagation of heating and an increasing gradient of pressure.

Heat and pressure are so high that the rate of creation of energy exceeds the rate of dissipation, with the consequence that both target and projectile are vaporised and, for thin targets such as tethers, a cone of ejecta is ejected from the back of the target.

The target structure is consequently damaged microscopically and macroscopically.

The ejecta cone continues its path until it strikes another obstacle [33].

4.1.2 Shape of the tether

Tethers can be divided in two categories concerning the shape: round shape and tape shape.

A tape shape is highly favoured regarding the survivability against debris flux because it reduces considerably the risk of a fatal-impact count [32] [33] [50].

With the same amount of mass, a tape shape has a surface larger than a round shape and its probability of survival is superior as explained in the following. The survivability of a tape can be as much as two orders of magnitude higher in comparison to a tether of the same mass and a round shape.

Another difference between the two configurations is the dimension of the holes inevitably created after a collision with debris. The debris has every time a level of energy capable of puncture side-to-side the tether, whatever its shape can be. In a thin tape shape, the shockwave generated with the passage of the debris inside it cannot propagate in the direction of the surface. For this reason, the holes have a dimension comparable with the dimension of the projectile. In a round shape however, the generated shockwave melts more material of the tether, with the consequence that the holes are up to 3 times larger than the dimension of the projectile.

The consequence is that the tether is severed by particles with diameters sizes of around $1/3$ of the orthogonal projection of the tape's section along the debris velocity vector, while for the tape tether the diameter of the particle should be comparable to the tape's section. Practically a tape shape can survive to a particle with a triple diameter in comparison to a round shape, with a consequent clear advantage because the flux of larger objects is much smaller.

A problem of the tape shape can lie in its thinness. If the dimensions of projectile are larger than the thickness of the tether, an impact with a direction parallel to the width of the tether could completely cut it. However, experimental results show that in this case the projectile is cut in a half in the moment of the impact and the tether is only lightly damaged [50].

4.1.3 Survival probability of tethers

Space is populated by moving particles attracted by gravity. Their distribution is quite uniform in the outer space, while the concentration increases near the planets. Earth in particular is also surrounded by particles with artificial origin. The particles are divided in two categories: debris, generated by humans (average density 2,8 g/cm³) and micrometeoroids, with a natural origin (average density 0,5 g/cm³).

The survival probability of a tether is the probability that the system would not be compromised by impacts with particles along the duration of the whole mission.

It is important to underline that the system taken into account is designed for long trip journeys in the deep space where the concentration of micrometeoroids is lower than around a planet. The deployment of the tether can be done either after the geostationary orbit, where the debris are rare, or before. This choice will be evaluated in paragraph 5.4. For the moment it is important to say that even following the second solution, the time exposed to the presence of a high concentration of debris is really short.

The formula (5) provides the probability of failure of the tether.

High survival probability P requires low fatal-impact count N in a Poisson probability distribution:

$$P = e^{-N_c} \approx 1 - N_c \quad (4.1)$$

$$\frac{N_c}{L\Delta t} \cong \dot{n}_c = \int_0^{\pi/2} \frac{d\theta}{\pi/2} I(\theta, v_p) \quad (4.2)$$

$$I(\theta, v_p) = \int_{-\infty}^{\delta_{\infty}} \frac{-dF}{-d\delta} d\delta D_{eff} \quad (4.3)$$

where $F(\delta, v_p)$ is the debris-flux and θ is the impact angle relative to the normal to the tape wide side. The upper bound δ_{∞} in the δ -integral can be any large debris size. v_p is the debris speed and D_{eff} the effective tape width.

Studies in papers [32] show the maximum number of fatal impacts over the time of exposure.

From the data gathered from the measurements over many years, different debris-flux models are available. In particular, around the Earth the most used are ESA's MASTER2009 [34] and NASA's ORDEM2000 [35], while in the outer space is valid the Grün interplanetary flux model [62]. These models show the concentration of debris in dependence of their dimensions and positions in the space. Below 2000 km there is the higher concentration of space debris, while for higher altitudes their number

decreases until it can be neglected.

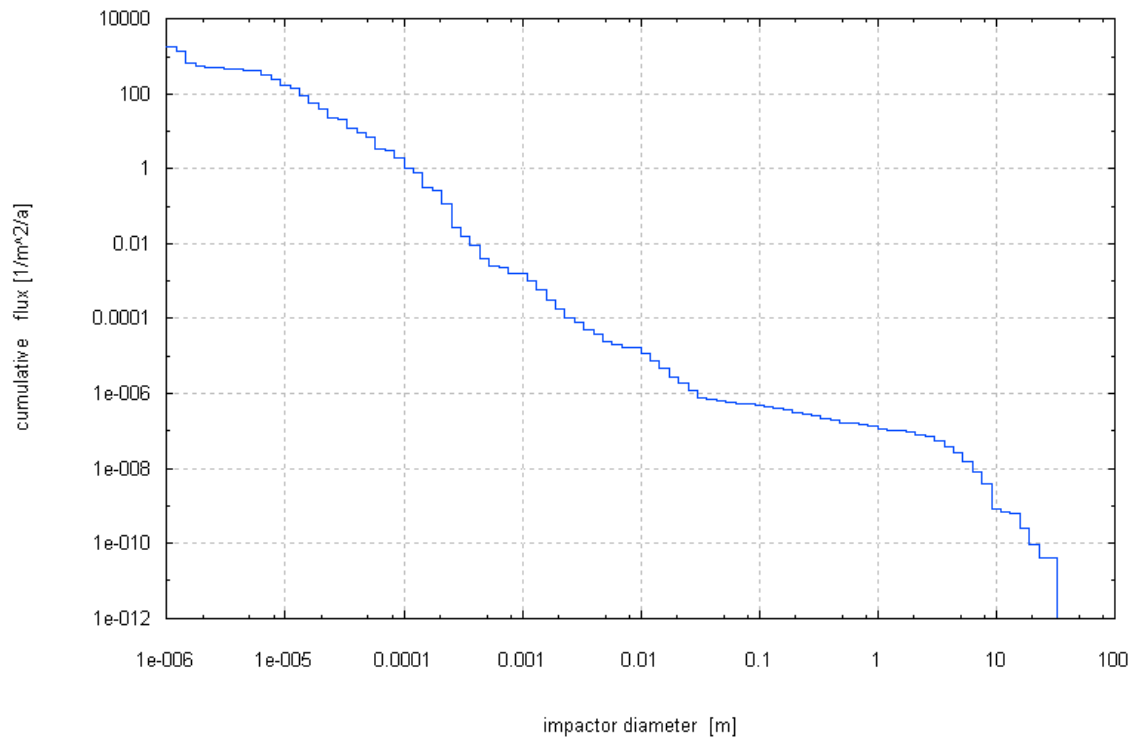


Figure 4.1. Flux vs impactor diameter at 400 km of high, inclination 51.6° MASTER model [34]

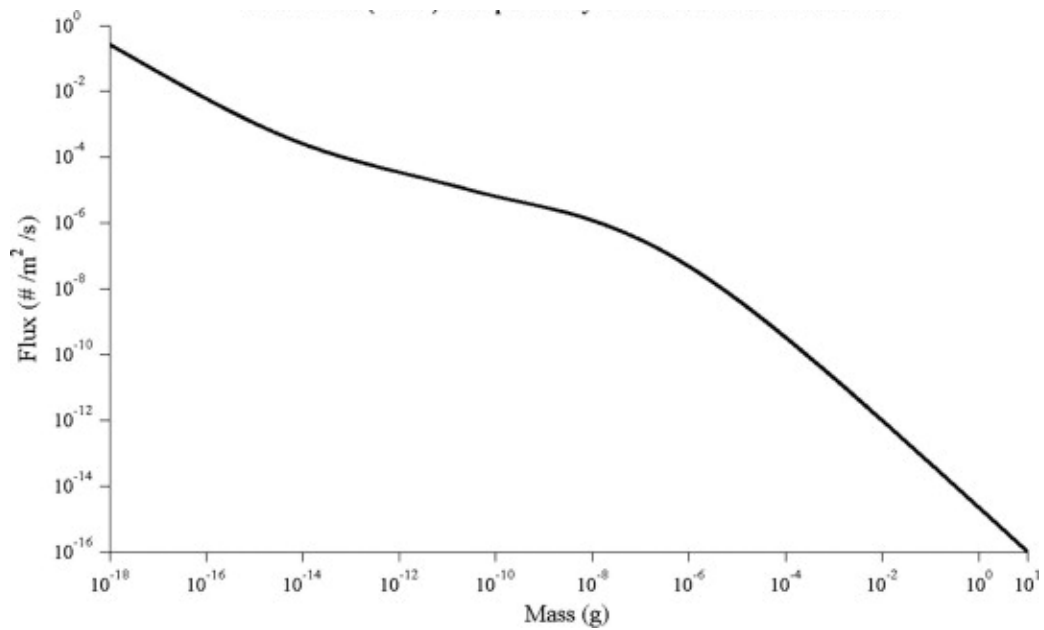


Figure 4.2. Grün interplanetary flux model [62]

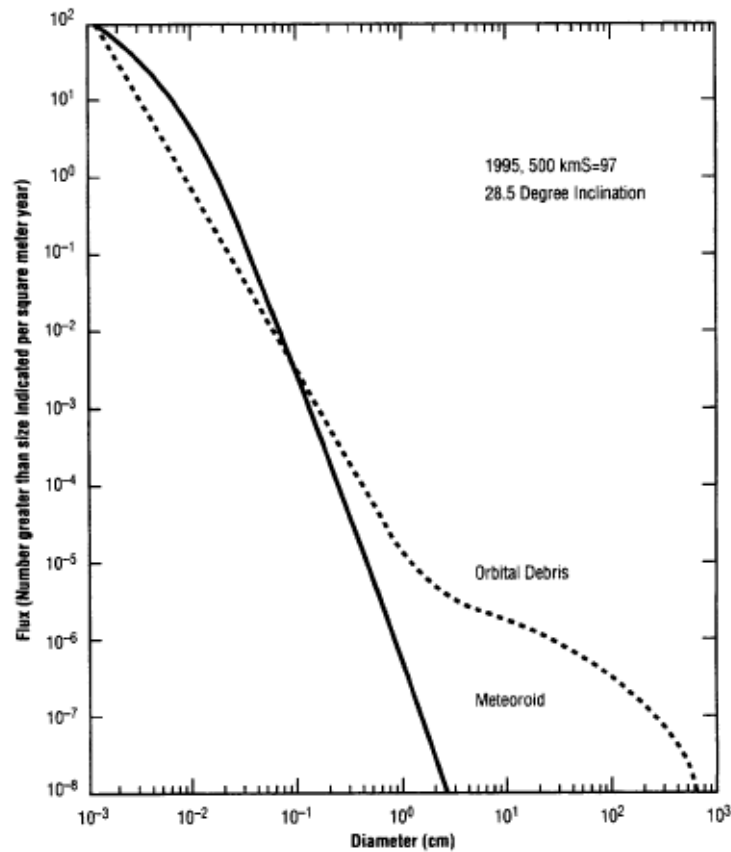


Figure 4.3. Comparison of debris and meteoroid fluxes in an orbit with $h=500$ km, inclination 28.5° [49]

A quick numerical example can be useful to quantify the probability of failure of a tether.

Let's assume a system composed by two modules of equal mass connected by a tether and rotating around the centre of mass. Assuming the length of the tether 400 m (so that the habitat module is rotating 200 m away from the centre of mass) and its width of 10 cm constant through the length. The total surface of the tether is of 40 m^2 . Let's assume for simplicity that an impactor with a diameter of half the width of the tether is sufficient to compromise the system. From the graph the probability of encountering this particle at 400 km height is around $10^{-6}/\text{m}^2/\text{year}$. Multiplying this value for the area of the tether, results that just 4 impacts in 10000 years are fatal. Thus, the probability of failure due to this fact is quite irrelevant.

This section is just a brief overview on the probability of failure of a tethered system hit by debris. For more information, it is suggested to investigate deeper the papers [32] [33] [36] [49] [50].

For what concerns with this thesis, it is important to show that the probability of failure due to impacts with debris is really low and so does not represent a negative and

limiting aspect for the design.

Apart of encounters with particles, other factors can compromise the integrity of a tether used in space. Some of them are: UV radiation, particular contamination, atomic oxygen, extreme thermal conditions. Some of them are more relevant than others. Atomic oxygen for example is present only around Earth, while it is absent in the outer space. For this reason, the tether must be design with a high margin of safety. Including the fact of the human factor, a factor of safety of 5 should be reasonable [5] [49].

4.1.4 Materials of space tethers

To achieve maximum performance, tethers need to be made of materials with a combination of high strength or electrical conductivity and low density. The system taken into consideration is only mechanical, so the electrical properties can be neglected.

Two characteristics are important to define the strength of the tether: characteristic length and characteristic velocity.

The characteristic length is the length at which a cylindrical tether suspended in a constant gravity field breaks under its own weigh.

$$L_c = \sigma / (\rho f) \quad (4.4)$$

with σ the tensile strength, ρ the density and f the factor of safety of the material.

The characteristic velocity is the velocity at which a cylindrical tether breaks in the proximity of the axis of rotation.

$$V_c = \sqrt{2\sigma / (\rho f)} \quad (4.5)$$

with σ the tensile strength, ρ the density and f the factor of safety of the material.

Good materials should present high values for both characteristic length and characteristic velocity. Moreover, a tapered tether is a tether in which the cross section is adjusted along its length in order to keep the mechanical stress constant.

Figure 4.4 shows how a tapered tether offers better performances in comparison to cylindrical tethers with constant diameter in term of characteristic velocity.

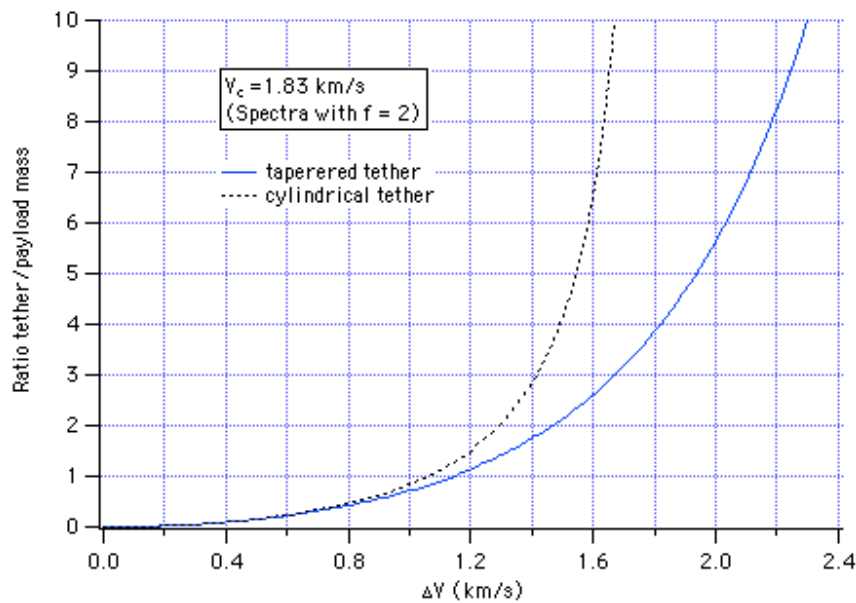


Figure 4.4. Characteristic velocity of tethers, it is showed how tapered tethers have a highest characteristic velocity in comparison to cylindrical tethers [37]

By the way, the choice of a tapered tether is superfluous for an artificial gravity system. In fact, the advantages of a tapered tether with respect to a tether with constant width are visible only for very high tip velocities. For this reason, the advantages do not justify the increased difficulty of the realisation of a tapered tether for human centrifuge.

In conclusion the shape of the tether will be a tape with constant width through the length.

Length and velocity of the tether are chosen to respect the limits imposed by the comfort zone. These values are very low in comparison to the characteristic lengths and velocities that materials used for space applications can provide.

As it is shown in equations 4.4 and 4.5, characteristic length and velocity are connected. For a rotational application like the spinning system the most important factor is the characteristic velocity.

The following table shows some of the materials more used.

Material name	Tensile strength [GPa]	Young's modulus [GPa]	Density [kg/m ³]	Charac. Velocity [m/s]	Charac. Length [km]
Steel	1-5	200	7900	503-1125	13-65
Al alloys	0.1-0.7	72	2700	272-720	4-26
Kevlar 29	3.6	130	1440	2236	255
Spectra 2000	3.4	170	970	2647	358
Carbon fibres	2-5	250-830	1850	1470-2325	110-276
CarbonNanoTubes (theoretical)	150	630	1300	15190	11774

Table 4.1. Characteristics of different materials for space tethers

Composite materials offer better characteristics respects to metallic materials. Their combination of low density and high value of Young's module makes them the perfect candidates for this application.

Dyneema and Spectra are ultra-high-molecular-weight polyethylene [63] with interesting characteristics for tethers applications. They are similar to Kevlar, or even better taking into account the lower density. They both could be good candidates, but their use is not recommended for temperatures below -150 °C because they become brittle or exciding the 80 °C because of the low melting point temperature (around 130 °C). Kevlar on the other hand can better support low and high temperatures [64].

Normally a good thermal control of the tether is sufficient to prevent the temperature to reach critical values. In fact, a white highly reflective dye can maintain the temperature inside the desired limits, allowing the heat in excess provided by the Sun to dissipate. Still, some dirty (maybe caused by the friction of the tether with the unreeling mechanism or by other causes) or the unpredicted increase of temperature in the deployer can be fatal for the mission. Thus, these materials should be avoided, promoting instead the Kevlar that does not presents similar problems.

Carbon fibres have excellent properties, but the material is quite rigid, while it is necessary a high level of flexibility because the tether must be reeled.

Other interesting materials could be carbon nanotubes [46] and graphene [47]. For the moment they are still under developing and the maximum sample's length is of the order of few millimetres, but maybe they can see applications in the future.

4.1.5 Geometry of the tether

The composition of the tether should be chosen in order to maximize the tensile strength and minimize the probability of break.

Thus, a conventional tape is not sufficiently reliable, and an enhanced version is needed. Here are suggested two possible configurations.

The first consists in the creation of a tether with a configuration of a webbing. The shape is a strong woven, similar to the one used for seat belts.

In the second, the tether is composed by long strong fibres, encased by two layers of a protective material.

Both configurations present advantages and disadvantages.

Speaking about the webbing option, the material can be Kevlar, as it is resistant but highly flexible at the same time. This option offers a good distribution of the material, as the different interweaved fibres are closed together and just a small level of volume is unutilised. Thus, it presents a good performance/weight ratio. The disadvantage lays in the fact that all the fibres are bond together. In this case if a fibre breaks (with an impact with a particle), the fracture could also propagate to the close fibres and eventually damaging the entire structure over a sufficiently long time.

In the second option the tension is almost only supported by the fibres. Practically, the two external layers result to be just a support and protection for the fibres. The material of the fibres is never in contact with the external environment so does not need to be resistant against temperatures, corrosion or other factors.

The fibres do not have to be in contact with each other. In this way, if one fibre breaks, the break cannot propagate to the next one. So, even with some broken fibres (if their number does not reach a critic value) the system is still capable of working.

The disadvantage of this option is a low performance/weight ratio, because the separation of the fibres leads consequentially to a sub-optimal utilization of the volume at disposal.

The two ideas presented are just examples due to explain how is possible to design a thin tape tether. The evaluation of a definitive geometry is beyond the goals of this thesis, and practical experiments are necessary for validating a choice.

4.2 Abort scenario

As it was previously introduced, a tethered system can offer the additional advantage of giving the possibility to have a backup plan for returning to Earth in case of mission's failure.

The base idea is that the momentum of the rotating tether system might be used to provide a propellant-free boost for returning the astronauts to home.

Thus, the tether can have a double use: generating artificial gravity and provide the necessary velocity change to return to Earth.

Following concepts are an example for an application during a mission to Mars.

Jokic and Longuski [31] investigated the characteristic of this solution. Basically, the idea is providing the ΔV of a deep space manoeuvre severing the tether connecting the habitat and countermass modules, so that the habitat has the velocity needed to return to Earth.

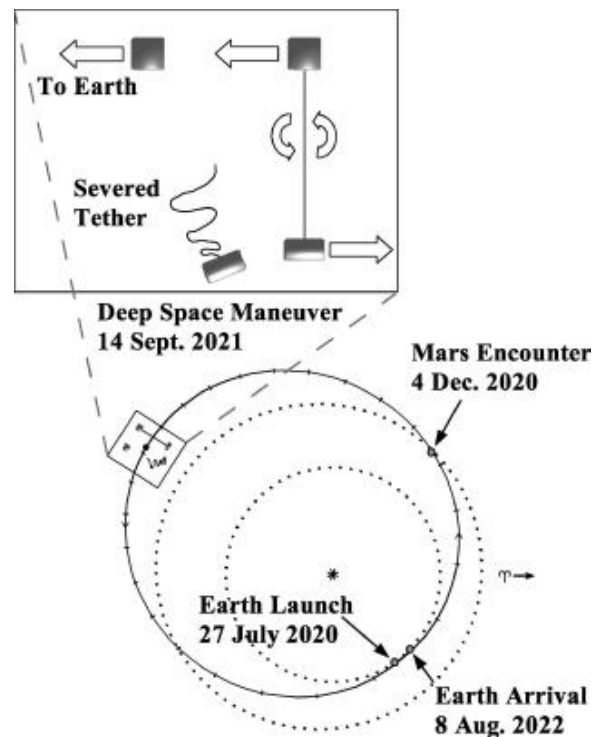


Figure 4.5. Schematic description of an aborted mission to Mars with ΔV achieved by severing the tether (Jokic and Longuski, 2005, [31])

The table 4.2 shows possible dates in which is possible to apply this strategy, with the relative ΔV required (DSM, deep space manoeuvre) and tether-propellant mass ratio. The propellant mass is the theoretical mass required for using a rocket with I_{sp} of 379s instead of cutting the tether.

Launch date, yyyy/mm/dd	Path	Launch V_{∞} , km/s	Mars arrival V_{∞} , km/s	Earth arrival V_{∞} , km/s	DSM, km/s	m_T/m_P	TOF to Mars, days	TOF to Earth, days
2014/01/13 ^a	E-M-V-E	3.60	6.98	4.81	0.00	— ^b	170	800
2015/06/12	E-V-M-E	4.50	5.20	9.30	0.90	2.3	352	588
2016/02/28 ^a	E-M-E	3.59	8.13	4.77	1.12	2.9	140	780
2018/05/10 ^a	E-M-E	3.90	7.09	5.06	0.71	1.9	187	759
2020/07/27 ^a	E-M-E	4.50	5.59	5.01	0.50	1.4	134	742
2021/11/22	E-V-M-E	4.50	5.42	6.48	0.00	— ^b	323	582
2022/09/12 ^a	E-M-E	4.52	4.94	4.90	1.01	2.5	171	753
2024/10/17 ^a	E-M-E	4.56	6.07	4.86	1.12	2.7	180	753
2026/11/21 ^a	E-M-E	4.51	7.83	4.85	0.91	2.3	172	747
2028/12/28 ^a	E-M-E	3.97	8.22	4.69	1.22	2.9	147	765

Table 4.2. List of hypothetical aborted mission to Mars with ΔV achieved by severing the tether (Jokic and Longuski, 2005, [31])

From the table is possible to extrapolate different dates when the abort scenario strategy is applicable. For instance, 2014 and 2021 do not require an input velocity for the deep space manoeuvre. On the other hand, other factors must be taken into account, for example the time for the returning trip, that is too long (800 days) in the 2014 option for instance.

Having a free abort option seems to be an undisputed advantage for using a tether rotating system. On the other hand is important to underline that the required tether's length is in the order of magnitude of hundreds of kilometres, that is three orders of magnitude bigger than the length needed to provide artificial gravity. Still, this represents a smart utilization of a rotating tethered system and it worth to be taken into consideration. Indeed, improvements in tether strength-to-weight ratios may produce more abort options and further investigation of potential transport configurations is needed to determine practical design limits for the tether mass ratios. For example, it can be chosen a system with thrusters in the habitat module that can be activated in case of necessity and would increase the tangential velocity of the module before severing the tether. In this way the length required can be diminished, as would instead be used a certain amount of propellant. It can be found an optimized system capable of providing the possibility of an abort scenario while having the shortest tether and the minimum mass propellant consumption.

Eventually this strategy can be used for sparing propellant in case of landing. Cutting the tether can provide to the landing module the necessary impulse for a land, or at least for a change of orbit.

In conclusion, even if the design necessary for an abort mission scenario in a Mars mission is something behind the design needed for just generating artificial gravity, this idea proves for sure the versatility of a tethered spinning system and could be better evaluated and implemented in future exploration missions.

4.3 Flexible design

A system with tethers has the unquestionable advantage of being flexible. While for a conventional spinning spacecraft the level of artificial gravity is fixed with dependence on the radius of rotation, in a tethered system it can be varied changing the length of the tether. For accomplishing this result is clearly necessary an active deployer, capable of varying the tether length at command. The geometry of the deployer will be better evaluated in chapter 5.

There are mostly two advantages with this configuration. The first is the possibility to create a unique research facility for studying the effect of a microgravity environment on humans. The second is the possibility for the crew for adapting to the specific gravity level of a planet in case of exploration.

With this design, a spacecraft can be used as a base for studying different mission scenarios. For example, it can be used for evaluating long time expositions to both Lunar and Martian gravity level. This can provide important results for understanding the feasibility of establishing a base on Mars or in the Moon in the future. Eventually can be utilised also for studying the response to a hypogravity environment. In fact, a practical space experiment concerning gravity still lacks. A facility of this kind can also cut the costs of the researches, as it can be utilised more and more time with different scenarios. Carrol [4] presented a report proposing a design for this facility.

The second advantage is achievable during an exploration mission to another planet. Taking into account a manned mission to Mars for example, the system can be designed to provide a level of gravity equal to 1 G for the first part of the mission and smoothly decrease it until the 0.38 G level of Mars. The astronauts have time to adapt to the new condition and be operative as soon as they reach the Martian surface. The same procedure can be clearly utilised in the way back to Earth. With this solution the deconditioning of the astronauts after the return from space would not be necessary anymore.

4.4 Habitat design

A spinning tethered spacecraft is likely divided in two parts: the habitat module and a counter-mass. While the counter-mass is not restricted by constraints, the habitat module has to rotate with velocities dependent on the comfort zone. Exceeding values of the velocities provoke an uncomfortable condition for the crew. But even inside the comfort zone, there are the effects of the cross-coupled rotations that have to be minimized.

Thus, the design of the habitat is a critical aspect that needs to be deeply investigated. This aspect was introduced by Hall [2] and later remarked by Carrol [4].

The following is a summary of the principal drivers that lead the design.

Coriolis forces and cross-coupled rotations depend on the direction of rotation. Consequently, the direction of rotation should be clarified at the beginning of the design and the internal of the habitat module should depend on this choice. This can help the crew to adapt to the undesired effects.

The acceleration generated by rotation is manifested in a direction perpendicular to the axis of rotation. For this reason, the astronauts would practically walk in the “wall” of the module. The change of weight due to walking is felt only while walking in the direction of rotation (or against it). So, the ideal orientation for the habitat would be developed in horizontal, with a shape similar to a long aircraft cabin. The following figure represents this idea. The habitat module is the rectangle and the counterweight the circle. The system is rotating about the y axis.

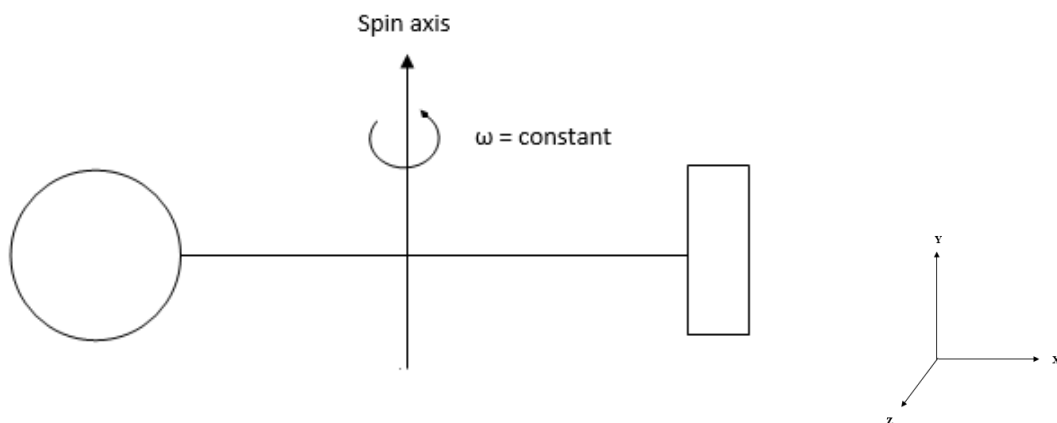


Figure 4.6. Schematic representation of the shape of the habitat module and its orientation. The round object is the counterweight, as its shape is not influenced by any constraints. The rectangular object represents the habitat module. Its shape is optimized in dependence of the direction of rotation.

In addition, it would be a good idea designing just one or at maximum two levels for reducing the use of ladders and exposure to gravity gradients. In fact, the most gravitationally critical element of this habitat is the ladder. It must be designed that the sum of the centripetal and Coriolis accelerations always presses the ladder against the climber, otherwise the resulting force could push the user away from it.

Concerning all these aspects, the advantages of this configuration are the following:

- The crew walks mostly in a direction parallel to the axis of rotation (axis y), limiting the cross-coupled effects

- The habitat module is “thin” (axis x), so every place inside it has more or less the same distance from the centre of rotation of the system. In this way the centripetal acceleration is equal in every point
- The habitat module is “narrow” (axis z), so there is not the possibility to walk in the same direction of the rotation of the module. In this way the level of the change of gravity due to a change of the speed is minimised

The geometry and position of rooms, laboratories and furniture should be chosen in function of their purpose. To better understand this concept, an orientation is provided to help to configure the positions of critical elements.

Figure 4.7 shows cardinal orientations to name the walls of the module. “East” is the direction of the tangential velocity and “West” its opposite. “North” and “South” are chosen with the right-hand rule for rotations.

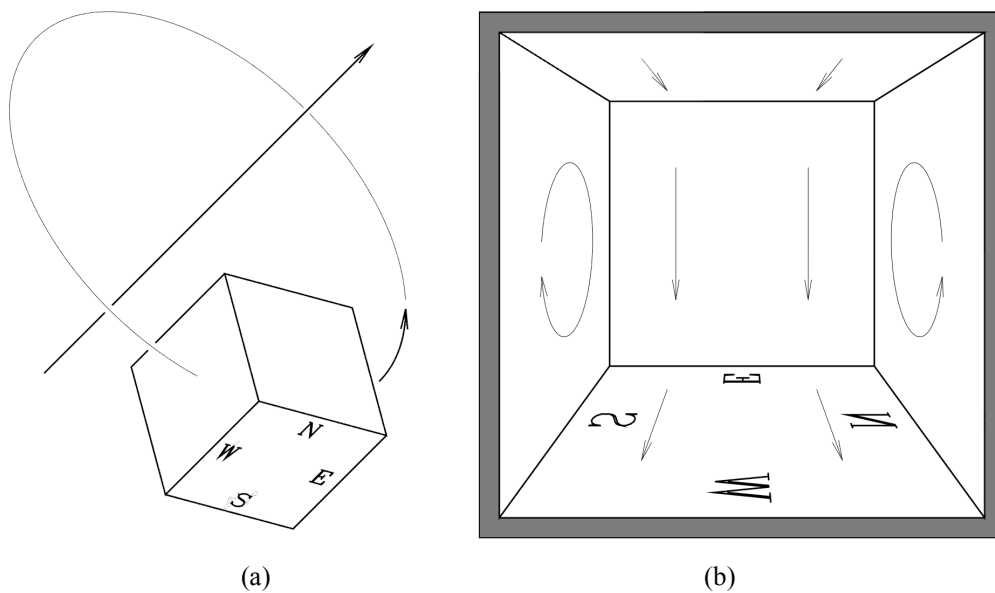


Figure 4.7. The cardinal directions (North, South, East, West) in artificial gravity (a). The arrows in (b) indicate the apparent rotation of the star field from the rotating point of view. Celestial objects set in the east and rise in the west (Hall, 2016 [2])

Choosing this orientation, it results that movements in a direction parallel to the axis of rotation (axis North-South) do not incur cross-coupled rotations. For this reason, tasks that require frequent head pitch (for example viewing a desktop work area and a vertical display) should be arranged so that the worker faces East or West.

Other actions, like sleeping and eating, are less susceptible to cross-coupled effects. The rooms where these actions take place can be set everywhere. Could be a good idea to choose their position at the end to fill any available space left.

As the effects of Coriolis force and cross-coupled rotation depend on the direction of the movements, a clear definition of the cardinal directions could help the crew to anticipate these effects and to adjust their actions for limiting them. This can be easily done colouring the internal walls for example.

The leading idea for designing the habitat module is that if it is possible to reduce these negative effects, the system can be spun with a higher velocity and a consequent shorter radius, with a resulting diminishing of mass.

Chapter 5

Deployment

The deployment is another critical aspect for the tethered system. This manoeuvre can be done inside an Earth orbit or outside it. Both strategies will be presented.

The design of the deployer is critical due to the large tension applied in the system.

The strategies of deployment are different, and their choice depends on the characteristic of the system and orbital parameters.

5.1 Deployment strategies

Basically, two different strategies of deployment exist: librating deployment and spinning deployment [37] [38].

The choice for the deployment strategy is determined by orbital conditions and the state of the tether system at the end of the manoeuvre.

A librating deployment is most suitable for a system that needs to be aligned with the local vertical. It is used for application in the Low Earth Orbit (LEO). It requires a relatively strong gravity gradient to keep the tether straight and bound with the local vertical. As the spacecraft is stationary during the release, the presence of centrifugal forces due to spin is absent so that the tether's tension needs to be increased with thrusters firing along the tether's deploying line.

This strategy has already been tested in several LEO missions.

A spinning deployment is the natural choice for a system that needs to spin after the deployment is complete. This strategy does not require the presence of a gravity gradient for unreeling the tether. Thrusters or the centrifugal force itself caused by the rotation provide the necessary tension to unreel the tether. This strategy is usually faster than a librating deployment because there are no limits imposed on the tether exit velocity by librational stability considerations.

The deployment in this case can be done in two ways.

In the first, the system is put under spinning during the deployment so that provides a centrifugal acceleration to facilitate the extraction of the tether from the deployer.

In the second the system is stationary during the deployment and thrusters provide the tension to the tether to deploy it. Then, when the tether is at the operational length, the system is spun up to the rim speed that is required for the mission.

Spinning deployments have not been tested in space yet but several authors have studied their feasibility [39] [40] [41] [42].

5.2 Deployer

Deployers can be stationary (passive) or reeling (active).

A stationary deployer is lighter and simpler than a reeling deployer but cannot retrieve or short the tether. Consequently, a stationary deployer is appropriate only for deployments in missions where the tether's length is constant. A stationary deployer utilizes a stationary spool with the tether that unreels from it along its axis. The tether can tolerate sudden accelerations without incurring in high tensions because the only moving part of the system is the tether itself.

Stationary deployers were successfully used in the SEDS and PMG missions [38].

Active deployers are necessary for systems that need to be retrieved or shortened, as the one for generating artificial gravity. They utilize a drum and an electric mechanism to reel out the tether. The electric motor can be programmed to deploy the tether with the desired velocity on every instant of time, but it can be subjected to break if the tension is too high. For this reason, strong accelerations must be avoided.

5.3 Choice of the deployment strategy

As the system that provides artificial gravity is spinning, the spinning deployment is the natural strategy to use. As it was explained, there are two different methods to accomplish the result, and they are now explained in detail and compared.

Equations 5.1 and 5.2 describe the phenomenon of deploying a tethered system orbiting around Earth:

$$\ddot{l} - l\dot{\theta}^2 - 3n^2 l \cos^2 \theta - 2nl\dot{\theta} = -\frac{T}{m_r} \quad (5.1)$$

$$\ddot{\theta} + 2\frac{\dot{l}}{l}(n + \dot{\theta}) + 3n^2 \sin \theta \cos \theta = 0 \quad (5.2)$$

with l the total length of the tether, θ the angle between the tether and the local vertical, and n the mean motion around Earth:

$$n = \sqrt{\frac{\mu}{a^3}} \quad (5.3)$$

μ is the standard gravitational parameter of Earth and a the semi major axis of the orbit. The parameter m_r is the reduced mass of the system:

$$m_r = \frac{m_1 m_2}{m_1 + m_2} \quad (5.4)$$

Figure 5.1 is a representation of the system described.

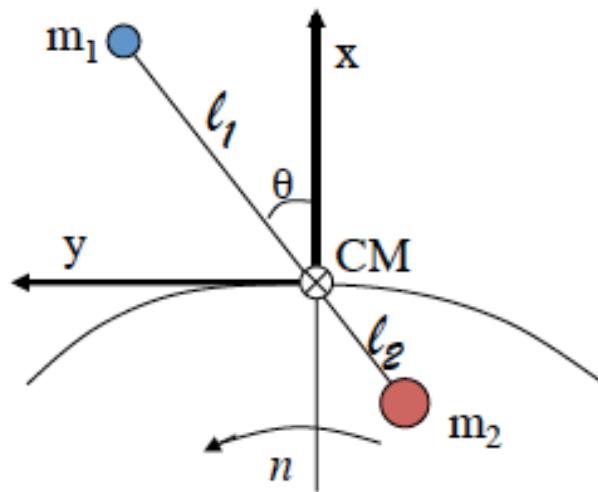


Figure 5.1. Representation of spinning tethered system orbiting around Earth [37].

5.3.1 Deployment of the tether followed by the spinning of the system

The deployer is programmed to deploy the tether following a determinate release profile. The control is made on the velocity of release. The deployment of the tether is divided on two phases. In the first the tether is released with a constant velocity until a predetermined value of time. In the second the velocity follows a sinusoidal law until the end of the procedure [43]. This solution is used for decreasing smoothly the velocity of release until it reaches zero, avoiding an abrupt brake.

The two following graphs (figure 5.2 and 5.3) represent the velocity of deployment in dependence of time. The numerical example has an unreeling constant velocity of 20 cm/s until the time $t_{limit} = 1000$ s, then it follows a sinusoidal law to reach the value $v = 0$ in other 10 seconds.

This can be an example for a system with a tether 200 meters long. Clearly, a different combination of values can be used.

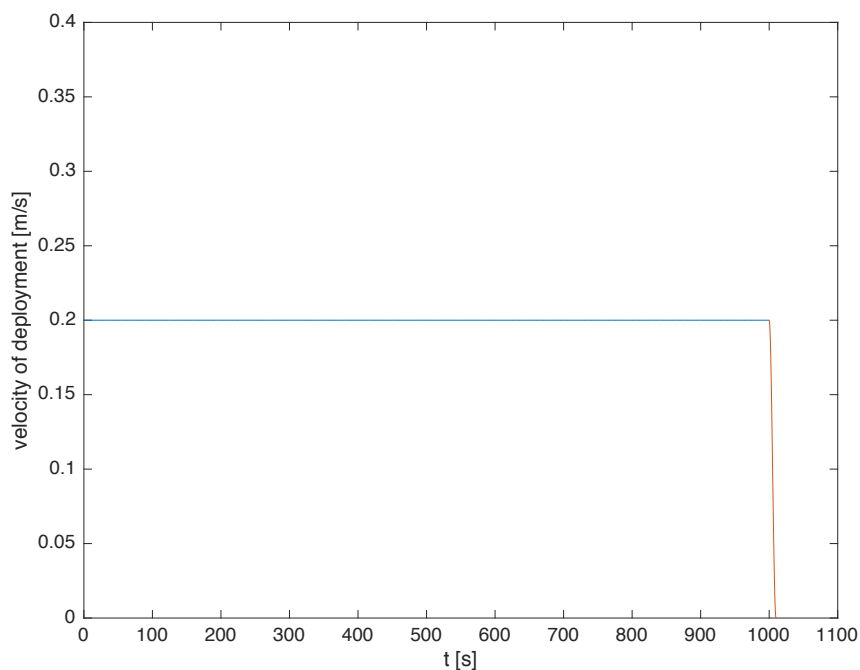


Figure 5.2. Representation of the velocity profile for a deployment of a tether 200 m long in 1000s. The velocity is constant until $t = 1000$ s, then it decreases.

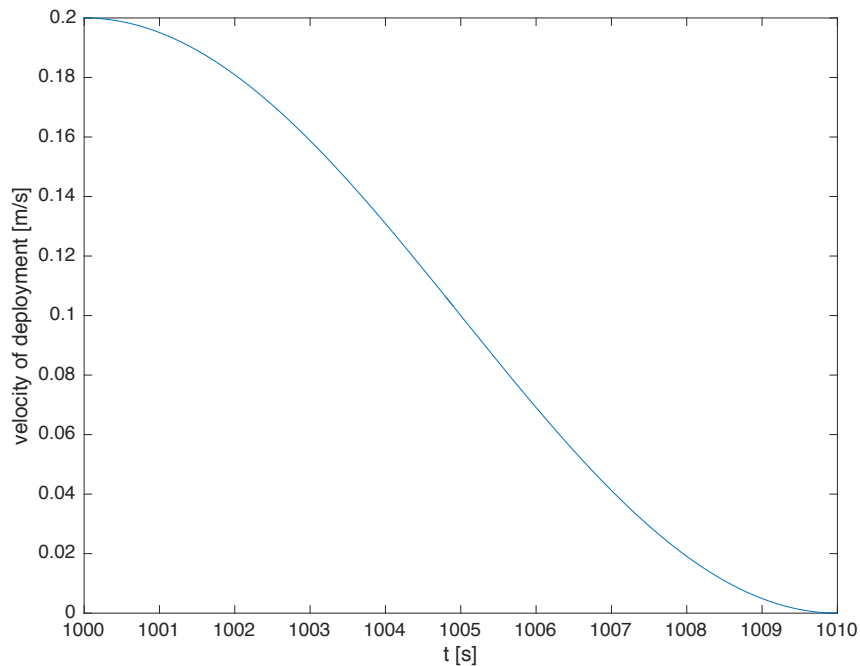


Figure 5.3. Velocity profile of the last part of the deployment, with the velocity that decreases following a sinusoidal law. The curve represents the last part of the curve in figure 5.2.

After the tether is completely unreeled, the system is spun up using thrusters.

During the deployment, a thruster in the habitat module firing in the direction of the deployment is necessary to provide sufficient tension to the cable, otherwise the system would simply not unreele. But, to avoid the creation of just a translational motion, another thruster firing in the opposite direction is needed. In conclusion two couples of thrusters are needed: one couple to separate the two masses and one couple to provide the spin at the end of the unreeling. So in the end the system results to be quite complicated.

There is a variant [5] for this option that consists in deploying the tether to a longer radius than l_1 , namely l_2 . Only then, with the tether deployed to l_2 , the thrusters introduce a slow spinning motion. While rotating, the tether is retracted to reach the desired end state prescribed by the limits of the comfort zone. For the conservation of the angular momentum, the system would spin faster when it reaches the final configuration. The thrust needed is smaller because is provided when the length is higher, and this leads to a save of mass propellant, which is dependent on l_2 . l_2 is longer than l_1 of a factor of k . For values of k higher than 2 (so with the tether with a maximum length of twice the length of the tether at nominal operation) the reduction of the propellant mass consumed by the thrusters is so small that it becomes unattractive to use

longer tethers. To achieve exactly the right end state after retrieval of the tether, the required initial spinning velocity v_{init} must be calculated as a function of the (extra) length of the tether.

If the tether is deployed to the full length l_2 , v_{init} can be calculated using the law for conservation of angular momentum and the following formulas.

$$l = \frac{v_{rim}^2}{g} \quad (5.5)$$

$$l_2 = kl = k \frac{v_{rim}^2}{g} \quad (5.6)$$

Conservation of the angular momentum: $lv_{rim} = l_2v_{init}$

$$v_{init} = \frac{lv_{rim}}{l_2} = \frac{\frac{v_{rim}^2}{g} v_{rim}}{k \frac{v_{rim}^2}{g}} = \frac{g_{min} v_{rim}}{kg} \quad (5.7)$$

Disadvantages of this alternative deployment strategy are:

- Higher tension in the deployer
- Longer tether
- More complex system operation

If the saved propellant mass with this alternative strategy outweighs the additional mass required, this solution can be accepted even with the additional disadvantages.

5.3.2 Deployment of the tether while spinning the system

Also in this case the deployer is designed to deploy the tether with a chosen velocity profile, and so the same considerations just explained for the velocity of deployment must be applied as well. Meanwhile deploying, the system is also put under rotation. The resultant centrifugal acceleration provides to the tether sufficient tension to keep it straight. Thus, it is not needed a thruster to deploy the tether, and consequently some fuel is spread. On the other hand, as the system is rotated before fully deployed, a bigger amount of propellant is needed. Thus, an analysis is necessary for evaluating the strategy with the lesser consumption of propellant.

Only one couple of thrusters (for the spin) is necessary. This reduced considerably the

mass (especially the inert mass of the thrusters) and the complexity of the system. In the end this strategy results to be simpler than the other previously explained, and therefore this solution is advised.

5.4 The manoeuvre of deployment

In this section is evaluated the moment of the mission in which the deployment should be done. The attention is only focused in an exploration mission to another planet, because the space facility is just designed for orbiting around Earth.

Considering an exploration mission, the deployment of the system can be basically done in two moments during the mission: in an orbit around Earth or in the outer space after the interplanetary impulsive manoeuvre. The same procedure can be applied while approaching the planet of destination (possible reel of the tether) and in the way back.

Both configurations present advantages and disadvantages.

The choice of the manoeuvre is always a compromise and it mostly depends on the profile of the mission to accomplish.

5.4.1 Deployment in the Earth orbit

The principal advantage of deploying the system in a stable orbit around Earth is the possibility of aborting the mission in case of failure of the deployment manoeuvre. In fact, as it still has to be applied the impulsive ΔV for the interplanetary transfer, the spacecraft can easily land on Earth. After the interplanetary manoeuvre this is not possible anymore and the spacecraft has to continue the trajectory planned until the end before having the possibility to land on Earth.

Secondly, the presence of the terrestrial gravity field can be exploited to unreel the tether with a librating deployment. But, as this strategy is not used for this system, this advantage is irrelevant.

On the other hand, this solution presents also some disadvantages.

First of all, the interplanetary manoeuvre, that requires an important level of ΔV , can compromise the stability of the overall system. This topic is better explained in the paragraph 5.5. The same problem is later manifested approaching the destination planet when a ΔV is required for breaking. The unreeling after the interplanetary manoeuvre and the reeling of the tether in space before the breaking manoeuvre can avoid the problem.

In addition, the flux of debris orbiting around Earth is higher than the flux of micrometeoroids in the outer space. This can increase the probability of encountering a fatal impact capable of compromising the system. It is important to underline that the time orbiting around Earth would be short anyway, with hours/days of permanence, so the probability of failure would not increase dangerously. Moreover, it was explained in the chapter 4 how the probability of failure of the system due to impacts with debris is quite irrelevant. In conclusion this disadvantage can be practically neglected.

On the other hand, the risk of fatal impacts with debris can become more dangerous in dependence on the profile of the mission. Let's consider for example a mission to Mars with the spacecraft orbiting around it. The orbiting time around the planet is the time necessary for the two planets for achieving a reciprocal favourable position for the return. This wait can be around one year, and for all this time the spacecraft is subjected to the presence of the flux of micrometeoroids orbiting around Mars. Contrarily, a mission designed to land and then returns after one year does not have this problem. The probability of failure due to impacts is different in these two cases.

In conclusion, the geometry of the mission can promote or discourage this strategy of deployment.

5.4.2 Deployment in the outer space

This strategy presents characteristics basically opposite to the deployment while on an Earth orbit.

The flux of debris around Earth or in general any planet is not relevant anymore so that the probability of failure is only linked to the flux in the outer space.

The deployment is done after the impulsive manoeuvre (the reeling before the breaking) so that the configuration is not influenced by abruptly accelerations. In this case the only disturbances are caused by the solar pressure on the spacecraft or by the small trajectory corrections that would be inevitably necessary. Both of them are insignificant enough and can be neglected.

Moreover, supposing to perform the deployment distant from any planet so that any gravitational field can be neglected, the system is not subjected to any external force so the two equations 5.1 and 5.2 can be simplified in the following:

$$\ddot{l} - l\dot{\theta}^2 = -\frac{T}{m_r} \quad (5.8)$$

$$\ddot{\theta} + 2\frac{\dot{l}}{l}\dot{\theta} = 0 \quad (5.9)$$

The principal disadvantage is the impossibility of a return to Earth in case of failure of the deployment.

5.5 Maintain the artificial gravity during manoeuvres

The purpose of this section is to briefly describe the procedure for manoeuvring with a tethered spinning spacecraft.

For the analysis is supposed to use a chemical thrust with a level of technology comparable to the one used in current missions. Hypothetical usage of futuristic electric propulsion with high level of thrust is not considered, and it would require in any case different considerations.

Manoeuvres can be divided in two categories: interplanetary manoeuvres and mid-term correction manoeuvres.

During interplanetary manoeuvres a spacecraft experiences high accelerations and fast decreases and distribution changes of the mass. These effects can extremely vary the orientation of the spacecraft.

Correction manoeuvres are necessary to perform small levels of ΔV to adjust the trajectory of a spacecraft. They can be used both for stabilization/station keeping and for correcting the interplanetary manoeuvres.

Concerning the interplanetary manoeuvres, a deployed tethered system presents difficulties in their realization. First of all, if the system is composed by two masses, two different thrusts must be performed, one for each mass. This doubles the quantity of propellant needed. Secondly, even a small error in the thrust level can compromise the stability of the system.

Let's make an example for clarifying this aspect. A spinning system is composed by two masses, the habitat module and the counterweight, rotating around the centre of mass. The thrust for the manoeuvre needs to be applied to both masses. Therefore, two different thrusters are needed. The system has to perform a manoeuvre with a ΔV of 3 km/s (an indicative level to reach Mars). Both thrusters should provide the exact quantity of thrust in the same amount of time and in the exact same direction, otherwise the system would be unbalanced. Supposing to have an error of 5% (an acceptable level

for a high thrust chemical engine) between the two levels of thrust, the resultant final error in the difference of velocities of the two modules is 150 m/s. This value is definitely too high. The tether would break or in any case the system would spit out of control. Just for comparison, the habitat module is rotating around the centre of mass with a speed rim of about 20-40 m/s.

The procedure just described is totally inapplicable.

Some authors have studied a method to perform manoeuvres in spinning tethered system using a single thrust. The subject overcomes the level of details necessary to this thesis so for more details is necessary to check in particular the works of Landau [30] and [44] [45].

Here are presented the conclusions of these studies.

The configuration of the system is composed by the habitat module and a counterweight mass.

There are three methods for applying the thrust without compromising the stability.

The first method is spinning down and reeling together the entire system. However, with this solution the artificial gravity is turned. In addition, it increases the possibility of mission's failure due to a larger number of deployments so this solution should be avoided.

The second method consists in thrusting through the centre of mass and constantly adjusting the tether to the centre of mass of the system. Its position will change during time because the tanks expend propellant and diminish their weight. Also this solution has to be avoided because of the continuous adjustment of the tether.

The third method consists in applying the thrust in a direction askew to the centre of mass. This creates a torque produced by the thrust offset that cancels the torque produced by the moment of inertia of the system. The consequence is that the orientation of the system remains stable. With this solution the configuration of the system can remain fixed during the manoeuvres.

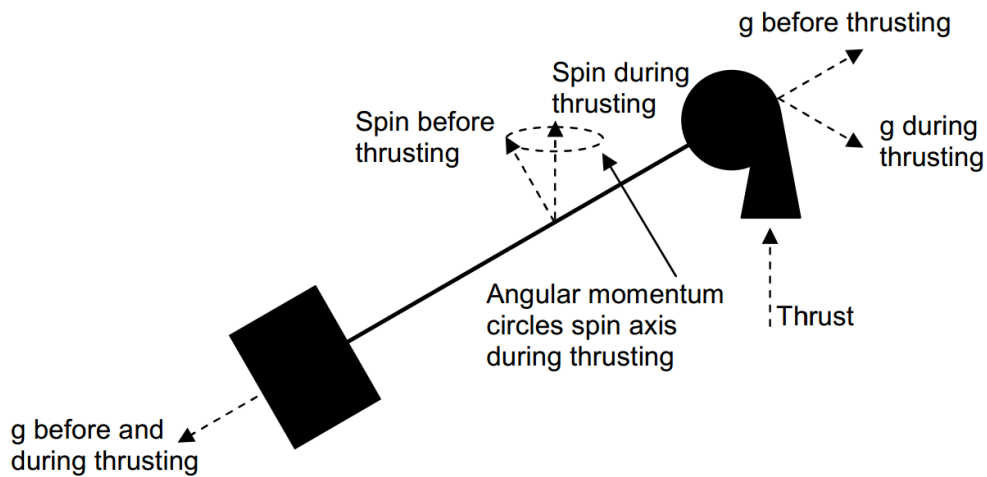


Figure 5.4. Method for thrusting a spinning tethered system without stopping the rotation or reconfigure the system (Landau, 2008)

In conclusion, the important fact is to prove that there is a method for performing manoeuvres and continuing the spinning of the system at the same time.

On the other hand, this procedure seems feasible only for small level of ΔV , while would probably fail for large manoeuvres. For example, in the analysis is not taken into account that the tether is intrinsically elastic, and this fact will have consequences on it if it is stressed by high forces. Thus, it is assumed to be possible to implement this solution only for the corrective manoeuvres, while for interplanetary ones the system must be reeled and treated like a single mass.

This brief analysis suggests that is more convenient to do the deployment in the space, after that the interplanetary manoeuvre has been performed. In this case, for the first part of the mission the system would be totally similar to a conventional spacecraft.

Chapter 6

Implementation of the system

In this chapter are described some practical choices for the design of a spinning tethered system for the generation of artificial gravity.

It is given an example comparing all the different aspects described in the previous chapters, and different choices are evaluated.

Aim of this thesis is not to present the best solution, as it does not exist because it depends on the profile of a hypothetical mission, but to show a list of logical and practical considerations that can help to better understand the overall design of this system.

6.1 Mass and dimension of the system

The spinning tethered system can be utilized in different mission scenarios. Here it can be useful to focus in one of them and study it in detail. The most probable use of this system would be for a manned mission to Mars, therefore this will be taken as an example.

A mission to Mars has still to be designed, so for the moment mass and volume budget is just hypothetical. Moreover, these two values greatly depend on the particular architecture of the mission (time, crew's number, possible landing on the surface...). Consequently, just giving a possible prediction is a hard matter.

Some studies [30] suggest a value of 40 tons for the habitat module. This value includes environmental control and life support system (ECLSS), shielding, thermal protection without including the mass budget of the propellant.

Without entering into details of these calculations, the habitat module is assumed to weigh 50 tons, and the counterweight hosts the propulsion system. The value is conservative and can be a useful starting point for the calculations. The mass of the

counterweight influences the design in term of changing the CM of the system and the tension applied to the tether.

The habitat module must rotate around the CM following the restrictions adduced by the comfort zone, while the counter mass does not have any limitations.

Thus, increasing the mass of the counterweight would move the position of the centre of mass closer to it (decreasing the total length of the tether), but the distance between the habitat module and the centre of mass of the system would remain unchanged.

The following values of angular velocity ω , the radius from the CM tether l and rim speed v_{rim} are chosen for the habitat module for a level of gravity of 1 G (9,81 m/s²):

- $\omega = 2$ rpm
- $v_{\text{rim}} = 46.93$ m/s
- $l = 224$ m

The level of artificial gravity provided is given by the equation 1.2.

The values chosen are quite conservative: the value of angular velocity is small enough to be considered acceptable for the cross-coupled accelerations, the speed rim high enough to avoid high gradient of gravity in dependence on the speed of walking inside the module, and the radius of rotation does not have a prohibitive length. It is important to remember that this is the length of the tether from the habitat module to the centre of mass, at which it must be summed the length of the tether from the centre of mass to the counterweight. Assuming to have a counterweight with a mass equal to the habitat module, the total length of the tether is double the l now chosen.

The following factors are chosen to evaluate the mass and size of the tether.

Supposing to have these characteristics:

- Material: traditional Kevlar (an enhanced version of the tether would increase its strength and consequently diminish the mass)
- Total length of the tether: 600 m (this value is justified in paragraph 6.4)
- Factor of safety of 5
- Two modules of equal mass of 50 tons. Consequently, the maximum tension in the tether is 981000 N

The shape of the tether is a thin parallelogram with a volume of 0.831 m³ and a mass of 1200 kg. Supposing a width of 0.15 m, the thickness results to be around 1 cm.

These values are chosen just to give a practical example of the sizes of the system, and they can be adjusted if it is required by the mission. Moreover, this scenario represents one of the worst situation possible. In fact, the system would likely have the mass of the

countermass higher than the mass of the habitat module. As it is explained in paragraph 6.3, an increase of the mass of the counterweight leads to a decrease of the length of the tether while the tension remains constant. Thus, increasing the mass of the counterweight would decrease the mass and size of the tether.

In conclusion, the dimension of the tether presented in this example is conservative and it will decrease with dependence on the mass ratio value between habitat module and countermass.

6.2 Deployer

The deployer for the mission must be active because the system needs to be reeled and unreeled different times.

The system is composed by two masses spinning around their CM. Consequently, the following design can be proposed.

Two equal deployers are present in the two modules. In this way both masses move from the CM at the same velocity. This solution can add a factor of safety in the system. In fact, the system could still work even if one of the two deployers fails: it is just necessary to have a longer tether than the nominal. The mass increase due to this aspect is still small in comparison to the mass of the total system.

For achieving a total level of safety, the length of the tether must be doubled, and it has to be stored half in every module. In this way, even a complete failure of one of the two deployers can be completely solved by the other. Probably this is not necessary, as the system can work also with a length of the tether shorter than the nominal: in this case the comfort zone could not be completely respected, and the astronauts can suffer of motion sickness. Nevertheless, a level of artificial gravity is provided anyway, and this is still a better situation than the alternative without it.

The shape of the deployer can be similar to what is shown in the following picture.

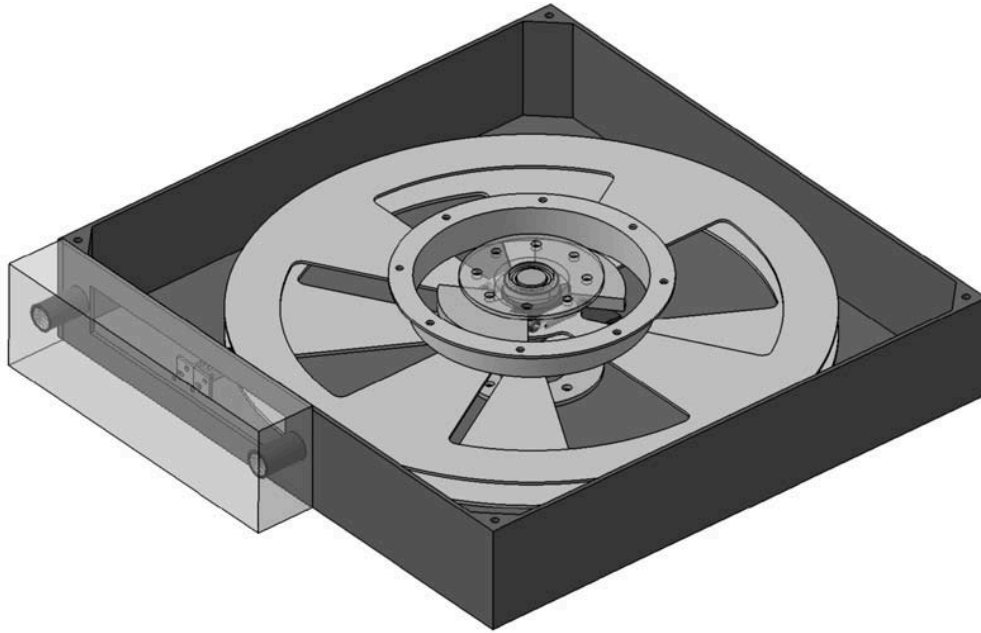


Figure 6.1. Shape of a possible deployer: the tether is stored as a cylinder with the height equal to the tether's width. [36]

Choosing the same values of the tether used in the previous paragraph, the tether has the shape of a cylinder with a radius equal to 1.3 m when stored. If the tether is divided in two deployers, each part is a cylinder with a radius of 1 m. The height is 15 cm.

6.3 Strategy of deployment

The deployment of the system is done in space after the interplanetary manoeuvre. In this way the system is considered as a unique mass during the manoeuvre, and it does not incur in any instability.

The system is put under rotation during the deployment so that the resultant centrifugal force is sufficient for providing sufficient tension to keep the tether straight. The tension of the tether must be sufficient to win the friction inevitably generated inside the deployer. As the modules are heavy (50 tons each), even a small centripetal acceleration is enough to provide sufficient tension.

The tether is considered without mass and inelastic.

Thus, the equations result to be:

$$\ddot{l} - l\dot{\theta}^2 = -\frac{T}{m} \quad (6.1)$$

$$\ddot{\theta} + 2\frac{\dot{l}}{l}\dot{\theta} = \frac{\tau}{J} \quad (6.2)$$

With J the moment of inertia of the system

$$J = l^2 m_r \quad (6.3)$$

and τ the torque moment needed to spin up the system

$$\tau = m \cdot a \cdot l \quad (6.4)$$

For general values of \dot{l} and $\dot{\theta}$ the two equations are not linear. On the other hand, a choice of constant values for \dot{l} and $\dot{\theta}$ makes the equations linear.

$$l\dot{\theta}^2 = \frac{T}{m_r} \quad (6.5)$$

$$2\frac{\dot{l}}{l}\dot{\theta} = \frac{\tau}{J} \quad (6.6)$$

\dot{l} is the velocity of unreeling of the tether and it is regulated by the deployer, so it can be programmed to follow the desired profile.

$\dot{\theta}$ is the velocity of rotation and depends on the τ provided to the system, which in the end depends on the thrust given by the thrusters designed to spin the system.

In conclusion both of the values can be easily controlled and maintained constant if it is necessary.

During the unreeling of the tether the angular momentum is preserved so an increasing of the tether's length leads to a decreasing of the angular velocity. Practically it is like if the system is braked. A tangential acceleration (provided by thrusters) is necessary to maintain constant the angular velocity. As the velocity of unreeling \dot{l} is constant, the tangential acceleration is constant and its value depends on \dot{l} : the slowest the \dot{l} , the smallest the tangential acceleration.

Let's present now the passages for the deployment with constant values of \dot{l} and $\dot{\theta}$:

- 1) Initially the system is fixed and habitat module and counter mass are united. The first step is to divide them with a beam that can be elongated. In this way the system will start to rotate from a position with $l \neq 0$, avoiding undetermined results.

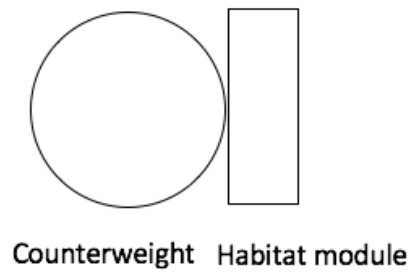


Figure 6.2. Initial configuration of the system, the counterweigh and the habitat module are united.

- 2) The thrusters provide a constant tangential acceleration until the angular velocity reaches a value of 2 rpm. This value will be later maintained during the manoeuvre.

At the end of this step the system reaches the values:

- $\omega = 2 \text{ rpm}$
- $v_{\text{rim}} = 2.09 \text{ m/s}$
- $l = 10 \text{ m}$

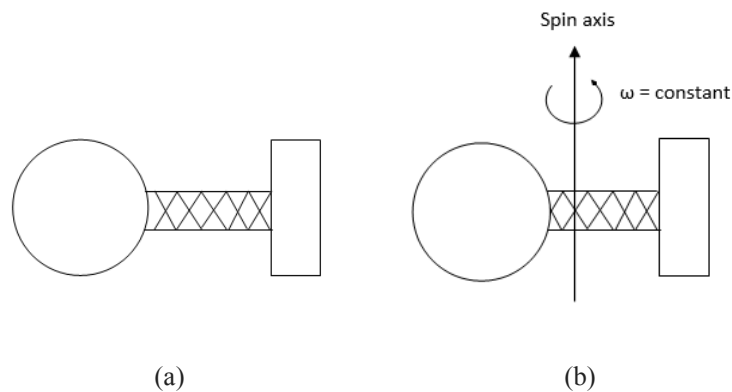


Figure 6.3. The counterweigh and the habitat module are separated by an extensible beam (a), then the system is put under rotation until reaching the desired value of ω (b). ω remains constant during all the manoeuvre.

- 3) Now the tether is unreeled with constant velocity and the constant tangential acceleration maintains constant the angular velocity at the value of 2 rpm. The level of artificial gravity increases linearly with time. The operation is shown in the Figure 6.5 of the comfort zone.

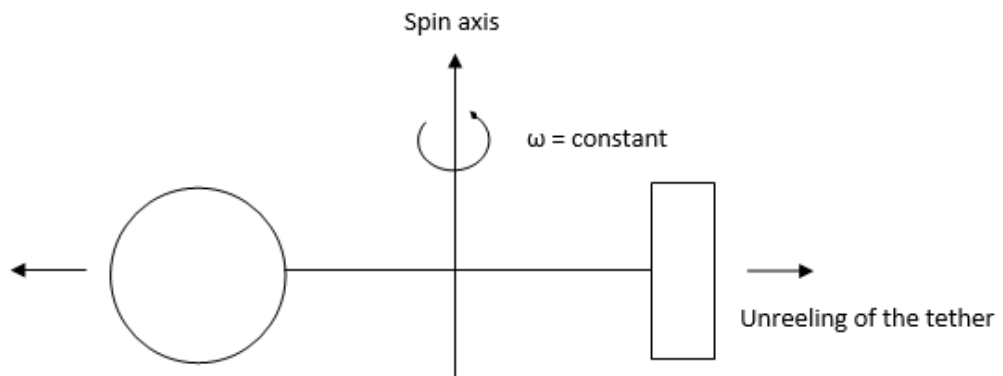


Figure 6.4. The tether is unreeled with constant velocity while the system is rotating.

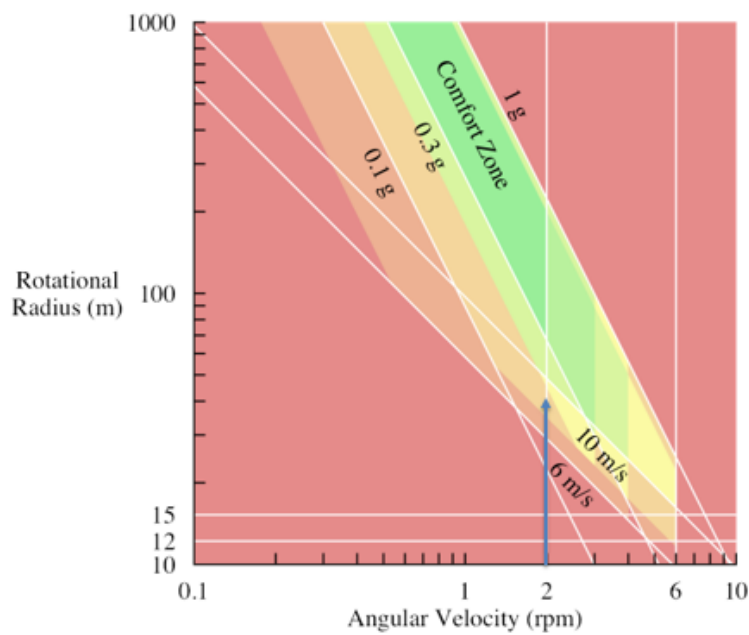


Figure 6.5. The arrow represents the changes in the comfort zone during the deployment manoeuvre. The level of gravity increases constantly during time until reaching the desired level.

- 4) When the tether reaches the maximum length, the unreeling is stopped. In the example the nominal length is 224 m from the centre of mass, or 448 m of total length if the masses of the modules are equal.

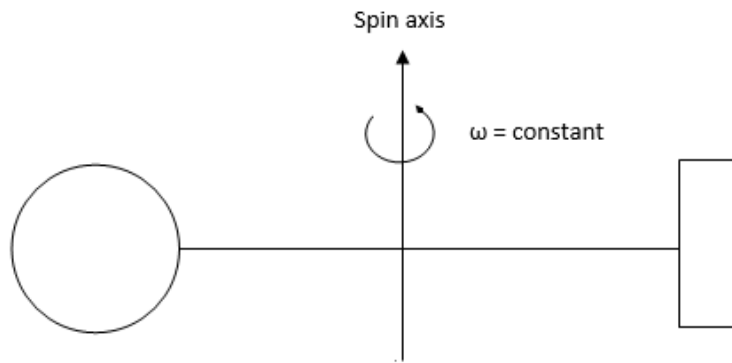


Figure 6.6. The system is in the final configuration.

Now let's analyse the level of tangential acceleration in dependence on the velocity of unreeling. The velocity of the unreeling influences the total time for the deployment.

$$\Delta t = \frac{l}{\dot{l}} \quad (6.7)$$

And the tangential acceleration is derived from:

$$a_t = \frac{v_{rim} - v_{in}}{\Delta t} \quad (6.8)$$

The force provided by the thrusters is:

$$F = ma_t \quad (6.9)$$

The specific fuel consumption of any thruster is given by:

$$\dot{m} = \frac{F}{c} \quad (6.10)$$

c is the characteristic velocity of the propellant. The total fuel consumption is given by:

$$m = \dot{m}\Delta t \quad (6.11)$$

Two thrusters in the two different modules are necessary to spin the system, so in the end the consumption is doubled. It is clear that is possible to choose small level of a_t during a long amount of time or the opposite. The total fuel consumption is unaltered. Adding in the previous formulas a value for \dot{l} permits to calculate the tangential acceleration and the consequent fuel consumption.

Example 1

$$\dot{l} = 10 \text{ cm/s}$$

$$\Delta t = 2140 \text{ s}$$

$$a_t = 0.0209 \text{ m/s}^2$$

$$F = 1050 \text{ N}$$

$$c = 2450 \text{ m/s (hydrazine)}$$

$$m_{\text{fuel}} \approx 900 \text{ kg}$$

Example 2

$$\dot{l} = 1 \text{ cm/s}$$

$$\Delta t = 21400 \text{ s} \approx 6 \text{ h}$$

$$a_t = 0.00209 \text{ m/s}^2$$

$$F = 105 \text{ N}$$

$$c = 2450 \text{ m/s (hydrazine)}$$

$$m_{\text{fuel}} \approx 900 \text{ kg}$$

From a comparison the level fuel consumption is unaltered.

Now let's make again the calculation with a \dot{l} really small, in the order of mm/s.

Example 3

$$\dot{l} = 1 \text{ mm/s}$$

$$\Delta t = 214000 \text{ s} \approx 2.5 \text{ days}$$

$$a_t = 0.000209 \text{ m/s}^2$$

$$F = 10.5 \text{ N}$$

In this case the level of thrust required to spin the system is way smaller. And these low levels of thrust can be provided by electric propulsion. In this way the mass of the fuel and in general of the propulsion system becomes much smaller. On the other hand, the time of deployment increases, but this is not a big concern, as the astronauts can live for some hours in absence of gravity or with a level that is smaller to 1 G.

Indeed, also the really slow unreeling velocity can be a problem because it necessitates an extremely high accurate control mechanism. But this is a compromise that can be accepted as an accurate mechanism is just a matter of cost while the possibility to utilise electric propulsion can revolutionize the system.

In conclusion this is a smart choice that permits to utilise electric propulsion to spin up the system and consequently reduce the overall mass.

6.3.1 Electric propulsion

Electric propulsion consists in electrically expelling propellant to produce thrust. There are many different ways to do that and many different systems exist [48] [51].

Normally electric propulsion is used for producing small levels of thrust, and it is mostly used for station keeping and attitude control of satellites.

Here is presented the possibility to use it for spinning the system, while the interplanetary manoeuvre is performed by conventional chemical thrusters.

It was explained that the level of necessary thrust is around 10 N. Without entering too much into details, it is assumed that this level can be obtained with electrothermal propulsion [48]. One example can be the usage of an arcjet thruster [51] [52]: depending on the size, the input power can reach 100 kW with a I_{sp} of 1000 s (around 4 times higher than the hydrazine). Consequently, the propellant mass required is decreased. The power is provided by solar panels (which would be needed in any case). Just for a comparison, the solar arrays of the ISS are capable of generating 80-120 kW of power [65], so the quantity is perfectly achievable. In addition, this amount of power is only necessary for a short amount of time and then no more. Therefore, during this operation, other subsystems can be turn off to save power and redirect all of it to the electric thrusters.

A limitation of this system can be the utilisation in a position distant from the Sun where the efficiency of the solar arrays is diminished. By the way, even close to Mars where the power generation is decreased of 67% with respect to that near the Earth, the quantity is still achievable without using an enormous surface of solar panels.

Additional considerations are necessary to completely evaluate the details for this strategy. For what concerns this thesis, it is important to remark how this solution is feasible and useful to save propellant mass.

6.4 Mass ratio variation

In the previous section was described a situation with equal masses of the habitat module and the counterweight. That is a simplified condition useful to focus the problem, but in realistic situations is more probable that the two modules have a different mass. In particular, the mass of the counterweight would be higher, as it has to carry the propulsion system and the propellant. In addition, its mass will change during the mission after every utilisation of propellant.

Here it is calculated how the total length and total tension of the tether changes in dependence of a change of the masses of the two modules.

The calculations are parametrical, so the results are consistent with any value of masses and tether's lengths. The only value that matters is the mass ratio between habitat module and counterweight.

The habitat module has to respect the limit derived from the comfort zone while the counterweight has not. In particular, the distance of the habitat module to the centre of mass (that is also the centre of rotation) of the system must remain constant. Thus, when the mass of the counterweight increases, the total length of the tether decreases, and the centre of mass will move closer to the counterweight. The result is shown in figure 6.7.

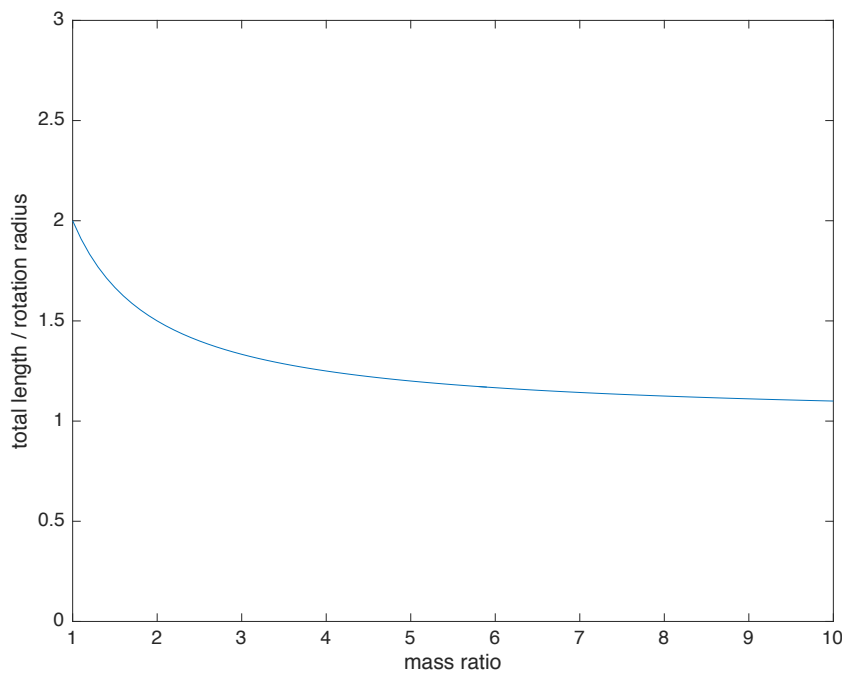


Figure 6.7. Decrease of total tether length in dependence of the mass ratio between counterweight and habitat module.

An increase in the mass ratio between counterweight and habitat module influences positively the length of the tether, possibly reducing its mass.

The change of mass ratio of the system influences also the tether's tension. The increase of the weight of the counterweight decreases the radius of rotation around the centre of mass. Consequently, the counterweight will spin with the same angular velocity of the habitat module but with a smaller speed rim due to the smaller radius of rotation. The consequence is a decrease in the centripetal acceleration created in the counterweight and therefore a decrease in the tension of the tether. On the other hand, the increase of the mass of the counterweight leads to an increase of the tension of the tether. Thus, these two phenomena are antithetic: the tension increases linearly with the increase of the mass of the counterweight, but at the same time decreases linearly with the decrease of the radius of rotation. The result is that the two factors compensate, and the total tension of the system remains unchanged. Figure 6.8 represents this result.

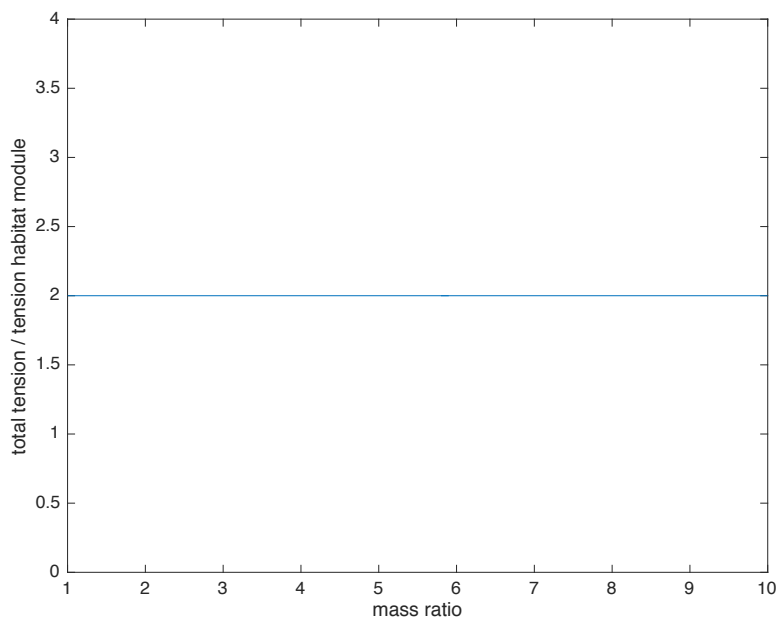


Figure 6.8. The tension of the tether remains unchanged in dependence of the mass ratio of the system

It can be concluded that an increase of the mass of the counterweight leads to positive consequences for the system: the length of the tether decreases while the total tension remains unchanged.

6.5 Obtaining a change of artificial gravity

The possibility to change the level of artificial gravity during the mission is one of the most interesting aspect of the tethered system. This permits to the system to adjust to different requirements. In particular it is possible to change the level of gravity during the flight in order to permit to the crew to adapt.

Taking into account again a mission to Mars, the level of artificial gravity can be changed from 1 G to 0.38 G. This operation can be done slowly, with small decreases in several days. Practical experiments can better evaluate the velocity of changing of the level of gravity that could permit the astronauts to adapt without problems.

The interesting aspect of this operation is that it can be done without any consumption of propellant. In fact, it is just necessary to elongate the tether to a new length that provides the centrifugal acceleration desired. For the conservation of the angular momentum, an increase of l leads to a decrease of v_{rim} and ω . Thus, the only consumption would be the electric power necessary to activate the deployer.

Utilizing again the values previously used ($l = 224$, $v_{rim} = 46.93$ m/s, $\omega = 2$ rpm), the level of 0.38 G is obtained by the combination:

- $l = 310$ m
- $\omega = 1.04$ rpm, 0.109 rad/s
- $v_{rim} = 34$ m/s

The calculations are done utilising the formulas of centripetal acceleration and angular momentum in a system:

$$a_c = \frac{v_{rim}^2}{l} \quad (6.12)$$

$$L = l \times m \cdot v_{rim} \quad (6.13)$$

The new value of centripetal acceleration presents values of l , v_{rim} , ω that still respect the constrains of the comfort zone.

This option is something only achievable with a tethered system, while a fixed system is designed just for one determinate level of artificial gravity.

Conclusions

The thesis has presented the effects of a weightless environment with particular attention to the medical problems on the human body.

Different solutions to counteract the deterioration of the human body have been presented. By a comparison among them, it emerges that a spinning spacecraft can provide a reliable and constant source of artificial gravity while requiring a low mass.

A design for a spinning spacecraft that utilizes a tether to connect two modules has been analysed. The choice of this particular system instead of a traditional spacecraft is justified by a decrease of mass and the possibility to change the configuration of the system with ease.

The principal characteristics of this system have been evaluated to conclude that the system has great potentials to address the issues related to long exposure to weightlessness.

In particular, the following considerations apply:

- Human body suffers various deficits related to weightlessness
- A valid solution to solve the problem is providing continuous “artificial gravity” by the utilisation of a spinning system
- Tethered spinning systems are promising solutions
- The probability of failure of the tether caused by hypervelocity impacts with micrometeoroids is very low if a proper tether design is utilized
- The design of the habitat module and of the tether are critical aspects
- Strong impulsive manoeuvres compromise the stability of the deployed system and consequently the deployment should take effect after the escape ΔV has been applied
- It is preferable from a dynamical point of view to deploy the tethered system while the system is slowly spinning
- The deployment can be done with electric propulsion if a slow deployment is realised

The thesis presented a general overview of the system comparing pros and cons, while a detailed analysis for every subsystem was not carried out.

However, the analysis leads to the conclusion that the advantages associated with this system overcome the disadvantages and consequently a tethered spinning spacecraft can be proposed for the generation of artificial gravity for long exploration missions.

Future work can be focused on studying in more detail the different aspects that are related with this topic.

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