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# Study of artificial gravity systems for long duration space missions

Final Degree Project

**REPORT**

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# Abstract

We are living the dawn of a new era in space exploration. Space agencies and recently created private companies are retaking interest in sending humans to explore the outside of our home planet, beyond low earth orbit. NASA has plans for human exploration in The Moon and Mars, and many other entities are willing to collaborate in this missions. While private companies like SpaceX or Blue Origin are developing plans for Mars colonisation and space habitats for a large number of people.

Taking the current situation into account and analysing the direction of the space industry, it is reasonable to predict that the number of people that will leave earth in the next years is going to increase. Humans have not evolved to endure the roughness of the space environment. One of the most challenging factors that astronauts have to overcome when adapting to space is weightlessness.

If we want to live in space for long periods of time without severe medical intervention, some form of artificial gravity is going to be needed. This study has the aim of analysing the different designs that have been proposed to generate artificial gravity for long duration space missions, and adapt them to the current technologies and plans for the colonisation of space. A design of a structure to generate artificial gravity for SpaceX missions to Mars will be proposed and simulated.

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# 1 Aim

This project focuses on the study of systems and structures that could provide artificial gravity for long duration space missions. These missions can vary from long trips to Mars or the outer Solar System, to permanent space habitats where astronauts could live.

The project will be divided into two main parts. The first part will consist of a bibliographic research, and exposure of the state of art of this kind of technologies. While the second part of the project will consist of a design process of an artificial gravity spacecraft.

In the first part, problems related with weightlessness will be exposed, such as possible solutions that have been proposed (either in academic or fictional context), and possible issues with those solutions. Including a physical explanation of the principles that allow us to generate artificial gravity.

In the second part, after exposing the state of art, an analysis of the current plans for long duration space missions will be carried out. And based on the results of the analysis and the conclusions taken from the previous research for the "State of art" section, a design of space hardware will be done. Said hardware will be a structure that provides artificial gravity for SpaceX's Starship, although it could be adapted for other missions and ships (NASA). The design will undergo structural simulations to verify its viability.

The intention is to provide a design that is economically plausible in the context of the space industry current budgets. Launch costs have been the main issue for artificial gravity hardware in the past, and one of the reasons why we have not seen them in space yet. But there have been some recent changes in the launch market that might be about to change that.

# 2 Scope

The project will accomplish the following parts:

- Understanding the effects of weightlessness on the human body and performance, and thus the necessity of artificial gravity.
- Brief explanation on the history of the concept and terminology.
- Exposing ways to generate artificial gravity in space, understanding the physical principles that allow it.
- Knowing the problems derived from artificial gravity and how to solve this problems effectively.
- Researching and exposing designs of artificial gravity spacecraft.
- Understand SpaceX's plans for Mars missions and colonization and expose how artificial gravity would be beneficial for their mission.
- Select a design that fits the plans of SpaceX and enables to generate artificial gravity with minimum distortion of their current plans.
- Make a Matlab program to carry out the structural analysis, based on a bar element algorithm.
- Performing a structural study for the selected design. Taking into account different maneuvers and possible loads that the spacecraft would have to resist in a mission.

# 3 Introduction

The time has come for artificial gravity to shine and become a reality. For many years there have been a large number of concepts and designs of rotating space stations and spacecraft that generate gravity for astronaut comfort, but those concepts have never left the engineering rooms. The reason why this happened is that those designs were simply not necessary for what space agencies were looking for, and they were far more expensive than the zero gravity solutions. Missions like Apollo wouldn't need the extra complications that artificial gravity structures would require to be build. And for example, the ISS, has been used as a laboratory to test zero gravity.

But the time may have come when artificial gravity is not only helpful for our purposes in space, but critical to achieve them. The global space industry has been predicted to grow significantly in the coming years. Studies like the one conducted by Morgan Stanley in 2018 predict that the industry will rise it's value from 350 billion dollars to 1 trillion dollars by the year 2040 [9]. Said growth will rely on an increased human presence in orbit, or even deep space. Future planned missions include orbital lunar permanent habitats like the *Lunar Gateway*, trips to Mars or space hotels for tourists in low earth orbit. All those missions require astronauts living in space for weeks, months or even years.

Since the first days of human spaceflight it has been known that zero gravity affects our bodies in an unhealthy way. Before the first humans were sent to space, the Soviets and the US tested if living beings could survive zero g environments by sending animals to orbit, being Laika the most famous of them. Today, thanks to the experiments done in the ISS and on ground laboratories, we know that we can survive to zero g environments. But we also know that it has really damaging effects on our physiology. Most of the effects of weightlessness go away in time, after initial adaptation periods for the astronauts. But, for example, in a mission to Mars, the astronauts would be exposed to 6-9 months of zero gravity and then would have to survive the high g-forces of the reentry. And after that they would suddenly be in 0.38g. This would require about two weeks of recovery for the crew before starting the mission, which is clearly unacceptable.

The conclusion is clear, some form of artificial gravity is going to be needed in the future of space travel. Now that we know that, let's figure out how to simulate gravity in space.

## 3.1 How to simulate gravity

There have been many different designs and concepts in academic articles or science fiction. The main idea is to rotate the structure to keep the astronauts attached to the floor of the habitat. This is possible thanks to the centripetal force, and inertia. When you are inside the rotating habitat, your body, because of inertia, wants to keep moving in a straight line. But the walls of the habitat would keep you from doing so. In the same way that you get pushed to the wall of a car that makes a sharp and fast turn (Figure 1). The point is to keep the "turn" constant, so the force pushing you into the wall is constant.

Figure 1: Formula 1 car resisting high g forces from a fast turn. Photograph by Óscar Santín.

If we do this in orbit, where there are no other forces acting on our bodies, this is the perfect way to imitate gravity. But we don't only want it to be constant, we also want it to be equal to the force of gravity on the surface of earth. We can control this by manipulating two variables. The radius of rotation, and it's angular velocity. Here on earth, the acceleration of gravity has a value of g=9.8$m/s^2$, we call this 1g. The equation that gives us the relation between the acceleration of gravity, the radius of the spin, and the angular velocity is the following:

$$g = \omega^2 R \tag{1}$$

But rotating gravity is not the holy solution to all of our problems with gravity and comfort. It has some side effects that we must take into account in order to make the best design possible for our spaceship or space station. As the equation (1) shows, for a fixed value of g, we can increase radius and reduce the spin rate, or increase the angular velocity while reducing the radius.

A low value for the radius would keep the construction cost low, and therefore a more realistic and viable design. But a low radius means a high angular velocity, and this comes associated with some problems of comfort that will be exposed later. An excessively high spin rate would make the habitat impossible to adapt. For ideal comfort but, less ideal construction cost, we need a very large radius with a low spin rate. Theory says that with a radius big enough, the force that the inhabitants would feel inside the habitat would be indistinguishable from real gravity. Knowing this, we must find some middle values that keep the construction costs achievable while not making the habitat too uncomfortable or difficult to adapt.

Spacecraft design is a very complicated topic itself, and it gets worse when you have to add artificial gravity. Engineers have looked for ways to incorporate rotation to spacecraft for many years and have come up with different solutions. There are two main ways to design the structure of a spacecraft with artificial gravity:

- **Partial rotation of the spacecraft**: There is a section of the vehicle that rotates to produce gravity, while the rest remains in zero-g. The pros of this design are that it reduces the mass of the spacecraft, it keeps a zero-g environment to do experiments and the vehicle is less complex to steer and control. The cons are that it has complex rotating joints that make the construction more complicated and the crew has less space to enjoy gravity.

- **Full rotation of the spacecraft**: The entire vehicle spins and creates gravity. The only volume in zero-g is the center of rotation. This design is less complex to build because it doesn't have rotating joints and offers a better experience for the astronauts. It usually allows for larger radii than partial rotation. The main difficulty in this designs is that the spacecraft is harder to maneuver, and it is more difficult to dock with them when they are in rotation.

  This type of design can be done in two ways. The first one is building a structure that rotates completely, and the other is to build two separate modules connected by a tether or a series of tethers and make them rotate around each other.

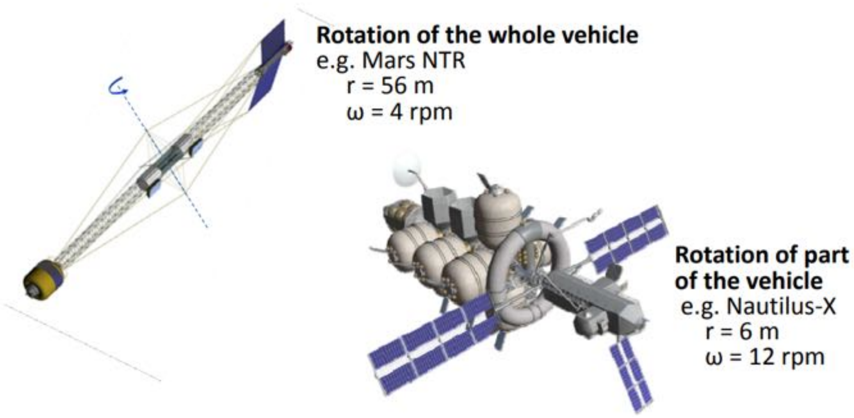



Figure 2: Different ways to generate artificial gravity in a spacecraft. [1]

There have been numerous proposals of spacecraft and space stations with artificial gravity since the early days of space travel, some of them are just eccentric and too imaginative but others are very realistic designs. In the next chapter we will go through an historical review of the concept and we will see the most influential designs along different periods of the last century. Starting with Tsiolkovsky in the 1900's and finishing with contemporary technology from our decade.

# 4 History of the concept

Since the late 1800's there have been different proposals for space habitats that feature artificial gravity. In this section, some of the most relevant designs will be exposed and briefly explained. There are thousands of very complex proposals and a vast bibliography on the topic, but only the most important ones will be discussed, since the intention of this section is to give the reader notions about the evolution of science and technology in this field.

## 4.1 Tsiolkovsky

Konstantin Eduardovich Tsiolkovsky is best known for developing the Rocket Equation, which is still used nowadays in rocketry and launch system engineering. But the Russian physicist was one of the first, if not the first, to describe the concept of artificial gravity. Between the years 1903 and 1920 he published articles and books where he developed the basis of modern spacecraft engineering [10]. These documents had illustrations of large rotating structures to generate the force needed to keep the astronauts from floating. He also predicted some of the problems associated with the lack of forces acting on our body, such as muscle and bone damage.

## 4.2 von Braun

Wernher von Braun was the chief designer of the V-2 German rocket and one of the key parts of the Nazi missile program. When World War II ended, he was brought to the United States to participate in their missile program, which later became the space program. Von Braun was one of the chief designer of the Saturn V Moon rocket, but he also worked on plans about trips to Mars. He thought that one of the most important requirements for a trip to Mars, would be to have a space station in Earth orbit. He envisioned a rotating torus of 76 meters in diameter and 9 meters wide. It would be made of flexible nylon-plastic fabric and it would be launched in separate sections in a collapsed state and then inflated in orbit. Von Braun believed that it was not necessary to produce 1g of gravity, because it would require rotation rates too high. He proposed a 1/3g gravity that would require a reasonable 3 revolutions per minute.

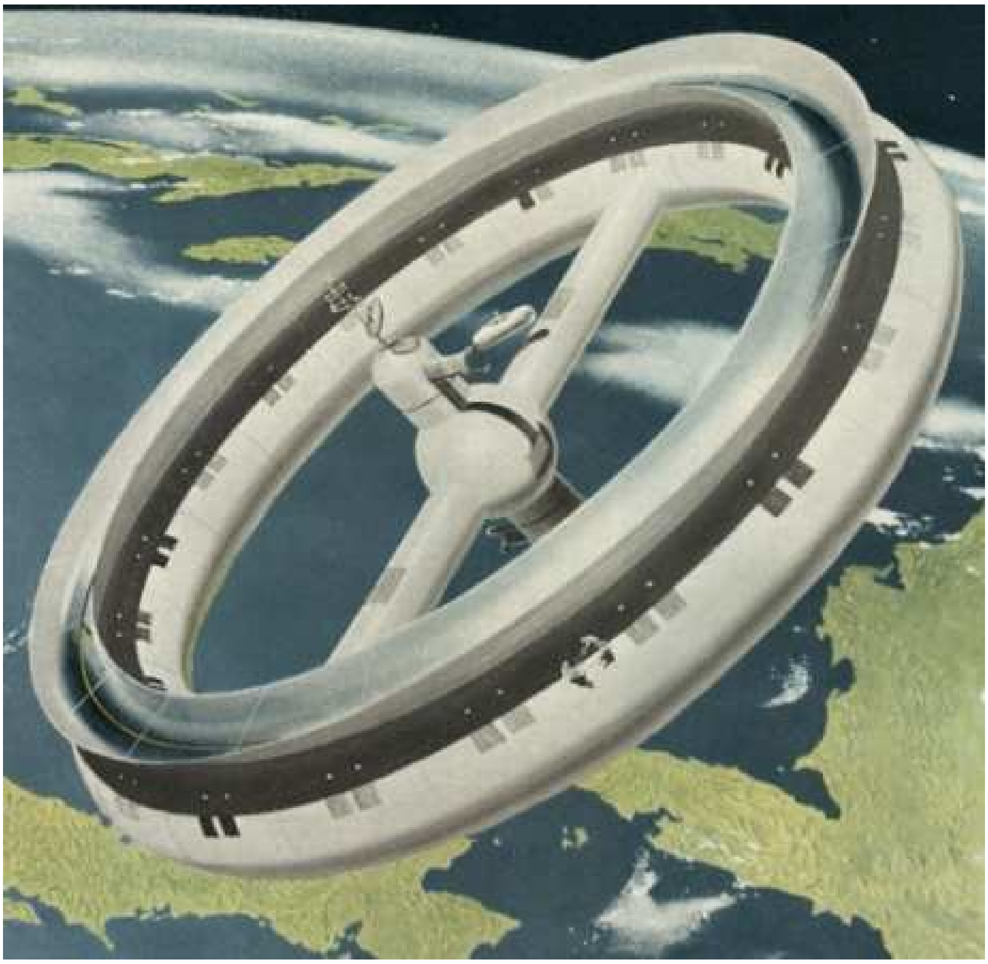


Figure 3: Space station design by von Braun

### 4.3 Lockheed Aircraft Corporation

Saunders A. Kramer and Richard B. Byers, of the Lockheed Aircraft Corporation, published in 1960 *A Modular Concept for a Multi-Manned Space Station*, in which they proposed and described with detail a design of a rotating space station. The station was had 10 cylindrical modules which were 9 meter long and 3 meters in diameter, and 6 spherical modules which were 5,5 meters in diameter. It would feature an artificial gravity part, which would be the outside cylinders, and a zero-g part which would be in the center axis of the station, as shown in the figure 4. It would provide the artificial gravity rotating the external modules, and the radius of rotation would be approximately of 15 meters.

The authors believed that high rotation rates were good to deal with coriolis effects, since it decreases the ratio of coriolis-to-gravity. This is because coriolis increases with rotation speed and gravity increases with the square of rotation speed.

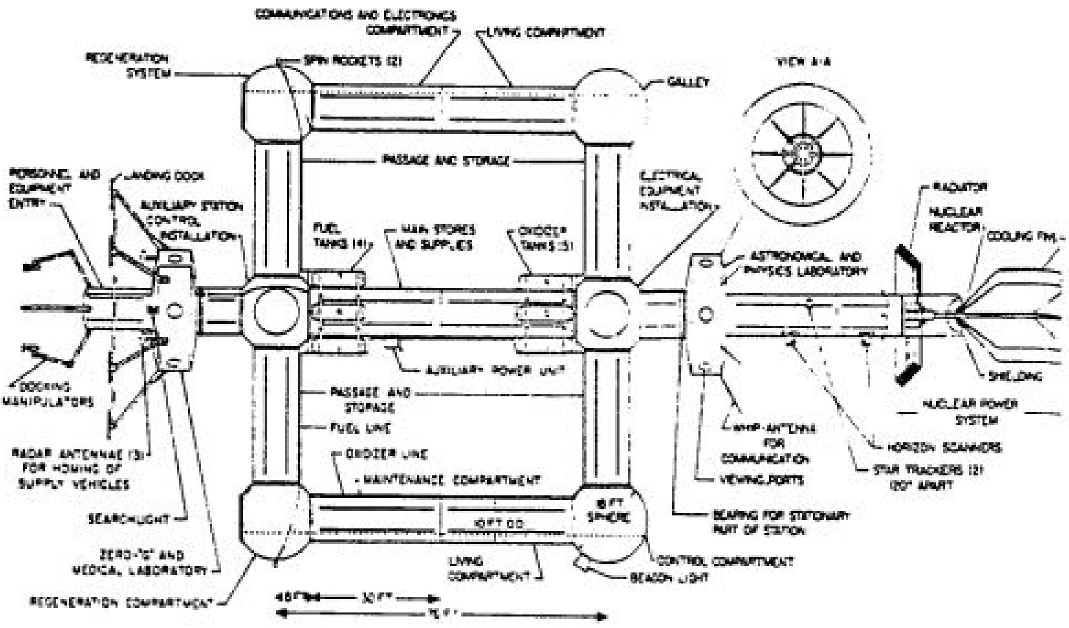



Figure 4: Space station design by Kramer and Byers (Schematic), 1960. Taken from [2]

## 4.4 NASA Langley Research Center

Scientist of NASA Langley Research Center, with North American Aviation, conducted studies that lead to the description of an *automatically erectable modular torus* (AEMT). The results were published in a series of different papers from numerous scientists, each paper describing one part of the design of the station.

The final design was an hexagonal torus formed from 6 rigid cylinders with mechanical joints. The station could be folded and launched to space, and then erected in orbit. This would reduce launch costs since it would require only one launch to put the entire habitat in orbit. The selected radius was 23 meters (75 feet), which was considered to be the lower limit at the time. A rotation speed of 4 rpm was selected to give 0.4g of gravity. The cylinders were 27 meters long (90 feet), and 3 meters in diameter (10 feet). The floor of the cylinders had to be curved for the gravity to be pointing always downwards form an astronaut's perspective, but the cylinder was too long. So the floor had to be divided into steps of concentric arcs, as shown in the figure 6. The station was designed for a crew of 21, for missions up to 6 weeks.

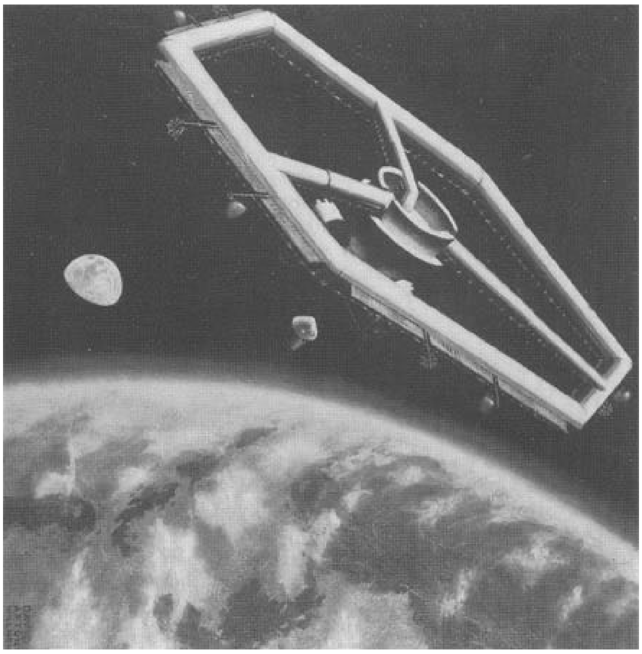


Figure 5: Space station design by scientists of the NASA Langley Research Center. Image from NASA History Division

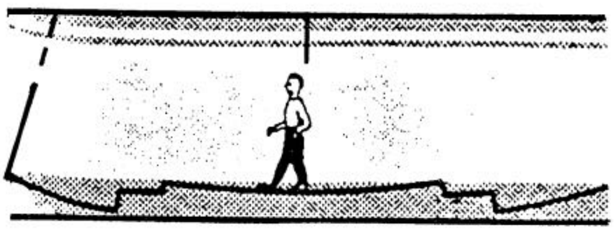


Figure 6: Representation of the divided curved floor. Taken from [2]

## 4.5 2001: A Space Odyssey

Although this is not an academic proposal, it's important to analyze it because common knowledge of artificial gravity has been strongly influenced by this work. Science fiction has always been influential to actual science, being like a "test bench" where authors can imagine freely, without the restrictions of the real world.

Stanley Kubrick and Arthur C. Clarke created in 1968 the movie *2001: A Space Odyssey*. This movie features a lot of space technology that seamed feasible at the time, since the movie was released in the golden era of space travel, a year before the first Moon landing. The *Space Station V* is a huge rotating space station with 300 meters in diameter, it rotates at 2.5 rpm to provide an Earth-like gravity for the passengers. The station is used as an hotel or transfer point form Earth to the Moon and other planets. It has restaurants, bars and lounge areas for the passengers to enjoy their time in orbit, before they head to their destination.

This design is probably feasible from an technical point of view, but the launch costs of sending all the mass of the station to Earth orbit look rather impossible nowadays.

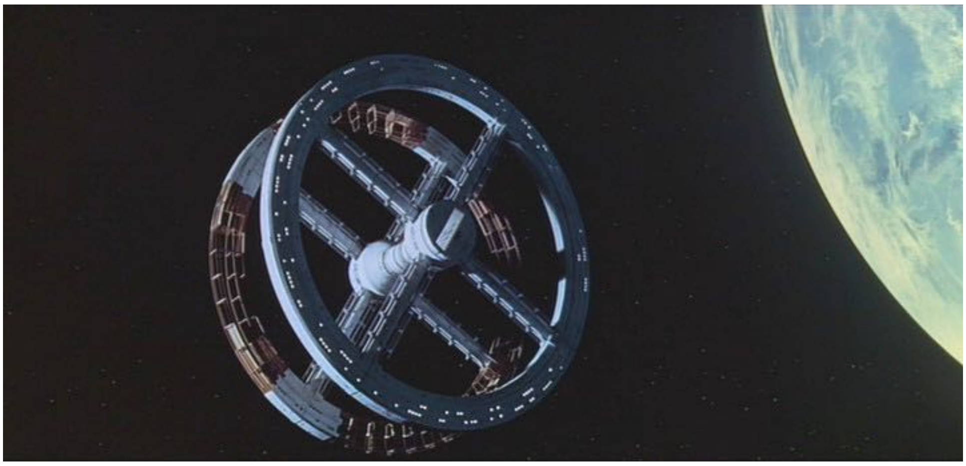


Figure 7: Space Station V from the movie 2001: A Space Odyssey. [3]

## 4.6 O'Neil Cylinder

Moving on to the 70s, Gerard O'Neil published in 1977 a book titled *The high frontier: Human colonies in space*, [11] where he developed the famous *O'Neil Cylinder* concept. It was a 5 mile diameter spinning space habitat, with a length of 20 miles, the inner wall of the cylinder would serve as the floor where people could live and work and experience gravity in a very similar way that they do on earth. The habitat is so big that requires lunar and asteroid mining to be constructed, since the launch costs to bring all that mass to space would be, quite literally, astronomical.

Figure 8: O'Neil cylinder space station in the movie *Interstellar* [2014]

## 4.7 The Stanford Torus

Another concept from the 70s is the *Stanford Torus*, which was the product of a NASA sponsored workshop at Stanford University in 1975. Gerard O'Neil, the creator of the O'Neil cylinder, was the technical director for this study. It envisions a rotating torus where people would live in a similar way to the cylinder. Both concepts have the same aim and both have pros and cons that will be mentioned later in the project.

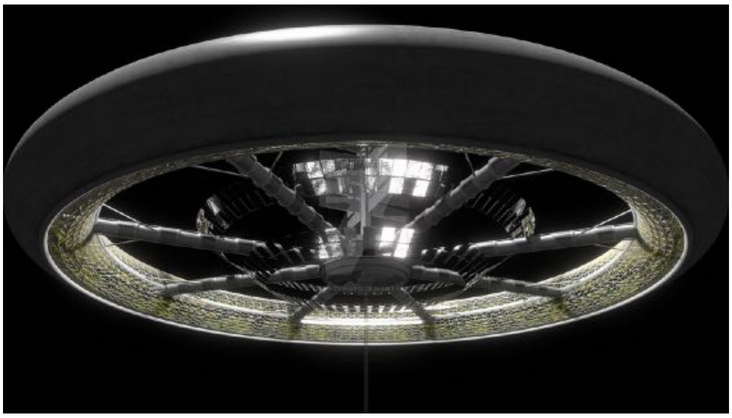


Figure 9: Illustration of the Stanford Torus

## 4.8 Nautilus-X

The *Nautilus-X* is a concept spacecraft designed by NASA engineers Mark Holderman and Edward Henderson. It was first proposed in 2011 for long duration space missions such as trips to the Moon or Mars. The spacecraft has a modular design for a crew of 6 astronauts, with a centrifuge to mitigate the effects of weightlessness. But the majority of the volume is in zero-g. It was designed to be build with a relatively low budget compared to other crewed vehicles (3.7 billion US dollars) and in a short time (64 months). The program did not advance form the initial drawings and proposal.

Figure 10: Representation of the Nautilus-X spacecraft.

It is quite strange that given the plans from NASA to go to Mars and the Moon in the coming years, there is not an actual design of a spacecraft that features artificial gravity for the crew. There are thousands of papers and reports from NASA that confirm the importance of artificial gravity for long duration space missions, and the adverse effects of weightlessness, but a solid proposal of hardware is still a long term goal that no one seems to be willing to make a reality.

## 4.9 Contemporary Science Fiction: The Martian and Interstellar

Things have changed in the Sci-Fi world since *2001: A Space Odyssey* was released. To finish this historical review of artificial gravity we'll go through two of the most scientifically accurate space-movies ever created. Both show spacecraft that feature artificial gravity for their crews.

The Martian's *Hermes* is a spacecraft designed to take a crew of 6 from Earth orbit to Mars' orbit. It has a rotating gravity segment where astronauts can exercise and live, but the other parts of the spacecraft are in zero-g. The spacecraft was constructed in a collaboration between NASA, ESA, Roscosmos, JAXA and ISRO. It took a decade to construct, with the help of SpaceX launch systems.

The movie shows a realistic picture of what the future could be, with collaborations between the most important space agencies and the world's most advanced launch systems (SpaceX's). Building a modular spacecraft like this with today's technology is not only technically possible, but also economically viable.

Figure 11: Representation of the Hermes spacecraft from the movie "The Martian". [4]

The movie *Interstellar* pictures a very different situation. It shows a future where Earth is in a climatic crisis, and space programs have nearly disappeared. The spacecraft "Endurance" was build for interplanetary travel, with the aim to look for new worlds where humanity could live. The entire spacecraft rotates to produce gravity, and it's constructed from different modules launched separately and assembled in orbit. At the center of the spacecraft there are two smaller ships docked, these are used to descend to planets, since the Endurance only moves between orbits.

Although the situation that Interstellar shows is less realistic than the one shown in The Martian, the design of the spacecraft is really interesting and could offer possible solutions or paths to follow for engineers to think about the future of space exploration.


Figure 12: Representation of the Endurance spacecraft from the movie "Interstellar". [5]

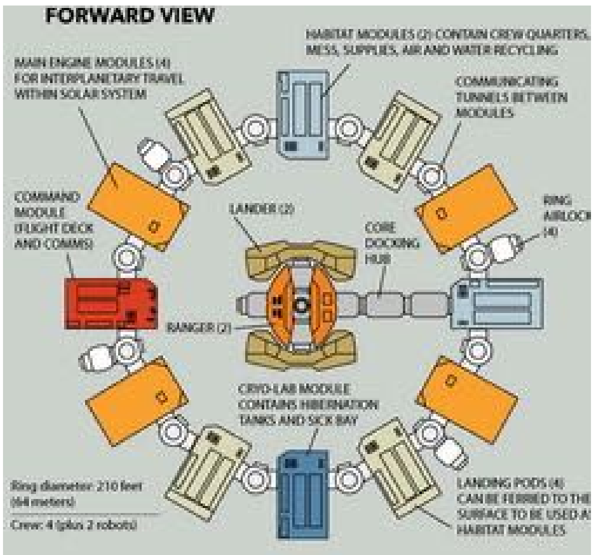



Figure 13: Schematic view of the Endurance spacecraft. [5]

## 4 HISTORY OF THE CONCEPT

# 5 Effects of weightlessness on human physiology

The only purpose of artificial gravity on a spacecraft or space station design is to maintain the crew healthy and ready to handle the physical and mental challenges typical of space missions.

As has been mentioned in chapter 4, since the start of spaceflight, there has been concern about how weightlessness affects human physiology. Research on the topic has focused mainly on two types of studies: Micro-gravity research and artificial gravity research.

Micro-gravity research studies are conducted on micro-gravity environments. Those environments can be simulated on earth through "Vomit Comets", airplanes that make parabolic flights and provide brief situations of weightlessness (around 30 seconds in each parabola). Another place where micro-gravity research takes place is the International Space Station (ISS). Astronauts like Scott Kelly, who has spent 520 days in space, have helped to improve our understanding of the human body.

Artificial gravity research takes place mainly on earth, through rotating structures that try to simulate the forces of gravity. The problem with this kind of studies is that on Earth's surface, there is real gravity acting on the bodies and the results are always less accurate than it would be if we conducted these studies in space. Some experiments of artificial gravity for the ISS have been proposed by teams of scientists, but none of them have make it to space.

## 5.1 Micro-gravity research

In this section I will expose the effects that have been found to appear on human physiology after long exposure to zero gravity environments. These results have been obtained through experiments in orbit and on earth. Experiments in orbit consist basically of long periods of stay in space stations such as ISS, Skylab or MIR. Astronauts stay in orbit for long periods of time and then go through medical tests to observe the changes on their bodies. Experiments conducted on earth consist of long periods of bed rest, water immersion or head-down tilt. These experiments help us understand factors like body fluid redistribution or muscle and bone loss.

One of the most important studies on this topic has been published recently.[12] The study conducted by NASA involves two astronaut twins. Astronaut Scott Kelly spent one year in space, while his brother Mark Kelly stayed on earth. Over the 25 months of the study, which includes time before, after and during Scott's spaceflight, NASA obtained physiological, telomeric, transcriptomic, epigenetic, proteomic, metabolomic, immune, microbiomic, cardiovascular, vision-related, and cognitive data.

Figure 14: Scott Kelly stands in an Extravehicular Mobility Unit, or EMU, during Earth-bound training in 2010. Photograph by Mark Sowa, NASA.

The results of the study show that many of the measures of Scott's body were altered during spaceflight. Principal alterations were found in telomere length, general DNA damage, gut microbiome composition or carotid artery dimensions. Some other alterations, like less cognitive performance, were found. But they were a product of the stress of the reentry to earth's atmosphere.

Even though many of the alterations disappeared after returning to earth, some of the measures show that some changes persisted after 6 months from the return. Especially DNA damage.

After many years of studies and results, there is a long list of harmful effects of extended weightlessness. In the following pages this list will be shown and supported with a brief explanation or studies related with the topic. The list has been taken mainly from [2], where Doctor Theodore W. Hall makes a deep bibliographic revision on the topic. After every title there will be a letter. (C) after the title means that the problem exposed can be mitigated completely with diet and exercise. (P) means that the problem can be partially mitigated by diet and exercise. (N) means that there is no possible mitigation for that problem.

- **Fluid redistribution (N):** Our body fluid systems have evolved to live in earth's gravity. They have to pump the fluid to the upper parts of the body to compensate the gravity pulling it down. When there is no gravity there is no force to compensate and the fluid starts shifting towards the head. This is the origin to many of the other problems described below. There have been experiments with pressure suites, like the ones used by fighter pilots, to force body fluids into the lower parts of the body.

- **Fluid loss (N):** Our brain interprets the increase of fluid in the head as an increase in the total volume of fluid. This activates the excretory system producing an unnecessary fluid loss. This causes bone demineralization and calcium loss, as well as a decrease in blood pressure. The crew must stay very hydrated to compensate all this effects.
- **Electrolyte imbalances (C):** The fluid loss leads to imbalances in the levels of potassium and sodium. One of the solutions adopted has been to swallow 3 grams of sodium chloride in 400 milliliters of water three times on the last day in orbit before reentry.
- **Cardiovascular changes (P):** As fluid increases in the thoracic area due to the lack of gravity, the size of the left ventricular volume increases initially. But as the body loses fluid it leads to a decrease in blood pressure, cardiac output, and left ventricular volume. Cardiac volume and blood pressure return to normal values once back on earth, but the process can take some weeks.
- **Red blood cell loss (P):** In space, the volume of hemoglobine increases due to the increase in fluid volume and plasma volume. Some studies are looking into the possibility that weightlessness produces changes in splenic function which may cause red blood cell destruction. It has also been found that microhemorrages in muscle tissue can occur, leading also to a decrease in red blood cells. Scientists think that this is an adaptation to the environment of space and it is not a threat to human health.
- **Muscle damage (P):** This is one of the worst issues for long duration space missions like missions to Mars. Muscles atrophy from lack of use. Researchers have found that in weightlessness, our muscle tissue reduces the number of red fibers and increases the number of white fibers, which are bulkier and weaker. It has also been found that muscles present damage in nerve endings. Damaged blood supplies can also affect adversely to muscle composition, as less oxygen arrives to the tissue.

  There are other factors that cause muscle damage a part from weightlessness; stress, bad nutrition and poor circulation are also responsible for this issues, but they are not the main ones.

  After long duration stays in space (around 200 days), astronauts that return to earth are barely able to walk for a week, and need weeks of recovery to be able to walk normally. Even if they exercised daily during the mission.

  In low-earth-orbit missions, intense daily exercise and steroids are used as a countermeasure for this, but in future missions to Mars this is not a plausible solution. If a crew of astronauts spends 6 to 8 months traveling to Mars, in absolute weightlessness, their muscles and bones would be very fragile and weak. If they were lucky to support the high forces of reentry (which is a challenge itself), they wouldn't be able to start a the mission on the surface of Mars without some weeks of recovery. This is very problematic for a lot of reasons. But the main one is that you would have a crew on a distant planet which is barely able to perform any kind of physical task for weeks. The best solution for this issue is artificial gravity, and this is one of the strongest points when discussing if artificial gravity is necessary or not for Mars missions.

- **Bone damage (P/N):** Our body deposits bone tissue where it is most needed while it absorbs bone tissue where is not needed. In micro-gravity our bones are not under stress and are not required to support our weight, so they basically dissolve. The symptoms of bone damage are calcium loss, nitrogen loss, phosphorus loss, decreased size and volume and urinary stones. Research in Skylab and Mir have found the following data: after 3 months in space, astronauts lost around 8 percent of bone tissue, and after 6 months, they lost 14 percent. Non-weight-bearing bones like skull and fingers are less affected by this issues. It has also been found that diet and exercise are not an effective form of mitigation of the symptoms, so the best way to deal with the problem would be through artificial gravity.

- **Hypercalcemia (P):** Fluid loss and bone demineralization increase the calcium levels in the blood, increasing the risk of developing urinary stones.

- **Immune system changes (P):** Researchers have found that micro-gravity leads to changes in the immune system, it is still not known if this changes can be hazardous for the human body. Some astronauts appear to be more susceptible to infection after returning to Earth. There is a concern that an infection could spread quickly in the closed environment of a spacecraft.

- **Interference with standard medical procedures (P):** Fluid loss affects the way the body processes drugs. This would affect space pharmacology. Space surgery would also be a huge challenge, without gravity holding the organs in their place and blood spreading in the operational field.

- **Vertigo and spatial disorientation (N):** Without a stable gravitational reference, astronauts experiment changes in their sense of verticality. Our brain starts to rely more on visual references instead of gravitational references. This is no problem if the astronaut stays in orbit, but once it returns to a gravity environment it will cause problems in equilibrium. This would be a problem in a mission to Mars where there would be a sudden increase from 0 g to 0.38 g. As an example, a Skylab astronaut that had returned from space, fell in his house when lights went out unexpectedly.

- **Space adaptation syndrome (P):** Usually called motion sickness. It is caused by sensory conflicts between vestibular and visual systems. Half of the astronauts suffer it and the symptoms include nausea, vomiting, anorexia, hedache, lethargy and sweating. It lasts from one to three days and can be mitigated with drugs, head movement schedules or head restraints.

- **Loss of exercise capacity (N):** This is basically due to the complications of exercise in space and lack of motivation. Exercising in space is clumsy and difficult. Sweat does not drip off creating unpleasant pools on the skin. Clothes become saturated and several towels are needed.

- **Degraded sense of smell and taste (P):** The increase of fluid in the head causes effects similar to a head cold. The food becomes less tasty and therefore less pleasant, which could lead to psychological problems for the crew.
- **Weight loss (P):** Due to fluid loss, bone and damage loss, lack of exercise and less appetite.
- **Flatulence (P):** Digestive changes lead to an excessive volume and frequency of flatulence. In space there is not convection so the digestive gas remains suspended in the air for more time.
- **Facial distortion (N):** The face becomes puffy and there are changes in the voice tone. It may cause miscommunications between the crew or with ground controllers.
- **Changes in posture (P):** In space, the neutral position of the body approaches to fetal position. Spine straightens and lengthens. Astronauts gain more than an inch during spaceflight.
- **Changes in coordination (N):** Without gravity, there is no force to beat and astronauts tend to reach too high to grab tools.
- **Visual changes (N):** Recent studies conducted aboard the ISS have found that headward fluid shift produces an increase in eye pressure. This can lead to vision problems. There is concern that this vision problems might be permanent even after returning back to Earth.

A part from the physiological problems that micro-gravity causes, there are other problems that are less concerning but still quite uncomfortable. Space toilets are difficult to use and sometimes tend to malfunction. Showering in space is also a problem, with extra equipment needed to swallow all the extra water. For example, in the Space Shuttle missions there were no showers, and astronauts used wet wipes. Workplaces are usually quite uncomfortable also, with paper and pens floating around. Cooking in space is another issue. Since there is no convection due to the lack of gravity, conventional ovens do not function well in space. There are some ovens designed specifically for space use, but they are complex and still have not been tested in space.

## 5.2 Back to gravity

Most of the physiological problems exposed above go away in time as the crew adapts to the weightlessness environment. But in an interplanetary mission, this would cause massive problems when arriving to a gravity environment. The crew of astronauts would need some time to adapt to the new gravity and they would have very limited capabilities. Most of the planned missions to Mars schedule a period of one to three months on the surface of the planet, so long adaptation periods would make it very problematic to conduct the mission normally.

Several long duration spaceflights have been done, and we can use them to estimate how our bodies adapt to gravity after long periods of weightlessness. In 1984, a crew of soviet cosmonauts returned to Earth after a 237-day mission. They reported that they felt that if they have stayed in space for much longer, they would have not survived reentry.

In 1987, soviet cosmonaut Yuri Romanenko spent 326 days in space. At the final periods of his mission Romanenko was highly fatigued and his work hours had to be reduced and his sleep hours extended to 9 hours per day. At the end of the mission, the soviets sent a "safety pilot" to escort Romanenko back to Earth during the process of reentry. NASA reported about Romanenko that he had lost about 15 percent of muscle volume of his legs.

In 1988, Vladimir Titov and Moussa Manarov stayed in space for 366 days. When they returned to Earth they looked pale and weak. But their adaptation was quite good. After 3 hours they could walk with assistance. Within 48 hours they could walk freely. After 2 months on Earth they had adapted perfectly to normal gravity with no apparent aftereffects from spaceflight.

Adaptation to gravity after weightlessness is one the main problems in interplanetary missions, and 2 months of convalescence looks very bad in terms of mission efficiency. Drugs, diet and exercise seem not enough to mitigate the negative effects and the difficulty of adaptation, so the best way (or maybe the only way) to deal with this problem seems to be artificial gravity. Although no artificial gravity for humans has been tested in space, some research on Earth laboratories has been done. In the next chapter we will look at these studies that will help us understand the principles of artificial gravity and how it would affect to human physiology.

## 5.3 Artificial Gravity research

Gravity can only be replaced by some sort of acceleration. The only way to generate that acceleration without a constant energy input is through rotation. Artificial gravity research has been conducted mainly on Earth, with centrifuges that simulate rotating spacecraft or space stations. Although the concept first appeared in Tsiolkovsi's works in 1890, the first real research on the topic began in the 1950's.

The main goal of these studies is to know precisely how rotation and rotational parameters affect human physiology and performance. It is important to establish thresholds of human endurance in order to make better designs for the future. In the following paragraphs, the most relevant studies on the topic and the results of these studies will be exposed. This will be helpful in the next parts of the project, specially in the design part, where those results will be needed to establish design parameters.

In 1977, the soviets conducted an experiment with rats. The rats were put in a centrifuge with 1g of gravity in a satellite. A space centrifuge large enough to support research on humans has never been tested to date, and it should be one of the next steps if we want to make artificial gravity a reality. Said that, most of the research takes place on Earth.

Initial assumptions on the topic were made by different researchers and scientists. Tsiolkovski predicted in 1916 that small rotation radius with large angular velocity would produce non desirable effects on the crew. Von Braun was very focused on reducing structural mass of the habitat. He stated that reproducing 1g would not be strictly necessary. He suggested a 1/3g with a radius of 38 meters, that would require a rotation rate of less than 3 rpm. In 1960, Kramer and Byers of the Lockheed Aircraft Corporation, proposed a full 1g of gravity with a radius of 15 meters and a rotation rate of 7.5 rpm. They were very focused on reducing the mass of the station, but 7.5 rpm would be very difficult to adapt for the crew, as found in later studies.

In 1960, Carl C. Clark and James D. Hardy of the Navy's Aviation Medical Acceleration Laboratory published *Gravity problems in Manned Space Stations* [13]. They were concerned about the coriolis effect that appears in head movements, which can produce sickness and disorientation. Clark subjected himself to a 24 hour rotation in a centrifuge supporting 2-g acceleration at 1 rad/s. What produces sickness is the vector product between the rotation vector of the centrifuge and the rotation vector of the head. Typical head movements are done at 5 rad/s. They established that the threshold for sickness is 0.06 $rad^2/s^2$. And the threshold for nausea is 0.6 $rad^2/s^2$. Clark and Hardy's results proposed a maximum rotation rate for a space station of 0.01 rad/s (0.6/5), or about 0.1 rotations per minute. This would require a radius larger than 97 km, which seems pretty unlikely to achieve. The study was later considered to be incomplete, because it was only tested in one individual and without varying rotation speeds. Future studies concluded that humans can be comfortable with higher rotation rates, which allow for smaller radius and therefore easier to achieve.

### 5.3.1 Artificial Gravity design chart

To design a functional rotating space habitat one must get the rotational and construction parameters right. These parameters are usually represented in a chart that shows the rotation rate of the habitat on the X-axis, and the radius of the habitat on the Y-axis. This chart is very useful to represent the limits of what is possible and what is not. We can set limits for gravity levels, radius, rotation rate, tangential velocity, etc. The studies performed throughout history have helped to calibrate and adjust this chart to get as close as possible to reality.

The first lines of the chart are constructed from the equation (1), which tells us that the force an astronaut would feel is proportional to the radius and to the square of the rotation rate. If we want that force to be the same as gravity on earth we need to set g=9.81$m/s^2$. This gives us a line of possible design points:

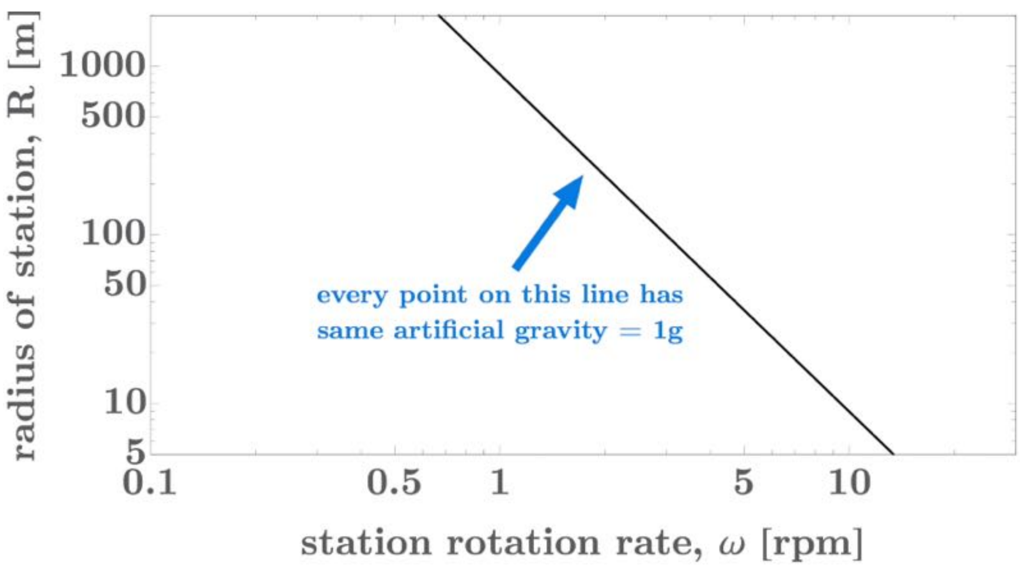



Figure 15: Artificial gravity chart with line of 1g. Taken form the video essay: *Artificial Gravity*, of the Youtube channel: *Cool Worlds*.

#### Gravity levels

As the chart explains, every point on the line has 1g of gravity, so we can see which rotation rate we need for a given radius, or vice versa. But rotating space habitats give us the possibility to simulate different levels of gravity, perhaps the gravity of Mars (0.38g) or The Moon (0.17g). This is useful since a lower gravity can reduce construction costs drastically and reduce negative effects of high spin rates while still providing the necessary force to keep the astronauts healthy. This could also be useful for space travel to Mars, for example, where the spin rate could be adjusted to martian gravity while traveling to Mars, and then augmented gradually to Earth's gravity for the return trip. This would help astronauts to adapt to the destination's gravity.

Some studies have tried to establish how much gravity force is needed for humans to have a sense of up and down. To know the lower limit for artificial gravity. The study by Laurence R. Harris et al, called *How Much Gravity Is Needed to Establish the Perceptual Upright?* [14], concluded that less than 1/6g make it difficult for humans to have a sense of up and down and maintain balance. On the higher limit, forces stronger than 1g are generally uncomfortable for humans. Habitual tasks require a great amount of energy and could potentially cause injuries due to high stress on the muscular and skeletal systems. With this values we can draw another line on the chart, that will give us the lower limit of gravity. Now we have a region between 1g and 1/6g where the design of an artificial gravity habitat is possible.

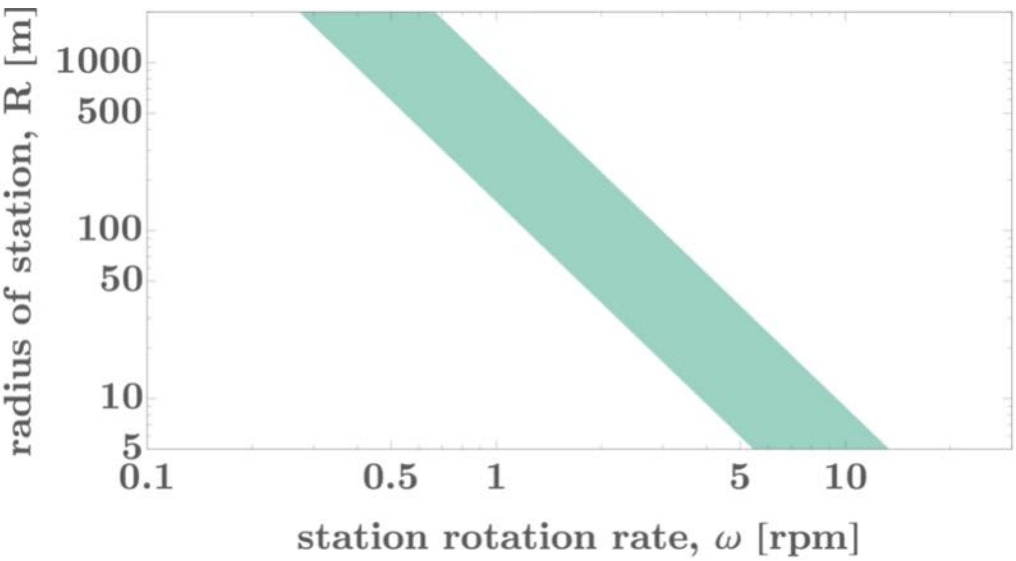



Figure 16: Artificial gravity chart with "comfort zone" between 1g and 1/6g. Taken form the video essay: *Artificial Gravity*, of the Youtube channel: *Cool Worlds*.

**Gravity gradient**

Although smaller radii reduce construction costs and make the designs more feasible, a radius two small can lead to some problems. The first one is that with a small radius, livable space and head space for the crew is reduced. This can cause problems of comfort, or even psychological problems. Living 8 months in a very small place without enough personal space is a very hard experience even for trained astronauts.

The other major problem with small radii is that an astronaut would feel a difference in the force of gravity between their head and their feet. Since the simulated gravity increases with the radius, the head of the astronaut would be significantly closer to the center of rotation, where there is no gravity, and his feet would be further. This is called gravity gradient. A high gravity gradient can cause problems on human physiology, like changes in hydrostatic pressure. Those changes affect the circulation of blood from the head to the lower extremities and can affect negatively to the cardiovascular system.

Radii close to typical human height would clearly be a bad choice. The head of the astronaut would be feeling no acceleration at all, while his feet would be feeling a full 1g. So the astronaut would be feeling a tidal force of 1g. There is not much research on how much gravity gradient is good for humans. But general assumptions from different authors set the limit for gravity gradient in 10 percent. So if an astronaut felt 1g of gravity at their feet they would be feeling 0.9g at their heads. With this limit we can draw another restriction line on the artificial gravity chart. The lower limit for radii that will cause a gravity gradient lower than 10 percent in a human of average height, is 17 meters. This is an assumption that requires further research and studies to confirm, and it is a high limit.

If we were to build a rotating space habitat today, it would probably be wise to chose a radius higher than 17 meters to leave a decent security margin and stay clear of the limit. Having said that, the revised chart with the lower limit for the radius is shown in the figure 17:

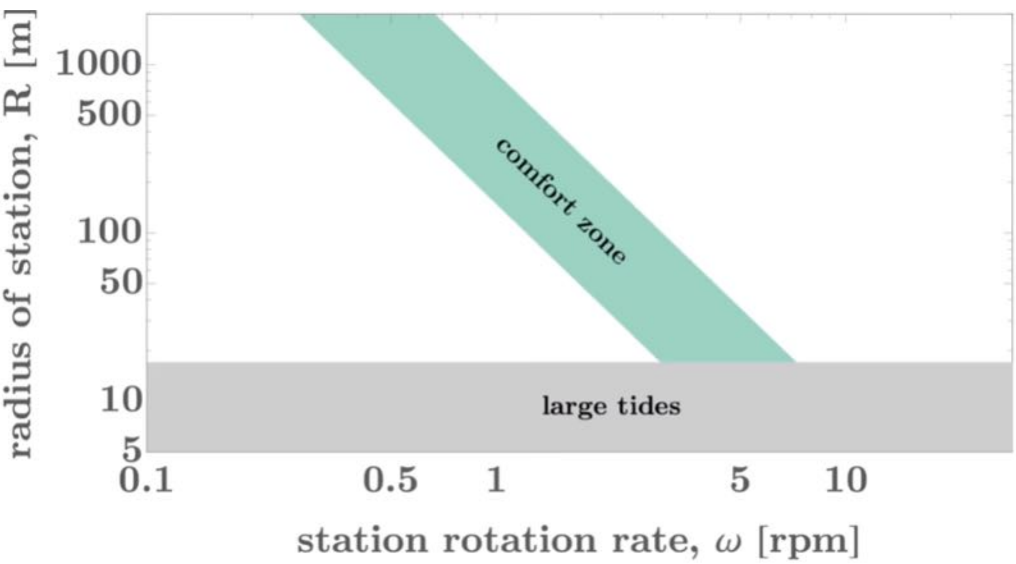



Figure 17: Artificial gravity chart with tidal force restriction. Taken form the video essay: *Artificial Gravity*, of the Youtube channel: *Cool Worlds*.

**Coriolis**

Staying completely stationary inside of a rotating habitat can be practically indistinguishable from real gravity. Put one the inhabitants start to move around, some undesirable forces start to appear. Coriolis force has been one of the main concerns in artificial gravity since the beginning of the concept. It is vital to minimize the it's effects to design a good habitat.

The Coriolis effect is an acceleration vector which is the result of the cross product between the angular velocity of the habitat, and the linear velocity of the astronaut inside. The resultant Coriolis acceleration is a vector perpendicular to the other two. In order to analyse the effects of the Coriolis force, we have to separate it into two different types. Vertical Coriolis and lateral Coriolis.

- Vertical Coriolis: It causes a change in apparent gravity. It appears when an astronaut moves in a direction parallel to the tangential velocity vector of the rotating habitat. Walking pro-grade to the tangential velocity vector of the habitat, would increase the effective rotation rate, and thus increasing the force of gravity felt by the inhabitant. Opposite to that, if the astronaut walked retro-grade to the tangential velocity vector of the spacecraft, it would feel a decrease in the effective gravity. This effect is shown in the sections 2c and 2d of the figure 20.

  In order to put this in the artificial gravity chart, we have to set thresholds of what is comfortable and what is not. A study in 2014 by Alessandro Nesti et al [15], concluded that changes in gravity less than 5 percent are nearly imperceptible. The higher limit is less well studied, but experiments by NASA conducted in centrifuges in the year 2000 [16] suggest that an increase in gravity over 25 percent is generally uncomfortable. With these limits we can revise the chart and establish new comfort zone:

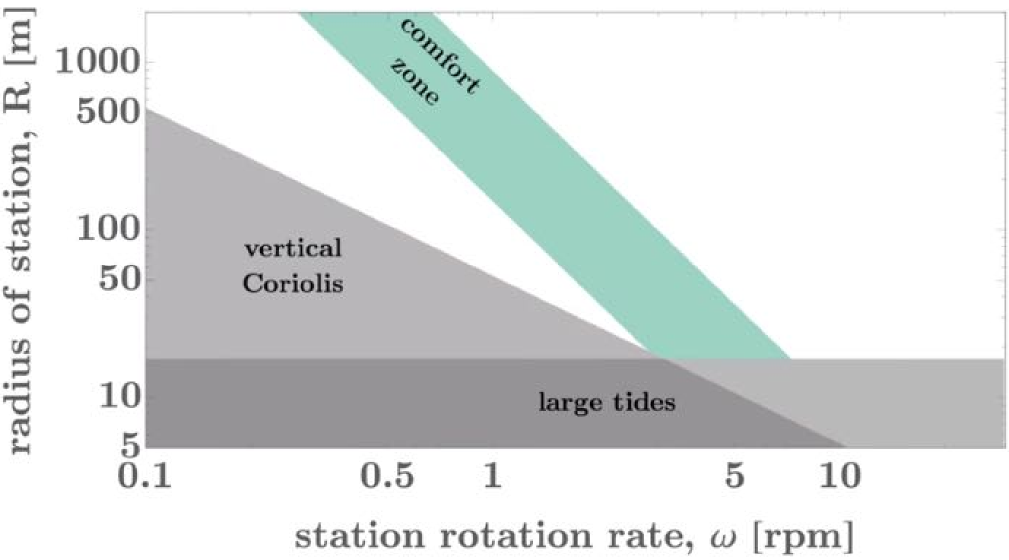



Figure 18: Artificial gravity chart with vertical coriolis force restriction. Taken form the video essay: *Artificial Gravity*, of the Youtube channel: *Cool Worlds*.

- Lateral Coriolis: It causes a tipping effect. Mostly exemplified when astronauts climb ladders to ascend to higher floors of the habitat. An astronaut climbing a ladder in a habitat rotating anticlockwise would feel a tipping force to his right. And if he was descending through the ladder the force would be to the left. But this is only if the ladder is oriented in the same way as in the figure 20. Depending on the orientation of the ladder, the coriolis force will try to tip the astronaut either to a side or to/from the ladder. Another consequence of the Coriolis effect is that objects falling to the floor won't fall in a straight line, but in following a curve.

Solutions for this problem include single deck spacecraft, specially designed ladders, training astronauts to stand up slowly, etc. The magnitude of these effects, as stated above, is directly proportional to the spin rate of the habitat and the velocity at which the astronaut moves. General assumptions from various authors set the velocity of ascend in 0.3 m/s. This gives us the following revised chart:

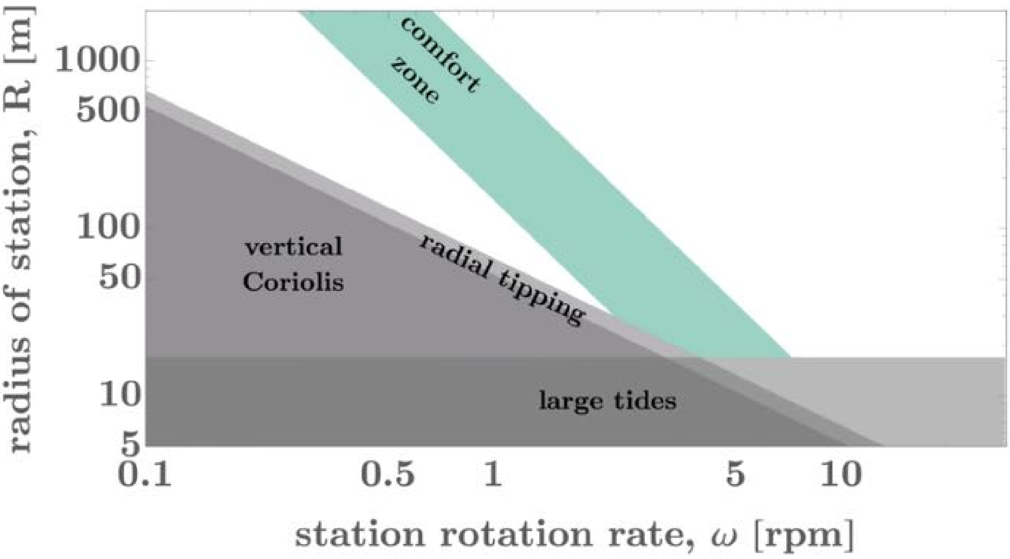



Figure 19: Artificial gravity chart with tipping coriolis force restriction. Taken form the video essay: *Artificial Gravity*, of the Youtube channel: *Cool Worlds*.

It's clear that rotational gravity won't feel exactly the same as Earth's gravity, but that's not the real goal. The real goal is to maintain the crew healthy so when they arrive at the destination they can start working with very few adaptation time. Astronauts are trained individuals, and they could adapt to an artificial gravity environment, even if has some challenges like the coriolis effect. The job of the designer is to make it as easy as possible for the crew, while maintaining the design realistic.

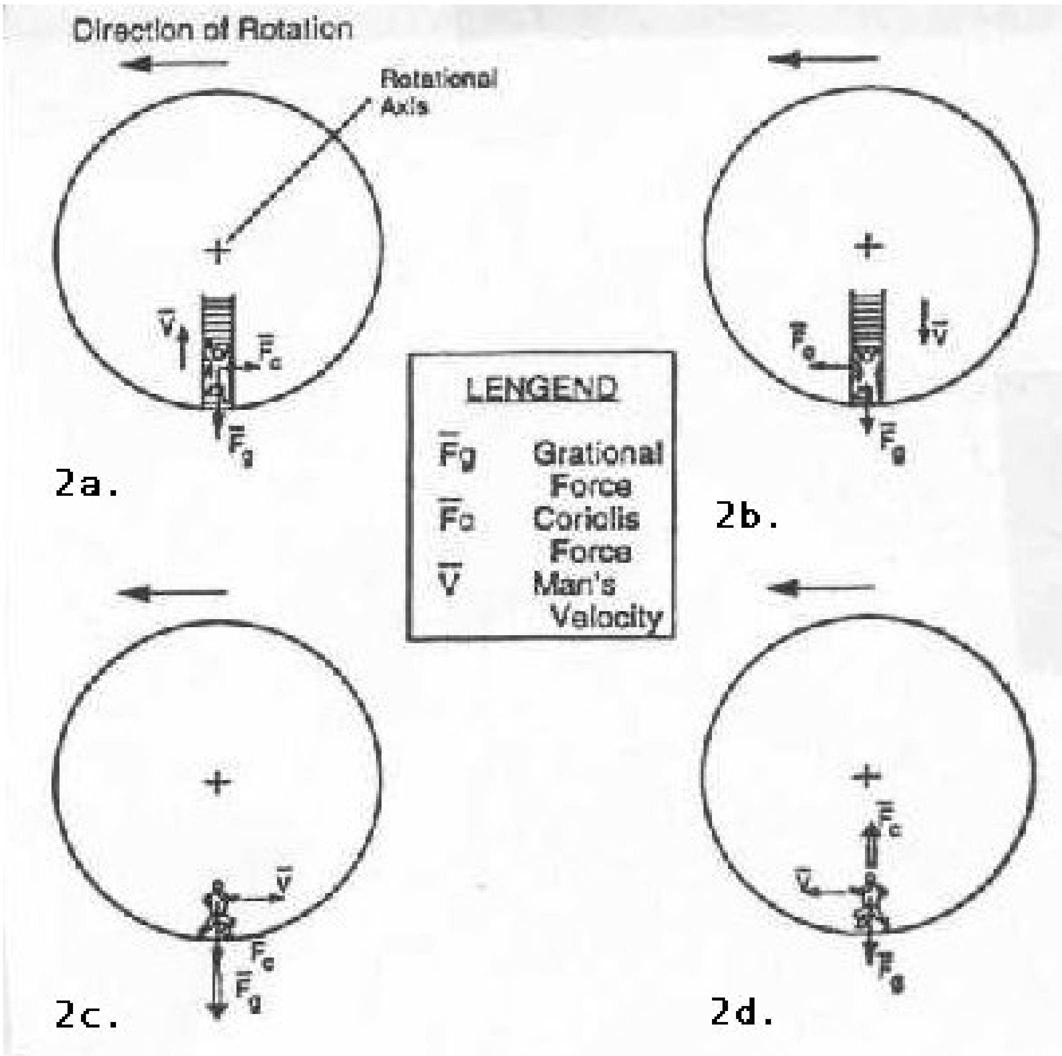



Figure 20: Coriolis effect representation. Image taken from [6].

**Canal sickness**

Coriolis does not only affect the movements of an astronaut's body. It also affects it's balance by acting on the vestibular system in our inner ear. The vestibular system consists of a series of tubes or canals filled with fluid, these tubes are oriented in a way that allows the body to know it's position and control it's balance. If someone turned its head while standing in a centrifuge that provides artificial gravity, the vestibular system would feel the coriolis force derived from the head's rotation. This causes confusion in our brains and causes a sensation of sickness, similar to being seasick.

This brings up the question of how fast rotations we can adapt. The answer to this question has been research in many studies, that try to establish limitations to the design of rotating habitats. In many of the proposals that have been reviewed in chapter 4, the effects of canal sickness are the ones that constraint the most the design parameters.

The studies conducted to find how rotation speeds provoke sickness on humans are conducted on Earth, in slowly rotating rooms. These studies vary in rotation speed, number of people studied, radius of the room, etc. One of the most famous study was done by Graybiel in 1960 [17]. In the study he put people in a rotating room at different rotation rates for two days. He asked them to do some tasks to see how rotation affected their performance. He concluded the following:

- 1.71 rpm: Very mild symptoms
- 2.2 rpm: One subject threw up (had history of seasickness), but the rest reacted similar to 1.71 rpm
- 3.82 rpm: Mild symptoms, and subjects adapted within a day. Adaptation was longer for the subject that had thrown up.
- 5.44 rpm: Highly stressful, but most adapted in a day or so. Subjects with prior rotation experience did better than those without.
- 10 rpm: Highly stressful, subjects could not complete all tasks. There was some adaptation over the two day run

The summary of the results of the study is taken from Doctor Theodore W. Hall's article *Space Settlement Population Rotation Tolerance* [18].

As we can see in the summary, subjects could adapt to 5.44 rpm rotations, although they needed some time to do it. The subjects from the studied were not trained specifically to resist fast rotations. Test pilots and astronauts are trained in centrifuges and can resist higher rotation rates than average people.

When looking at the results of studies conducted on Earth about rotation gravity, we have to take into account that the results shown by said studies doesn't completely show the reality of what would happen in space. This rotating rooms can't remove Earth's gravity, so there are two "gravities" acting on the subjects studied, the real gravity and the rotation gravity. This can confuse the vestibular system more than it would happen in space.

Let's see how this affects our chart, and it's comfort zone. We have to set a higher limit for angular velocity to constraint the chart for canal sickness. Taking the study's [17] results, which say that at 5.44 the subjects could adapt within a day and do all tasks, we will be optimistic and say that 6 rpm is our high limit. If an artificial gravity habitat was build, the astronauts sent to live there would be extremely trained and prepared for high rotation rates, and if average people could adapt to 5.44 rpm they would be able to adapt to more than that. But we will stick to 6 rpm because we don't want to be too optimistic. Let's see the revised chart:

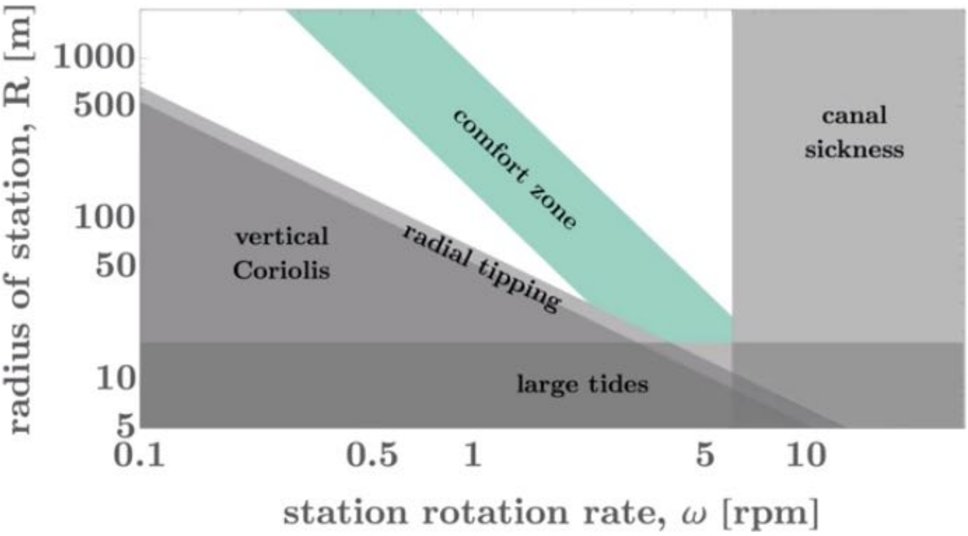



Figure 21: Artificial gravity chart with canal sickness restriction. Taken form the video essay: *Artificial Gravity*, of the Youtube channel: *Cool Worlds*.

This gives us the final chart of restrictions, with all the limitations from the different factors. We can see that the green comfort zone is pretty large and there is room for many different design points inside it. For optimizing costs, the ideal design points would be near the lower part of the green zone, where radius is minimized. But this also depends on what's the purpose of the habitat that we are building. If we are building a rotating space station for a crew of 30 we won't select the same radius than if we want to build a spacecraft for 6 astronauts. This chart will be very useful in the design part of the project.

If we are to make a feasible design of a spacecraft that features artificial gravity, we must understand perfectly all the physical principles that make it possible. In the following chapter, this principles will be discussed. Newton's laws, Coriolis effect, orbits, momentum or moments of inertia are some of the many topics that we will learn about. In order to go through all the important topics, which are many, every topic will be exposed but not discussed in deep.

# 6 The physics of artificial gravity

In order to create a good design of a spacecraft with artificial gravity, we must understand the laws that guide it's functioning. These laws were written by Isaac Newton back in the 1600's, and are a key part in almost every engineering-related activity. In this chapter we will go through the key concepts that are important for this project, with the intention of establishing the framework for the next steps.

The fundamental laws of physics can be found in any introductory physics books, like Sears and Zemansky's *University Physics* [19]. The symbols used in this chapter can be found at the start of the project in the *Nomenclature* section.

## 6.1 Motion and Orbit

The first and most basic laws that we need to know are the Newton's laws of motion and orbit. These will help us understand how objects move inside and outside the Earth, and how spacecraft can maneuver in space. Here are the Newton's three laws of motion and the law of gravitation.

First Law of Motion: A body at rest will remain at rest, and a body in motion with a constant velocity will remain in motion with the same velocity, unless an external force acts on it.

Second Law of Motion: The net force acting on a body is equal to the product of it's mass and acceleration, and the direction of the force is the same as that the acceleration:

$$\vec{F} = m\ddot{\vec{R}} \tag{2}$$

- $\vec{F}$ is the force acting upon the body.
- $m$ is the mass of the body.
- $\ddot{\vec{R}}$ is the acceleration of the body.

Third Law of Motion: The mutual actions of two bodies upon each other are always equal and opposite.

Law of Gravitation: Every body on the universe is attracted to every other body with a force directly proportional to each of their masses and inversely proportional to the square of the distance between them. The net gravitational force exerted on a body is the sum of the gravitational forces exerted on it by every other body.

$$\vec{F_k} = \sum_{j=1}^{n} \frac{Gm_j m_k}{R_{jk}^2} \frac{\vec{R_j} - \vec{R_k}}{R_{jk}}, k = 1, ..., n \tag{3}$$

- $\vec{F_k}$ is the net gravitational force acting upon the body k.
- $G$ is the gravitational constant ($G = 6.67 * 10^{-11} Nm^2/kg^2$).
- $m_j, m_k$ are the masses of the bodies j,k.
- $\vec{R_j}, \vec{R_k}$ are the positions of the bodies j,k.
- $R_{jk}$ is the absolute distance between bodies j,k.
- $\frac{\vec{R_j}-\vec{R_k}}{R_{jk}}$ is the unit vector directed from k toward j.

This equations are true for masses that are considered to be infinitesimal particles. We know that for homogeneous spheres, we can treat them as particles with all the mass concentrated. But this is not true for all sorts of shapes. This law is an approximation and for larger objects one must treat them as the sum of all their parts.

Talking about Earth, treating it as a sphere is a good approximation. We can deduce the acceleration of a body due to gravity on Earth's surface from equations 2 and 3. This acceleration is independent from the mass of the body, and the rest of the bodies around (a part from the Earth):

$$\vec{F_k} = m_k \ddot{\vec{R_k}} = \sum_{j=1}^{n} \frac{G m_j m_k}{R_{jk}^2} \frac{\vec{R_j} - \vec{R_k}}{R_{jk}}, k = 1, ..., n$$

$$\ddot{\vec{R_k}} = \sum_{j=1}^{n} \frac{G m_j}{R_{jk}^2} \frac{\vec{R_j} - \vec{R_k}}{R_{jk}}, k = 1, ..., n \tag{4}$$

To apply equation 4 to the Earth's surface situation:

$$g_0 = \frac{G m_{earth}}{R_{earth}^2}$$

$$g_0 = \frac{(6.67 * 10^{-11} Nm^2/kg^2) * (5.98 * 10^{24} kg)}{(6.38 * 10^6 m)^2}$$

$$g_0 = 9.81 m/s^2 \tag{5}$$

## 6.2 Free fall and weightlessness

When we throw a ball from the Earth's surface, it falls to the ground after some time, depending on the force that we have thrown it. This looks very different from what the ISS does, but it actually isn't. If we threw the ball at an astonishing speed, it would never fall back, because it would be constantly falling, but it would miss the ground in it's fall. This is the exact same thing the ISS does when it is orbiting the Earth.

The imaginary ball orbiting the Earth would describe an elliptical trajectory with one of it's focus coincident to the center of the Earth. The shape of the orbit will depend on how much energy we give to the ball. If the initial speed is below the escape speed, the orbit has an eccentricity below 1, and therefore the orbit is elliptical. If the initial speed is equal to the escape speed, the eccentricity of the path will be 1, and the orbit will be parabolic. Finally, if the speed is greater than the escape speed the eccentricity will be above 1 and the orbit will be hyperbolic.

The feeling of weightlessness that the astronauts feel aboard the ISS is not due to their distance from the Earth's surface. In fact, the acceleration of gravity at the ISS altitude (408 km in average) can be calculated using the equation 4. This is the same equation we have used to calculate the acceleration of gravity at the Earth's surface, but instead of using $R_{earth}$, we have to use $R_{earth} + h_{ISS}$:

$$g = \frac{Gm_{earth}}{(R_{earth} + h_{ISS})^2}$$

$$g = \frac{(6.67 * 10^{-11} Nm^2/kg^2) * (5.98 * 10^{24} kg)}{(6.38 * 10^6 m + 4.08 * 10^5 m)^2} = 8.66 m/s^2$$

$$\frac{g}{g_0} * 100 = \frac{8.66 m/s^2}{9.81 m/s^2} * 100 = 88\%$$

As we have calculated above, the acceleration of gravity at the altitude of the ISS is only 12% lower than the acceleration of gravity at the Earth's surface. As we can see, this is not the reason why astronauts float around weightless when they are in orbit. As has been stated at the start of the section, orbiting is equal to falling infinitely. The ISS falls, and the astronauts aboard the ISS fall. They feel weightless because their surroundings are falling at the same rate than they are. They are weightless relative to the ISS, but not to the Earth.

Often, when we imagine weightlessness, we think of an amazing and fun experience of floating like in a pool. But that's very far from reality. If we really want to have an image of how it feels like, we have to imagine that we climb something very high, like a cliff or a building, and we jump. And we keep falling indefinitely. This strange feeling that we have when we are falling free, but extended in time, it's how the *Space Adaptation Syndrome* feels like.

## 6.3 Weight

It is important to know the difference between gravity, acceleration and weight. Gravity is the force that pulls every molecule of our bodies to the center of the Earth. If we are not standing on the ground, this force, produces an acceleration that makes us fall to the center of the Earth. When we are standing on the ground, we are pushing the ground downwards due to the force of gravity. The ground is stopping us from falling into the Earth. According to Newton's third law of motion, for every action there's an equal and opposite reaction, so the ground will push us up with a force equal and opposite to the force which gravity is pulling us.

This force is applied to our feet, and produces a compression in our body that is not uniform. The compression is maximum at the feet and is zero at the top of our head, with every part in between supporting an intermediate value of compression depending on their height from the ground. This is the perceived weight of our body. We perceive weight not because gravity pulls us down, but because the ground pushes us up. So the apparent weight has nothing to do with gravity, but with other non-gravitational accelerations on our body. We can compute the apparent weight of a body using the following equation:

$$\vec{w'} = -m(\ddot{\vec{R}} - \ddot{\vec{R}}_g) \tag{6}$$

Where:

- $\vec{w'}$ is the apparent weight
- $m$ is the mass of the body
- $\ddot{\vec{R}}$ is the total acceleration of the body (gravitational and non gravitational)
- $\ddot{\vec{R}}_g$ is the gravitational acceleration of the body

Let's think of some cases that help us understand better the equation of the apparent weight. The first one is the simplest, a person standing on the ground. The total acceleration acting on a person on the ground is the sum of the acceleration of gravity and the acceleration that the ground is producing on the feet, which is equal in module and opposite in direction. The apparent weight of someone standing on the ground can be calculated as follows (vertical axis $z$ is positive upwards):

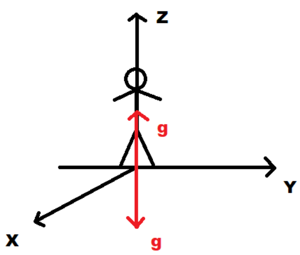



Figure 22: Apparent weight: Case 1

$$\ddot{\vec{R}} = \ddot{\vec{R}}_{ground} + \ddot{\vec{R}}_g = \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ -g \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

$$\ddot{\vec{R}} - \ddot{\vec{R}}_g = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ -g \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix}$$

$$\vec{w'} = -m(\ddot{\vec{R}} - \ddot{\vec{R}}_g) = -m \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ -mg \end{pmatrix}$$

As we can see, the result of the calculations matches our everyday experience, with the apparent weight being a force proportional to the mass and the acceleration of gravity on the surface of Earth. With the direction in the negative z axis (downwards).

The second case that we will study is the free fall. Since there is no ground to push up on their feet, a person falling from the sky should feel weightless, as has been explained earlier in this chapter. We can compute it's apparent weight for this situation:

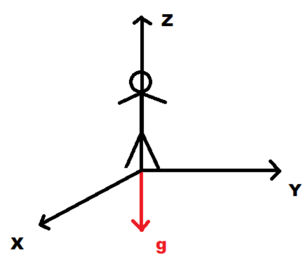



Figure 23: Apparent weight: Case 2

$$\ddot{\vec{R}} = \ddot{\vec{R}}_{ground} + \ddot{\vec{R}}_g = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ -g \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ -g \end{pmatrix}$$

$$\ddot{\vec{R}} - \ddot{\vec{R}}_g = \begin{pmatrix} 0 \\ 0 \\ -g \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ -g \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

$$\vec{w'} = -m(\ddot{\vec{R}} - \ddot{\vec{R}}_g) = -m \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

Finally, we will study the case of a person inside a rotating habitat in low Earth orbit. As has been explained, the acceleration of gravity is still about 88% of the surface gravity. But the apparent weight of the person will depend only on the centripetal acceleration of the person. Which depends on the rotation rate of the habitat ($\omega$) and the radius of rotation ($r$):

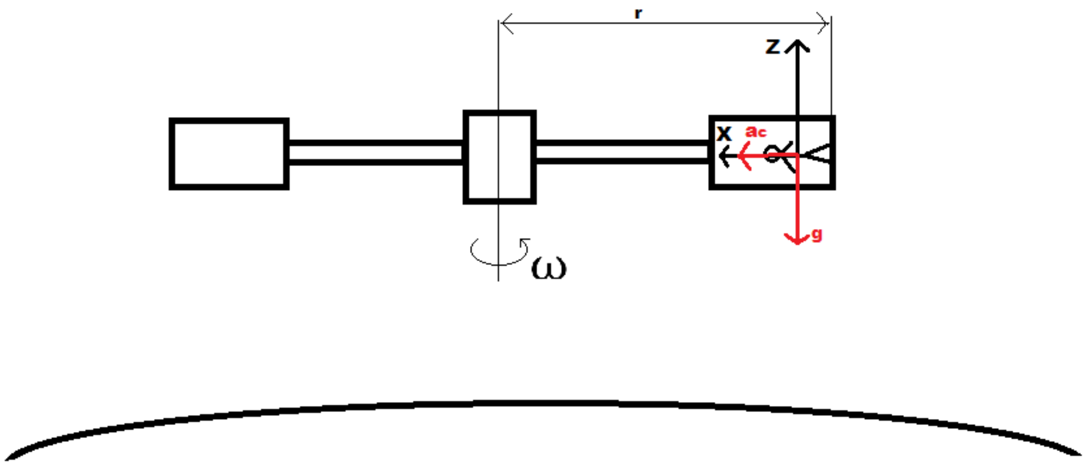



Figure 24: Apparent weight: Case 3

$$\ddot{\vec{R}} = \ddot{\vec{R}}_{cent} + \ddot{\vec{R}}_g = \begin{pmatrix} r\omega \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ -g \end{pmatrix} = \begin{pmatrix} r\omega \\ 0 \\ -g \end{pmatrix}$$

$$\ddot{\vec{R}} - \ddot{\vec{R}}_g = \begin{pmatrix} r\omega \\ 0 \\ -g \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ -g \end{pmatrix} = \begin{pmatrix} r\omega \\ 0 \\ 0 \end{pmatrix}$$

$$\vec{w'} = -m(\ddot{\vec{R}} - \ddot{\vec{R}}_g) = -m \begin{pmatrix} r\omega \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} -mr\omega \\ 0 \\ 0 \end{pmatrix}$$

A normal apparent weight is what keeps astronauts healthy in space, not gravity. So the name *artificial gravity* is not strictly correct. It is impossible to create gravity, since we would need enormous amounts of mass. What we are really trying to create is apparent weight, which, luckily, is independent of the acceleration of gravity.

## 6.4 Energy

We know that need to create acceleration in order to create apparent weight, we have a few different options to do so. The most used in artificial gravity is the centripetal acceleration that appears in rotation, but there are other accelerations that we should look into before discarding them. The most obvious is linear acceleration, we could use the acceleration of the spaceship to create apparent weight for the crew. We just have to accelerate at 1g until half of the trip, and then turn the spaceship around and decelerate at 1g. This sounds good at first, but it is not useful at all. Constant linear acceleration of 1g in interplanetary travel would require an amount of energy that is out of reach with the current technology.

We are going to look into why centripetal acceleration is better than linear acceleration by analysing the equations of work and energy. The work done in accelerating a body is equivalent as it's change in kinetic energy:

$$W = \Delta E_k = \int_{R_1}^{R_2} \vec{F} d\vec{R} = \int_{t_1}^{t_2} (\vec{F}\dot{\vec{R}}) dt = \int_{t_1}^{t_2} (m\ddot{\vec{R}}\dot{\vec{R}}) dt = m \int_{t_1}^{t_2} (|\ddot{\vec{R}}||\dot{\vec{R}}| cos\Theta) dt$$

$$W = m \int_{t_1}^{t_2} (AV cos\Theta) dt \tag{7}$$

As we can see, the work done over a time depends on the magnitudes of acceleration and velocity, and the angle between them. In linear acceleration, velocity and acceleration are in the same direction, so the angle between them will be 0º, this will make the cosine equal to 1 and the work needed will be maximum. For centripetal acceleration, the acceleration and velocity are always perpendicular, so the angle between them is always 90º. The cosine of 90º is 0, and therefore the work needed to maintain the rotation over time is 0. The only moment in which energy input is required in rotation, is when we need to change the angular velocity ($\omega$) of the rotation. Because to change it we need some tangential acceleration. Tangential acceleration is parallel to tangential velocity and therefor requires work and energy. For a long interplanetary trip, we would need to spend the energy necessary to accelerate the rotation to the angular velocity that we needed for the level of gravity desired, and then the rotation would keep going without any new energy input.

## 6.5 Centripetal acceleration

Earlier in this project, the formula $g = r\omega^2$ (1) has been used regularly. But if we want to fully understand artificial gravity we must know where this equation comes from. In this section, the process to obtain said equation will be shown.

The linear velocity vector in a rotating system can be written as:

$$\dot{\vec{r}} = vcos(\theta)\vec{i} + vsin(\theta)\vec{j} \tag{8}$$

Where $\theta$ is the direction of the velocity vector at a given time, and $\vec{i}$ and $\vec{j}$ are the unit vectors parallel to the x,y axes. Taking the derivative we obtain an expression for the acceleration vector:

$$\ddot{\vec{r}} = -\dot{\theta}vsin(\theta)\vec{i} + \dot{\theta}vcos(\theta)\vec{j} \tag{9}$$

$$|\ddot{r}| = a = \dot{\theta}v$$

$$\omega = \dot{\theta}$$

The expression of $\theta$ in function of the time is the following:

$$\theta = \omega t + \theta_0 \tag{10}$$

Then we can rewrite acceleration, velocity and position expressions as:

$$\ddot{\vec{r}} = -\omega vsin(\omega t + \theta_0)\vec{i} + \omega vcos(\omega t + \theta_0)\vec{j} \tag{11}$$

$$\dot{\vec{r}} = vcos(\omega t + \theta_0)\vec{i} + vsin(\omega t + \theta_0)\vec{j} \tag{12}$$

$$\vec{r} = \frac{v}{\omega}sin(\omega t + \theta_0)\vec{i} - \frac{v}{\omega}cos(\omega t + \theta_0)\vec{j} \tag{13}$$

$$|r| = r = \frac{v}{\omega}$$

In order to simplify the calculations, we will make $\theta_0 = \frac{\pi}{2}$, this will make the two elements of the sum positive in the expression for $\vec{r}$. For the following calculations we must know that $\vec{\omega} = \omega\vec{k}$:

$$\vec{r} = rcos(\omega t)\vec{i} + rsin(\omega t)\vec{j}$$

$$\dot{\vec{r}} = -\omega rsin(\omega t)\vec{i} + \omega rcos(\omega t)\vec{j}$$

$$= \vec{\omega} \times \vec{r}$$

$$\ddot{\vec{r}} = -\omega^2 rcos(\omega t)\vec{i} - \omega^2 rsin(\omega t)\vec{j}$$

$$= -\omega^2\vec{r} = \vec{\omega} \times \dot{\vec{r}} = \vec{\omega} \times (\vec{\omega} \times \vec{r})$$

$$|r| = r$$

$$|\dot{r}| = v = \omega r \tag{14}$$

$$|\ddot{r}| = a = \omega^2 r = \frac{v^2}{r} \tag{15}$$

The equations above are the basics of rotational motion, and the starting point for artificial gravity designs. As the equation 15 shows, the apparent gravity is proportional to the radius and rotation rate. But as we know, rotational gravity is not exactly the same as Earth's gravity. Gravity gradients, coriolis forces and other factors affect the gravity that a crew of astronauts would experience. In the next chapter, an explanation about the coriolis effect will be done, in order to better understand the problems that it can cause in rotating habitats.

The aim of this chapter is to explain the physical principles involved in artificial gravity. Understanding these principles is necessary in trying to determine the correct radius of rotation and angular velocity for the habitat. This section is also the last one of this project that is bibliographic, and in the following parts I will apply the contents to a particular case. For further physics of rotation (Coriolis, Cross-Coupled rotations and Momentum) see the Appendix **??**.

# 7 Particular case: Artificial Gravity for SpaceX Starship

Now that the context of artificial gravity has been exposed, it's time to apply it to a real life situation. As has been stated before, human missions to remote destinations are being planned for the next decade, and we should be ready for those long trips.

One of the strongest contestants in the race to go to the Moon, Mars (and beyond) is SpaceX, a private company founded by the South African Elon Musk, who is also the CEO of Tesla Motors, Solar City, Neuralink, and other successful tech companies. SpaceX has the goal of bringing the first humans to Mars in 2024. But that's only the beginning, since they plan to establish a human colony on the red planet, and ultimately making humanity a multi planet species.

Before explaining how artificial gravity can help SpaceX reach their ambitious goal, we have to know more about the company's context, their history, plans, successes and failures, etc. And this is what is going to be exposed in the first section of this chapter.

## 7.1 SpaceX

Space Exploration Technologies (SpaceX) was founded in 2002 by Elon Musk. Initially, it had the aim of making spaceflight affordable and reduce the cost of rockets used to get payloads to orbit. The key improvement that made the cost reduction possible is rocket reusability. Since the start of the space era, rockets have been designed to fly only once. Every rocket was build, flown and then left in the sea, or in some museum.

The first real attempt of reusing spacecraft was the Space Shuttle program, which flew to orbit attached to three boosters and came back to Earth flying like a glider. The problem with the Shuttle was that a huge part of the rocket (the three boosters) were not reusable, and the Shuttle itself needed a lot of refurbishing to fly again after coming back from orbit. This caused the system to be less efficient than the initial intentions.

SpaceX took a revolutionary approach to the problem. They designed rockets to make propulsive landings, and thus recovering the first stage. This helps to recover a big percentage of the rocket, bigger than the Space Shuttle, and it also needs way less refurbishing, which enables SpaceX to fly their boosters again short after they land. They also recover the fairings that cover the payloads using parachutes and boats to catch them. They try to reuse as much of rocket as possible to bring down the cost per kilogram to orbit. This technology has been improved since the start of SpaceX and they have gradually mastered it. A brief SpaceX's rocket list with a brief explanation of their main features will be exposed.

**Falcon 1**

The Falcon 1 was the very first rocket of SpaceX, it was a technology demonstrator and its main goal was to reach orbit. It had 3 unsuccessful launches between 2006 and 2008 before achieving orbital flight in its fourth attempt, on September 28th 2008, being the first private company to ever launch a rocket in to orbit. Musk has stated that, had the fourth flight of Falcon 1 failed to reach orbit, SpaceX would have never recovered and would have disappeared. The rocket flew a fifth and last time before being cancelled to move on to the program of Falcon 9, the rocket that took SpaceX to fame. Falcon 1 was planned to be reusable by landing with parachutes in the sea, but the technology was never demonstrated.

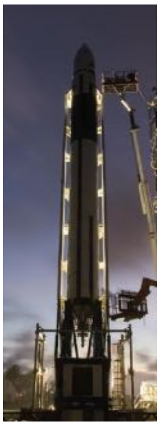


Figure 25: Falcon 1 first flight attempt.

**Falcon 9**

The Falcon 9 rocket is the most successful one from SpaceX. It is essentially a development from Falcon 1, with 9 engines instead of 1. Despite being a development, its substantially more advanced than its predecessor. It is a two-stage rocket capable of transporting cargo and humans to orbit. Falcon 9's booster can be landed and reused many times, bringing cost of space access down significantly.

It is also arguably one of the most revolutionary ones in the history of space hardware. It has set many spaceflight records, like being the first private rocket to fly to the ISS, first rocket to ever vertically land their booster on land (and on the sea), first rocket launched with a reused booster, and a large etc.

SpaceX uses Falcon 9 to bring payloads from contractors to Earth orbit, these payloads include satellites and cargo resppuly to the ISS. It is also the booster of the Crew Dragon capsules that bring NASA astronauts to the ISS. Falcon 9 is the present of SpaceX, since it is the rocket used to win contracts and rise their economy. But their long term goal is different.

Figure 26: Falcon 9 launch from Cape Canaveral. Photo: SpaceX

**Falcon Heavy**

The Falcon Heavy is the most powerful rocket available nowadays. It consists of two Falcon 9 boosters, attached to a larger center core booster. SpaceX designed the Falcon Heavy to carry larger payloads to orbit, and early Mars plans from SpaceX also included Falcon Heavy attached to a Crew Dragon caplsule, but since the Mars strategy has changed (we will see how), it is now used to bring large payloads that couldn't fit in Falcon 9.

The first flight of the Falcon Heavy was one of the most inspiring events of the 21st century. On February 6th 2018, SpaceX tested Falcon Heavy for the first time, and to do so they put Elon Musk's Tesla Roadster in an heliocentric orbit around the Sun. The car had some cameras installed that gave some memorable pictures to the more than 28 million viewers that followed the launch online.

Despite its superstar debut, the Falcon Heavy is a rocket that is less strategic compared to Falcon 9. It flies about twice a year (compared to the 15-20 from Falcon 9). Falcon Heavy has flown three times and it will likely keep its launch cadence constant until the Starship program takes over.

Figure 27: Falcon Heavy on launch platform. Photo: SpaceX

## 7.2 Starship

If Falcon 9 and Heavy are the present of SpaceX, their future is certainly Starship. It's been years since the company presented their first plans to aim for the interplanetary goal.

### 7.2.1 Starship's Timeline

The first official presentation to the general public took place in the International Astronautical Congress of 2016, in Guadalajara, Mexico. Elon Musk exposed plans for a huge vehicle that would have the capacity to get more than a 100 tons to the Moon, Mars and beyond. The vehicle was 12 meters in diameter and 122 meters tall. It would be the largest rocket ever built and flown. It had an outstanding capacity of 300 tons of payload to low earth orbit (the Saturn V of the Apollo era had a capacity of 135 tons to low earth orbit). It's goal was to carry 100 passengers per ship on a trip to Mars. At the time, SpaceX called this vehicle the *Interplanetary Transport System* or ITS.

One year after that, in the International Astronautical Congress of 2017 in Adelaide, Australia, Musk revealed an update of the ITS. The rocket had shrunk to 9 meters in diameter, and the capability reduced to 150 tons to LEO. They renamed the vehicle to BFR or *Big Falcon Rocket*, although some say that the F stands for something else. Since this presentation until now, the system has gone through some design iterations and changes. They decided to switch the construction material from carbon composites to stainless steel, because it made the construction process faster and way cheaper, and it also had advantages for the heat shielding during reentry to atmospheres. The final rename saw the vehicle change from BFR to Starship.

As we can see the design philosophy of SpaceX is completely different from the classical low-risk and high-cost approach of the majority of the other rocket companies. While the typical approach aims for security, reliability, and not taking big risks, SpaceX just builds, tests, explodes things, and then redesigns and rebuilds again. Like this they can iterate fast while keeping the cost low until they come up with a design that it's good to go. Elon Musk said "Failure is an option here, if things are not failing, you are not innovating enough".

Nowadays, in 2020, SpaceX has started construction of the first prototypes of Starship in Boca Chica, Texas. They have flown hops of 20 to 150 meters, testing the structure and the Raptor engine that will propell Starhip. To date, they have build, or are currently building 11 Starship prototypes, some are for pressure testing, some are for flight tests, etc. Now that we know a bit of the history of this ship, it is time to dive deeper and know what it is all about.

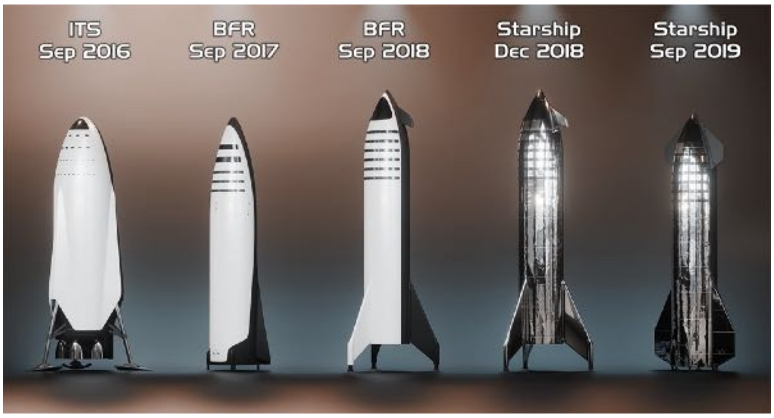



Figure 28: Evolution of SpaceX's Mars ships (upper stage without booster) from 2016 until today. Photo: Kimi Talvitie (Reddit)

Figure 29: Starship prototype Mk-1 in Boca Chica, Texas. Photo: SpaceX

Figure 30: 150 meter hop of the Starship prototype SN-5. Photo: SpaceX

### 7.2.2 Vehicle details and mission

Starship it is meant to replace Falcon 9 and Falcon Heavy, a part from being able to go to the Moon, Mars and beyond. So it has to be a very versatile ship. In the images shown above, we have only seen the upper stage of the rocket, but Starship is a two stage rocket. The upper stage is called Starship and the first stage is called Super Heavy Booster. The booster brings Starship to Earth orbit, and then comes back and lands vertically on the launch pad (as does Falcon 9's booster). It is designed to fly with little to none refurbishment, so it can fly short after it lands. SpaceX has claimed that the booster will be able to fly many times a day, so it can bring a lot of Starships to orbit.

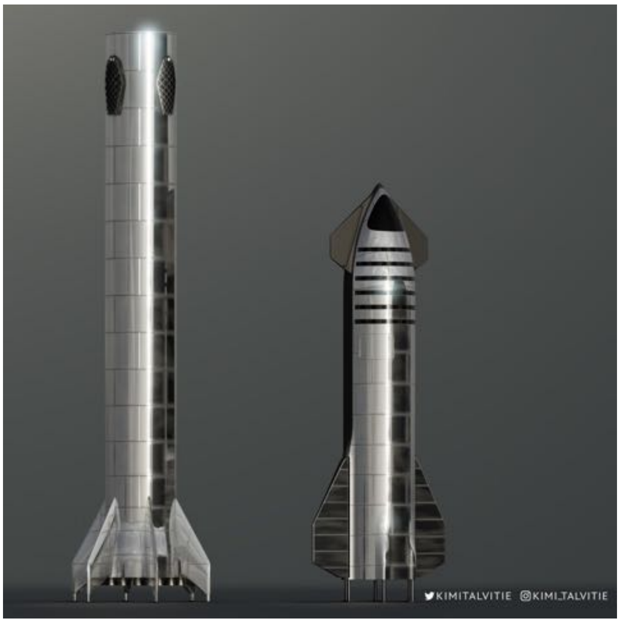



Figure 31: Starship (Right) and Super Heavy Booster (Left). Photo: Kimi Talvitie (Reddit)

Once Starship is in orbit with its payload, if its mission is simply to deliver the payload to orbit, it will open its cargo bay, deliver the payload to the desired orbit, and then perform an entry burn and reenter to the atmosphere. It will land vertically on the pad or in a sea platform like the Falcon rockets do.

But if Starship's mission is to go to, let's say, Mars, it needs a lot of extra fuel. Starhip is a big ship that has to carry a lot of dead mass only to get to orbit, so when it gets there it hasn't got enough fuel to accelerate to an heliocentric orbit. SpaceX will solve this problem by flying "tanker" Starships, full of fuel, to refuel the ship that will go to Mars. Orbital refueling is critical for SpaceX missions. 2-3 refueling processes will be necessary for a trip to Mars.

Once Starship is fully fueled and ready to go. It performs a burn with its Raptor engines that puts it into an heliocentric orbit that will get it to Mars. After the burn it takes about 6 months to get to the Red Planet. Once the ship arrives there (since we want it to stay and not fly by), it has to perform another fuel burn to break and get into an orbit around Mars. After entering said orbit, another burn is needed to land on the surface of the planet.

When Starship lands on the surface of Mars, it has very few fuel left, certainly not enough to get back to Earth. So how does SpaceX plan to bring it back? Their plan is to create the fuel there. Mars has the appropriate chemicals to manufacture Starship's fuel, which is Methane (CH4) as a propellant and Oxigen (02) as an oxidizer. Mars atmosphere has a lot of CO2, and the Martian soil has a lot of ice water. So by the chemical reaction CO2+H2O=CH4+O2, it is possible to obtain the necessary fuel. But for this, SpaceX will need to generate energy, a lot of it. Generating this energy with solar panels requires the surface of about $21400m^2$, which is about the size of 4 football fields. It is certainly not an easy task, but nor an impossible one. The first ships will bring the necessary equipment to establish the fuel base for the following ships. When a Starship is refueled on Mars, it only has to launch to space, perform a burn to get to an heliocentric orbit again and break when it gets to Earth. The ultimate goal is to establish a self-sustaining city on Mars, with people living and working there, and to explore the outer solar system.

Figure 32: Mars base with multiple starships, solar panels, and equipment for self-sustaining life. Photo: SpaceX

## 7.3 Artificial Gravity for Starship

SpaceX has shown no plans to incorporate artificial gravity to their transport system to Mars and the rest of the Solar System. Research shows how bad it is to be exposed to weightlessness for long periods of time (more deteiled description of the effects on chapter 5). All kinds of adverse effects like bone loss, muscle loss, fluid loss, cardiovascular problems, visual problems and a long list of changes affect our bodies.

But the problem isn't weightlessness itself, it's going back to gravity. Imagine arriving to Mars and not being able to stand up for days, or walk for a week. A part form the inconvenience of health problems when you don't have a decent infirmary to be treated. In Mars, any health complication could be potentially life-threatening, and it is crucial that we do anything we can to keep the astronauts in good health.

A side from the health issues, there should also be a concern about comfort aboard of the Starship, since the plan is to bring about 100 people traveling for several months. The first crewed flights of Starship to Mars, surely won't be that crowded, and it will be trained astronauts who will go first. But when production and infrastructure starts to be ready, and costs are brought down, SpaceX's idea is to bring to Mars anybody who wants to go and can pay the ticket (which they claim won't be prohibitive). The consequence of that is that maybe in the future SpaceX will have to transport passengers which are not trained astronauts with outstanding physical preparation.

Basic people necessities couldn't be covered, like showering, going to the toilet, brushing one's teeth or even cooking like we do on Earth. Everything would be very different and uncomfortable, specially for people not mentally trained or used to being in space, and enduring that for 6 months would bring a lot of problems to the mission.

**Solution for the gravity problem**

In this project a solution for the problem of the lack of gravity for the Starship passengers has been proposed. A similar approach to the problem has been proposed by SpaceX followers and online users, and the ideas of this work have certainly gained inspiration form their proposals.

The most common one is to tether two Starships together, and make them spin around each other, thus generating artificial gravity at the two ships. This has been proposed by many online users, and it has its advantages, a long tether has a relatively low mass, and could connect two Starships effectively during the rotation process, it would enable a very large radius of rotation and therefore a low angular velocity, making the experience inside more comfortable and Earth-like.

But it also has its drawbacks. The first one is deploying the tether, since it is not a rigid structure, it would be difficult to extend and quite a challenge to dock to an end of the cable. Then the acceleration of the rotation process would be unstable since the tether doesn't support bending and it would stay a little bit floppy in the early stages of rotation. Another problem I see is that it looks too risky to rely on a single tether from flying off uncontrolled into deep space. If for any unplanned reason the tether breaks, it would probably cause a lot of damage to the people inside and would end the mission.

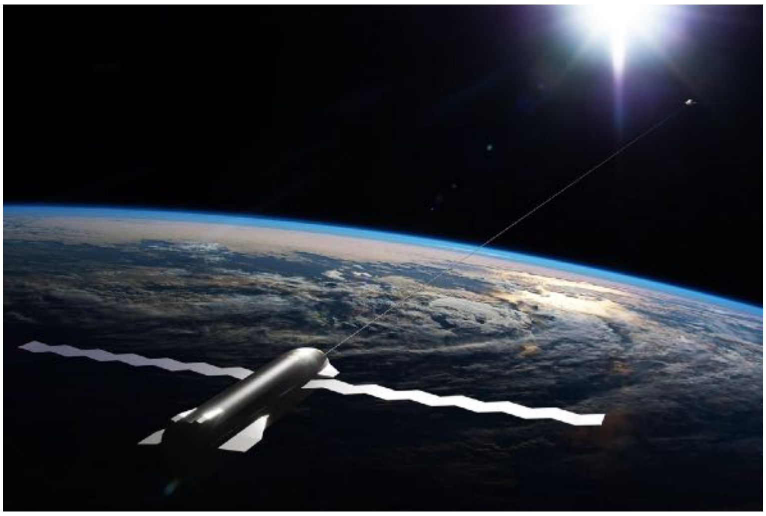


Figure 33: Two Starships connected by a tether to generate artificial gravity through rotation. Photo: Adonaisf (Reddit)

Another proposed solution, and the one that has infuenced this project's design the most, is the one proposed in the video *Artificial Gravity for SpaceX's Starship* from the YouTube channel *Smallstars*. The design consists on rotating two ships, like in the tether case, but in this one a third starship (called Gravity Link Starship or GLS) is used to bring a deployable structure (instead of a tether). The structure deploys and the two other Starships dock to each end. The structure features a hinge for the two external Starships to rotate around their center of mass and perform the acceleration burn for the rotation with their main Raptor engines. This is different from the tether case, where Reaction Control System (RCS) would be used to accelerate the rotation.

The GLS system works as follows. First of all, three ships are launched to Earth orbit, and they are refilled with fuel by other Starships until they are full. One of the three ships carrys the deployable structure inside, this is the Gravity Link Starship or GLS. After that comes the acceleration phase, where the theree ships burn their engines to put themselves in an heliocentric orbit to Mars. Once the acceleration phase is complete, the GLS opens its cargo bay and deploys the structure that will connect the other two as it is shown in the figures 34, 35 and 36:

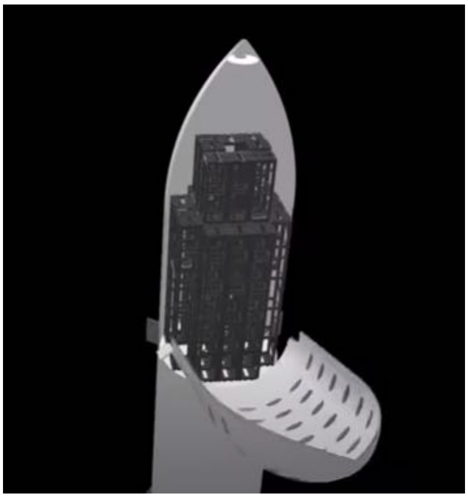


Figure 34: Gravity Link Starship opens cargo bay to deploy the structure. Photo: GLS2 Artificial Gravity for SpaceX Starship (smallstars)

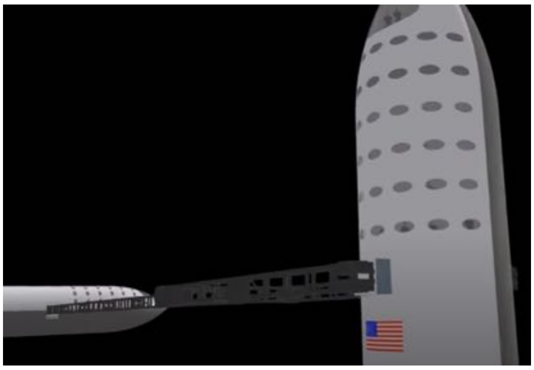


Figure 35: One Starship docked to the structure. Photo: GLS2 Artificial Gravity for SpaceX Starship (smallstars)

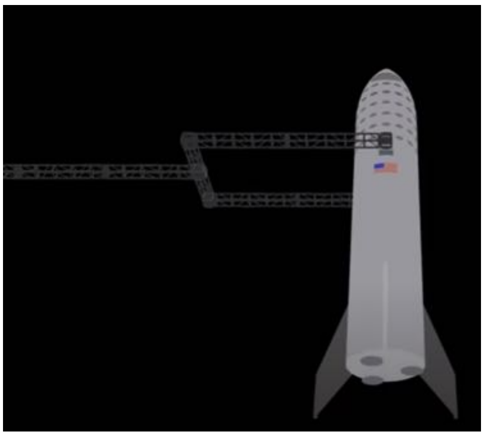


Figure 36: One Starship docked to the structure. Photo: GLS2 Artificial Gravity for SpaceX Starship (smallstars)

As we can see, the structure is made by a long straight truss with a ”U” shaped truss at the end. This is because it is designed for Starship to rotate around and face the other side, making the two ships face opposite directions in order to accelerate the rotation with the main engines. As shown in the figure 37

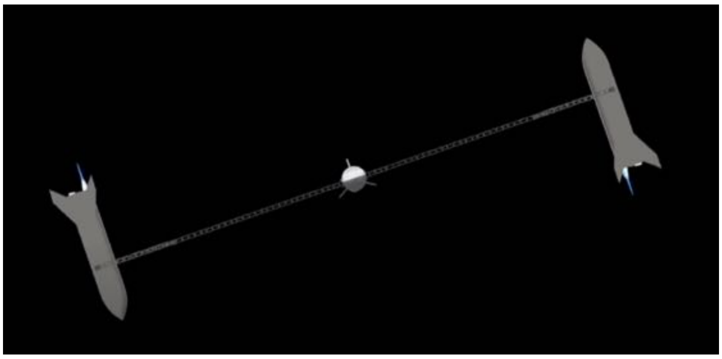


Figure 37: Two Starships face different directions to accelerate the rotation. Photo: GLS2 Artificial Gravity for SpaceX Starship (smallstars)

When the acceleration of the rotation phase is complete, the system will be rotating at the desired angular velocity to produce the necessary g force at the two outer ships. But in that moment, the force is applied sideways to the ships, and it is pushing the people inside against its walls instead of the floor. Since we want people walking on the floor and not on the walls, we have to rotate again the outer Starships in the way shown in the figures 38 and 39:

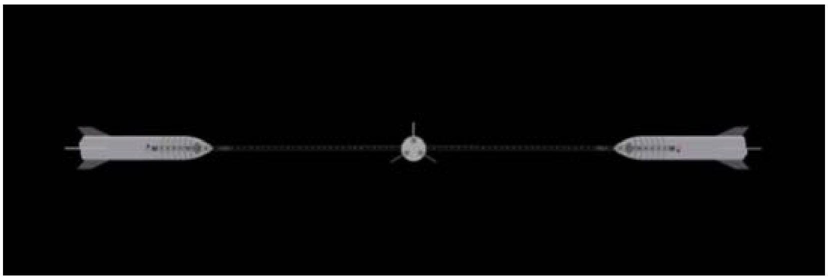


Figure 38: Rotated Starships to face the center of rotation. Photo: GLS2 Artificial Gravity for SpaceX Starship (smallstars)

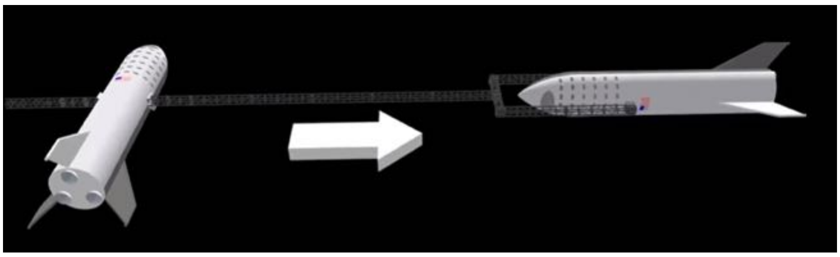


Figure 39: Starship facing the center of rotation. Photo: GLS2 Artificial Gravity for SpaceX Starship (smallstars)

When the rotation phase is finished, we have artificial gravity for the two outer ships, pointing in the correct duration. Giving a full 1g of gravity for the comfort and health of the passengers. The system will remain in rotation for the full duration of the trip to Mars (or other place), without requiring energy input. Since there is no friction in the vacuum of space, there is nothing that will stop the system from rotating.

When the ships are approaching Mars for the deceleration manoeuvre, they will perform the reversed process. First, the two ships will rotate to face opposite directions, they will decelerate the rotation until the angular velocity of the system is zero. Then, the two outer Starships will undock from the structure, and the GLS will fold the structure again and lock it in its cargo bay. When the process is finished, the three Starships are ready to decelerate and prepare for the landing in the surface of Mars.

The system that has been explained above is a very interesting one, since it offers a relatively "simple" way to offer artificial gravity to the Starship, without having to re-engineer the whole ship. It is safer than the tether option, since a truss has more redundancy, and if some part fails, it is not as critic as if the tether breaks. Bringing three ships to Mars also has some advantages, one could think that if it is extremely difficult to bring only one ship to Mars, how could we thing about bringing three. But SpaceX has never looked to send only one ship anyways. They envision a fleet of Starships traveling to the red planet, bringing tons of cargo and numerous people. The GLS could serve as the "cargo ship", a part form the structure, it could bring cargo to Mars, thus leaving more space and comfort for passengers in the other two ships. It could even be a "tanker" ship, bringing extra fuel that could be transferred to the other Starships to enable them to go further into the Solar System.

Although many opportunities are derived from this system, like the ones stated above, it also has its setbacks. One of the main difficulties is complexity. The docking mechanism is not an easy one to perform, and has a lot of possible failure points. The more movements, rotations, docking points, etc, the more risk there is that something will fail at some point. The GLS system has two docking points per Starship, docking like this is not as easy as the classical one point docking that could be done form the nosecone of the ship. A part from this, Starship has to perform three rotations to accelerate the spin (one to face the opposite way to accelerate and two to face every ship to the center of rotation of the sytem), and three more rotations to decelerate the spin.

Another problem with this system is that during the acceleration of the spin, the passengers would be pushed into the walls, making the experience very strange and not quite Earth-like. Although this is not a major problem since SpaceX could mount rotating seats that faced the passengers to the correct direction at every moment.

There are other proposals to create gravity for Starship, like creating a rotating ring around it, with several modules where crew could live with good gravity levels, but those are, in my opinion, too complex to be realistic. They resemble the Endurance ship from the movie Interstellar (Figure 12), and it would be fantastic if SpaceX developed such a structure, but it looks difficult that they will be willing to assume the costs of building and designing it, at least in the near future.

# 7 PARTICULAR CASE: ARTIFICIAL GRAVITY FOR SPACEX STARSHIP

# 8 Study and Simulation of a deployable Structure to provide Artificial Gravity for Starship

In SpaceX's CEO's words, the best design tends to be also the simplest one. If a design is taking too long, the design is wrong. "Best part is no part, it weights nothing, costs nothing, can't go wrong". This may sound very counter intuitive, since space engineering has never been and will never be simple. But that's the point. If the design is already very complex, trying to make it as simple as possible can be key to success. That's the philosophy this project has tried to follow during the process of designing the structure.

The idea started from the GLS (Gravity Link Starship) idea exposed in the past chapter, but as has been explained before, the proposal looked too complicated. The first thing thought was to remove the "U" shaped part of the truss at the end of the structure, and make Starship dock only by its nosecone. Starship would rotate around the hinge that would link its nose to the truss, accelerate the spin, and then, go back to its normal attitude, facing the structure and therefore the center of rotation.

After doing some calculations, it was clear that this design had some major difficulties. The main one was that during the angular acceleration phase, Starship's center of mass would not be aligned with the center of rotation and the structure. Thus creating a moment that would tend to rotate Starship to a position where the center of rotation is aligned with the structure and the center of mass. This means that it would require thrust from the engine and the RCS to prevent this rotation and the energy waste would be unsustainable. See figure 40 below:

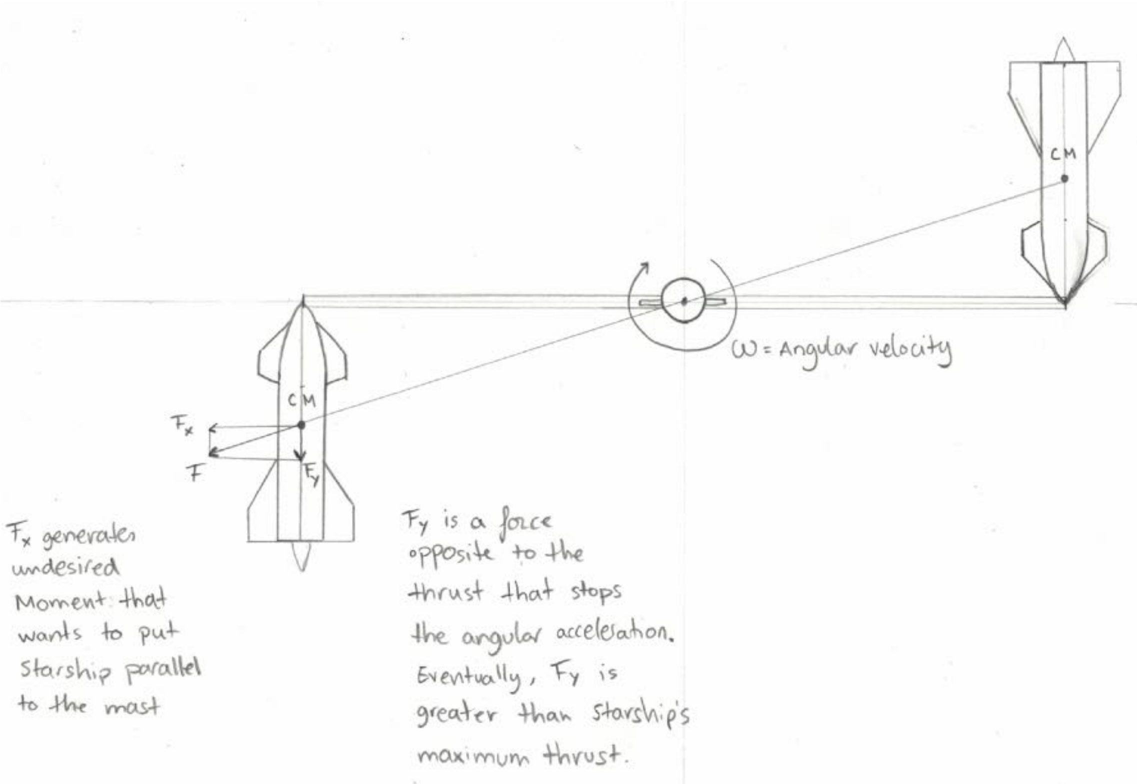



Figure 40: Drawing of the first design during the angular acceleration phase, with the outer Starships rotated to produce torque with their main engines.

After noticing the problems with the design, the decision was to switch to an even simpler one. The idea was that Starship would dock to the structure by its nosecone directly in the position of the rotation, facing the center of rotation and aligned with the structure. The angular acceleration burns would not be done by the main engines, but with the RCS. Like this there is no need to move Starship once it is docked, and the acceleration of gravity during the angular acceleration phase will always be to the floor and not to the walls, like it was in the other design and in the GLS.

The whole point of rotating Starship to perform the angular acceleration with its main engines was because the RCS simply don't have enough power and fuel to sustain the necessary thrust for the necessary amount of time. But accelerating with the RCS makes the design so much simple, elegant, easier and safer that it is worth to do some changes to the RCS system. SpaceX decided to use cold gas thrusters for Starship, as they do in the Falcon 9 and Heavy. But in the early design process of Starship, Elon Musk mentioned that they were willing to use methane and oxygen powered RCS's, which are way more powerful, and consume fuel from the main tanks in starship (so there is a lot of it). If in the future, SpaceX wanted to opt for a design like the one that has been proposed here, they would probably have to switch back to the Methalox RCS.

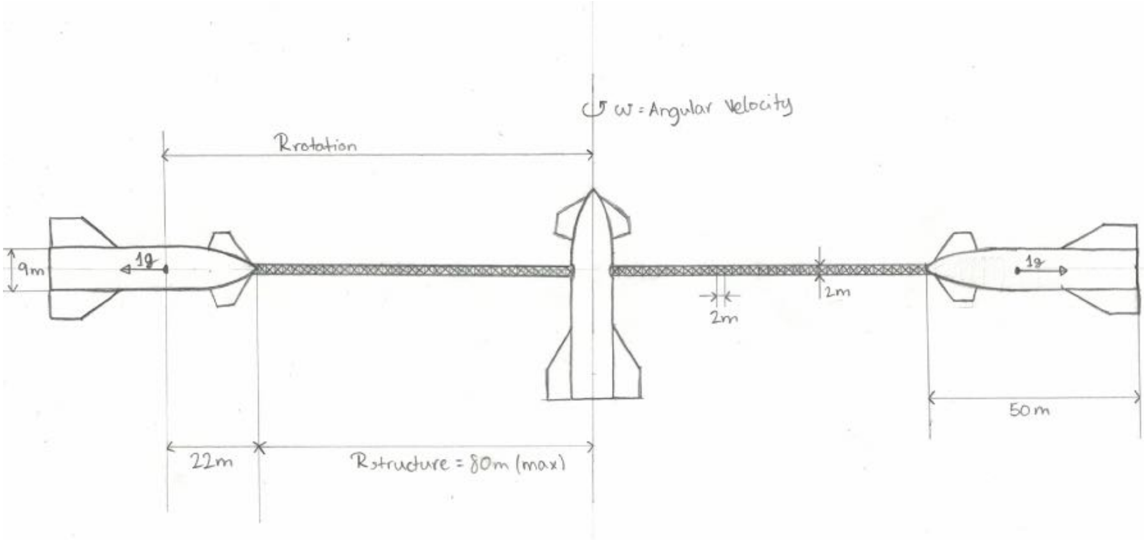



Figure 41: Drawing of the final design with its principal measures. Starships do not rotate to accelerate the spin with their main engines.

Another change that was made was regarding the deployable structure itself, if you see the figure 34, the truss packs in a way that it inevitably occupies nearly the entire cargo volume of the ship, this is bad in a lot of ways. If you use all the available payload volume, the center Starship is useful for only one thing: Generating artificial gravity for the other two. And this makes the whole system extremely inefficient. You are launching a ship, and many others to refuel it, with their own Super Heavy Boosters, just to have artificial gravity for two ships. It is not awful, since artificial gravity is critical, but it is not optimal either, especially if there are other solutions, and there are.

After some research on deployable structures, a type of structure that looked like the perfect one for this case was found. The ADAM mast (Able Deployable Articulated Mast), it is a mast-like structure, that is formed by cubic sections triangulated with cables, it has joints that allows to fold every cubic section of the mast, thus folding and deploying the structure linearly. It was used in the NASA mission SRMT (Shuttle Radar Topograhpy Mission) of the Space Shuttle in the year 2000. The mast can be stowed up to 1/20th of its maximum length. So if we know that the inner diameter of Starship is 8 meters, and that there would have to be two masts (one at each side for the two Starships), it is possible to fit two 4 meters stowed masts. This gives a maximum length of 80 meters for each deployed mast. Now we have a structure that can expand up to 80 meters at each side, and occupy a small fraction of the payload volume of Starship. Leaving room for many other useful thing to bring to a mission (cargo, extra fuel, equipmente, etc). This is only a brief explanation about the ADAM mast, further details will be explained in the following sections of the project.

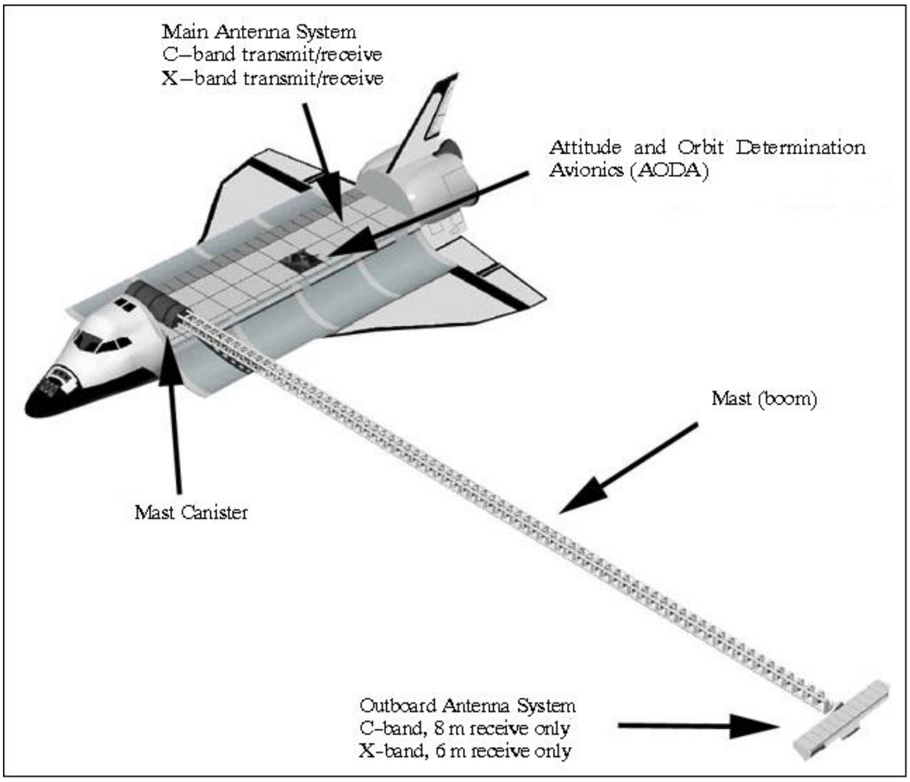



Figure 42: Representation of the ADAM Mast deployed from the Space Shuttle for the SRTM mission. Image: NASA

After selecting the geometry of the entire system and the type of structure, it was time to select the design parameters, such as the length of the mast, the materials that would be made of, the size of the cubes, the number of cubes, the angular velocity, etc. It would be necessary to know if the structure was capable of resisting the forces derived from the angular acceleration and the inertia of the stationary rotation. So a code was written where one could enter the design parameters, and the code would tell if the structure would fail or not, and its factor of safety. Like this one could select the right values for the structure knowing how far it is from failure.

## 8.1 The ADAM Mast

The ADAM Mast is a deployable structure that was used for the first time in the Space Shuttle mission SRTM in the year 2000. The mast was build by the AEC-Able Engineering Company. The original truss was made of 87 cubic shaped bays, with latches on the diagonals of every cube. The truss could be extended from its canister with an electric motor up to a length of 60 meters. The canister contained the truss inside the Shuttle cargo bay during the launch and reentry phases. The stowed mast would be 1/20th of the length of the deployed mast. The following figures show the mast deploying form the canister and the fully deployed structure:

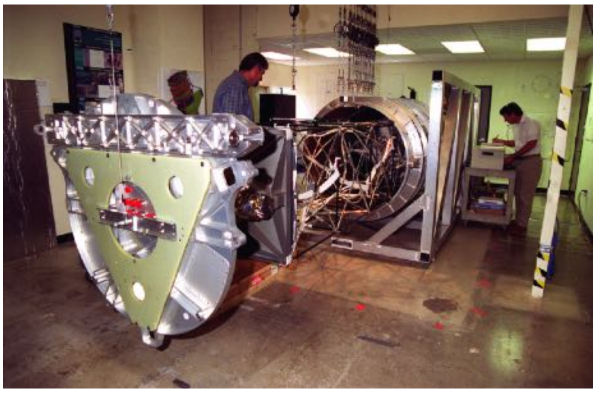


Figure 43: ADAM extending from its canister at AEC-Able Engineering. Image: AEC-Able Engineering

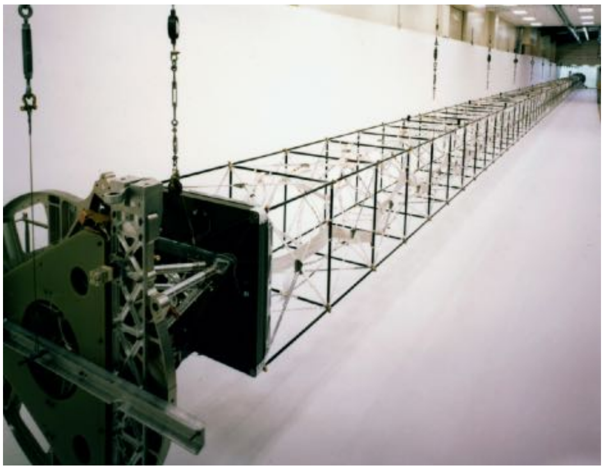


Figure 44: ADAM fully extended seen from the tip at AEC-Able Engineering. Image: AEC-Able Engineering

Figure 45: ADAM fully extended seen from the canister at AEC-Able Engineering. Image: AEC-Able Engineering

The original mast was intended to separate a big antenna from the Space Shuttle, the antenna was used for Earth topology analysis and had to be separated from the vehicle for the mission to avoid interference. When deployed, the mast acted as a rigid structure, but it was not thought to endure the forces of a huge Starship pulling the structure for artificial gravity. So I had to change the size of the mast, the diameter of the bars, the cables, and some materials.

**Mast Geometry**

To know the exact geometry of the ADAM, a thesis by Olive R. Stohlmann was used. It studied the repeatability of joint-dominated deployable masts [7]. The thesis featured a detailed description of the geometry of the mast. It sets the nomenclature for the different parts of the mast: The cubes are called bays, which have battens and longerons, linked by corner joints. Every bay has four faces and two batten squares. In the faces' diagonals there are two cables that cross from one corner joint to another diagonally. All the described above is shown in the figure 46:

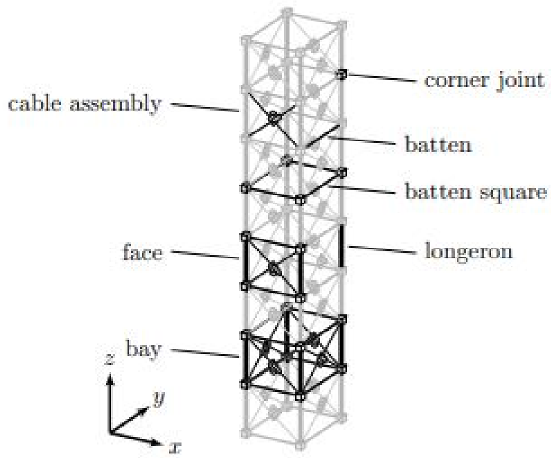



Figure 46: Description of the nomenclature of the different parts of the ADAM mast. [7]

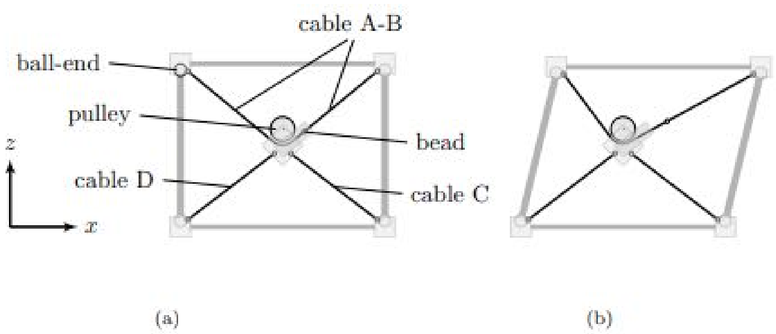
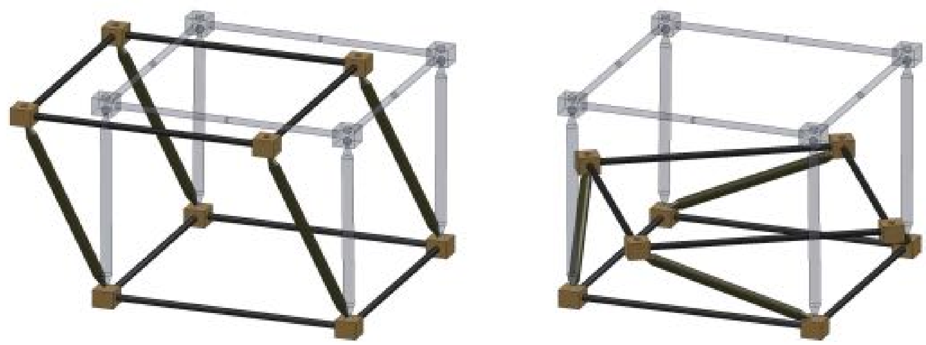



Figure 47: Cable assembly and nomenclature. Latched face (a) and deformed face (b). [7]

The cables are assembled in a way that allows the powered deployment and retraction of the truss. The mechanism of the cables is shown in the figure 47. Without the cables, a bay can be deformed through torsion or through shear. The torsion mechanism is used to deploy and retract the mast, by the interaction of the cables and the locking mechanism.

When the mast is fully extended, the diagonal cables are used to rigidize the structure, and prevent the torsion and shear deformations that the joints of the longerons and battens allow. The cables have to be preloaded for the structure to stay stiff and not become a mechanism. When the structure is deployed and the cables are preloaded, different parts of the structure will interact with the forces that it will have to support. Axial deformations will have to do with the stiffness of the longerons and battens. While torsion and shear deformations are related with the cables.



(a) Shear mechanism. (b) Torsion mechanism.

Figure 48: Two mechanism of ADAM without cables. [7]

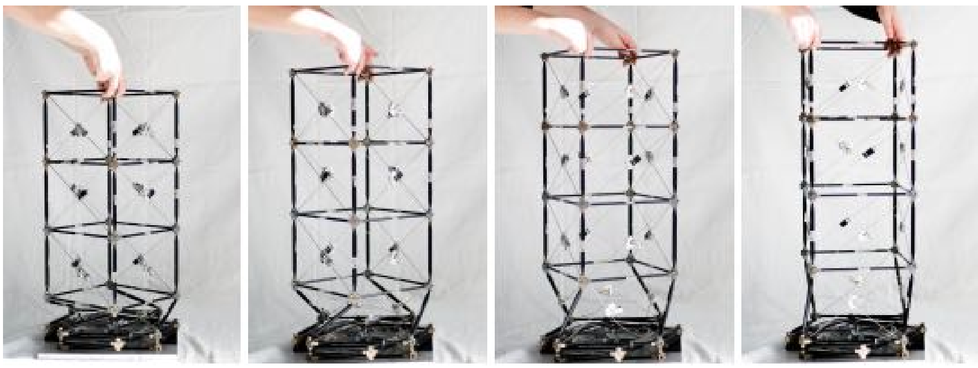


Figure 49: Deploying mechanism of ADAM shown with a sample mast. [7]

**Materials**

The materials used for ADAM are P75 graphite epoxy for the longerons and battens, and titanium for the joints. The cables are made of a flexible fiber to allow the deployment and retraction. The combination of the P75 and the titanium produce a very low net coefficient of thermal expansion, which is something to aim for in space. For the structure proposed for Starship, the P120 graphite epoxy will be used for the longerons and battens, which is similar to the P75 but it has a higer Tensile Modulus and Ultimate Tensile Strength. For the cables, the fibers are not strong enough. The decision was to switch to stainless steel wire rope, which is flexible and more resistant than the fiber. The size and diameters selection of the longerons/battens and the cables will be explained later, since the Matlab program was used to make that decision.

Solvay Thornel P-120 Carbon Fiber/Epoxy Advanced Composite properties:

- **Tensile Modulus:** 520 GPa
- **Ultimate Tensile Strength:** 1210 MPa
- **Density:** 1800 $kg/m^2$

For the cable selection some more research had to be done, since there are a lot of options available for the industry. A very useful document that helped with the selection of the cable was *General Guidance: Crane and Industrial wire and rope solutions for the world's most demanding applications* [20] from the British company Bridon International. It is a guide for wire rope selection that goes across the process of manufacturing the rope, selecting the correct rope for your needs, rope data and characteristics, etc. Once the information about wire ropes was acquired, the next step was to search for catalogs of ropes. And the one that looked to have a very good variety for many different applications and a lot of information for the user was Certex Lifting Solution's. Certex is a company form the United Kingdom that offers a wide variety of Steel Wire Ropes.

After going through many wire ropes, the selected one was the Certex Steel Wire Rope - 6x7-FC. This rope is one of the lightest ropes in the catalog and has a very good ultimate tensile strength. Since we need the cables to bend and occupy the minimum space when the structure is retracted, there is a need to minimize the diameter. The 6x7-FC allowed for a minimum diameter of 2 mm while maintaining a very good ultimate tensile strength.

The real elastic modulus of a wire rope can not be determined without doing a modulus test. It is possible to get an approximated value for each type of rope construction, and the list of elastic modulus for every rope construction is listed in Certex's web page. The elastic modulus for ropes with a construction of 6x7-FC is 6300 $kp/mm^2$ or 62 GPa.

Certex Steel Wire Rope 6x7-FC:

- **Tensile Modulus:** 62 GPa
- **Ultimate Tensile Strength:** 1770 MPa
- **Density:** 9495 $kg/m^2$

Figure 50: Stainless Steel Wire Rope Cable 6x7-FC side view. Image: Certex

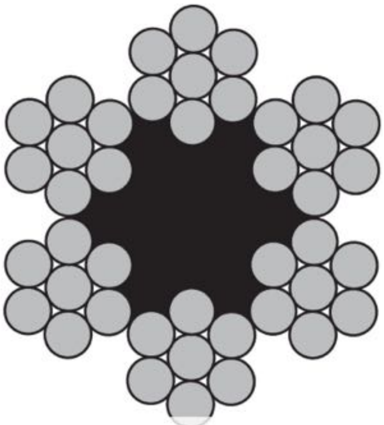


Figure 51: Stainless Steel Wire Rope Cable 6x7-FC cross section. Image: Certex

## 8.2 Matlab Code for the Simulation

The goal of the Matlab code is to determine the design parameters of the structure and the full rotating system of three Starships. In order to do so a script has to be created in which one can input the values of: Number of bays (cubes), diameter of the bars, diameter of the cables, gravity level at the outer Starships, duration of the angular acceleration, and fuel percentage of Starship. Then, the program will let know if the structure will resist the forces of the rotation and angular acceleration. It will give the factor of safety of the structure (FOS), to inform about how far is the structure from breaking. It can also give the displacement of the structure. With this program one can search for different input values that allow for a good factor of safety for the structure.

The program is based on a bar element algorithm. It starts with the inputs of the variables stated above, and proceeds to calculate the number of nodes, elements, degrees of freedom, etc of the structure. It also calculates the values of the force that the structure will have to resist, based on the gravity level desired at the Starships, the radius of rotation (length of the structure), and the duration of the angular acceleration (if the angular acceleration takes longer, it requires less thrust than if it takes shorter, thus demanding less bending from the structure).

The simulation its performed at the most demanding situation of all: At the end of the angular acceleration, when the axial force is at its maximum (almost 1g at outer ships) and the bending force derived from the angular acceleration is still acting on the structure.

Once the inputs, materials and forces are set, the next step is to build the matrices that describe the mesh of the structure, which sets an element for every bar or cable and a node in every joint. Every node has three degrees of freedom, one for each axis. Then the matrix of fixed nodes is built, which will always be the first four nodes, since they are the ones attached to the central Starship (the three degrees of freedom of the first four nodes are fixed). After that, a vector that calculates the internal forces of the structure is built. Said forces appear when the structure itself starts to rotate to generate artificial gravity.

The next step is to build the global stiffness matrix. Once the stiffness matrix is built, the global force vector is assembled, it will have the external forces done by Starship and the internal forces of the structure.

Now the global system of equations has to be set, from which the displacements of the structure can be obtained. When the displacements are obtained, it is possible to calculate the strains and stresses of the elements of the structures. The condition says that the cables have to be preloaded, and that the cables can not support compression. The article by Greschik [21], describes the concerns that appear when a truss is formed by rigid elements and cables. It says that the cable should be preloaded to at least, the maximum stress of the theoretical member it replaces. In order to apply that conditions to the program, the strains and stesses of the structure are calculated once, then the maximum stress of the cables are obtained. After that, the process is repeated but adding a prestress to the cables equal to the maximum stress of the previous calculation.

Then the factor of safety of the cables and the bars is calculated. Finally, a function that plots the whole structure and shows a color scheme with a scale that describes the stress of every element is added.

### 8.2.1 Calculation of Forces

In order to know precisely how the structure will perform, it is very important to predict correctly the forces that will act on it. In the case that have been studied, there are two main forces done by Starship to the structure. One axial, which is the centrifugal force, an apparent force that tries to push Starship away from the structure as the rotation speed increases, it is reaches its maximum when we reach the desired angular velocity. The other force is a tangential force that produces the angular acceleration necessary to reach 1g at the outer Starships. This force depends on the Moment of Inertia of the whole system (3 Starships and 2 Masts) and the duration of the acceleration (the longer it takes to reach the speed, the weaker the tangential force will be).

The other force that has to be taken into account is the internal force of the structure itself. The basic requirement for any structure is that it has to be able to sustain its own weight. The value of this force increases with the distance to the center of rotation.

**Internal Forces**

In order to know the internal force that has to be applied to every node of the structure, the method of virtual works has to be done. This method allows to build a vector of force for each element of the structure, which will have forces in the three degrees of freedom of the two nodes that the each element has.

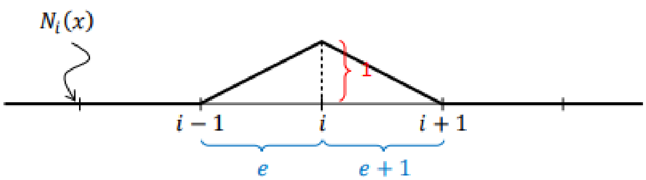



Figure 52: Form of the virtual displacement in the element being computed. Image: UPC

$$\delta W = \int_0^L \delta w(x) f(x) dx = 0 \quad (16)$$

Here, the force $f(x)$ is a force per unit of distance and $\delta w(x)$ is any virtual displacement. This has to be true for every node, so we can say that there will be N virtual displacements (being N the total number of nodes):

$$\delta w_i(X) = N_i(x) = \begin{Bmatrix} \frac{x-x_{i-1}}{h_e} & for x_{i-1} < x < x_i \\ \frac{x_{i+1}-x}{h_{e+1}} & for x_i < x < x_{i-1} \\ 0 & others \end{Bmatrix}$$

Equation for every node i:

$$\delta W = \int_{x_{i-1}}^{x_i} \frac{x - x_{i-1}}{h_e} f(x)dx + \int_{x_i}^{x_{i+1}} \frac{x_{i+1} - x}{h_{e+1}} f(x)dx = 0 \tag{17}$$

It is known that the work of the external forces must be equivalent to the one done by the internal forces, so $\delta W = \delta W_{int}$. This means that for every element:

$$\left[K_e\right]\left[u_e\right] = \left[f_e\right] \tag{18}$$

Then:

$$\left[f_e\right] = \frac{1}{h_e} \begin{bmatrix} \int_0^{h_e} (h_e - x')f_x(x')dx' \\ \int_0^{h_e} (h_e - x')f_y(x')dx' \\ \int_0^{h_e} (h_e - x')f_z(x')dx' \\ \int_0^{h_e} x' f_x(x')dx' \\ \int_0^{h_e} x' f_y(x')dx' \\ \int_0^{h_e} x' f_z(x')dx' \end{bmatrix} \tag{19}$$

Now that the force that we will have to put into each node of the structure is known, the force per unit of distance has to be found, in order to solve the integral. For that, it is needed a picture of how the force acts in every part of the structure depending on its distance to the center of rotation.

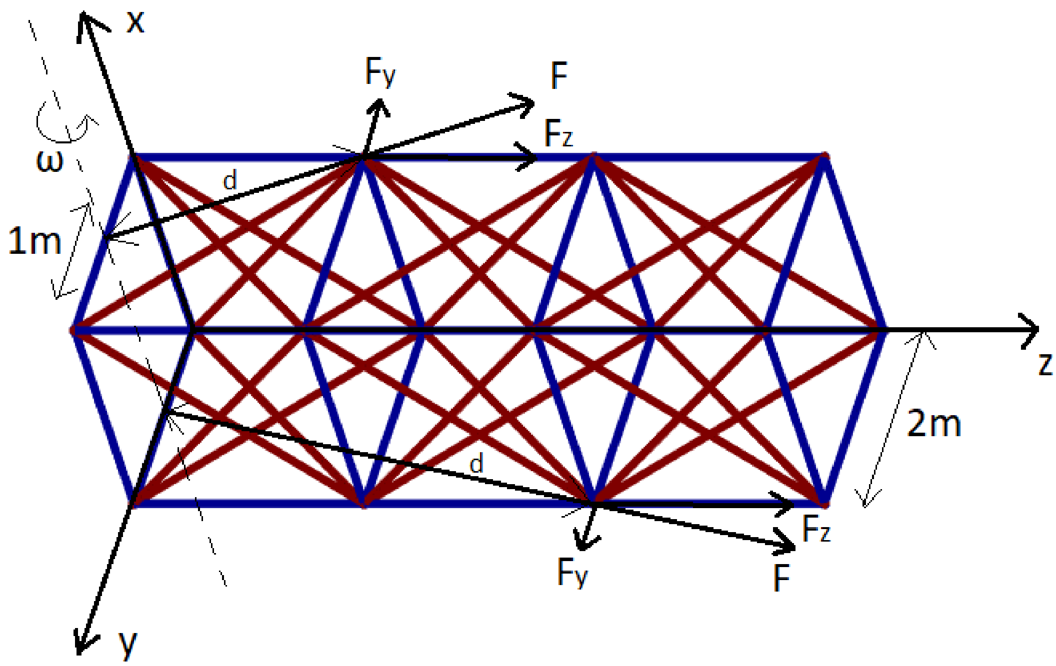



Figure 53: Representation of 3 first bays of the structure with a representation of the force for tow different nodes

The first thing that can be seen is that there will never be force in the x direction, so it will always be zero. The force F will depend on the distance to the center of rotation, the angular velocity and the mass of the structure:

$$F = ma = m\omega^2 d \tag{20}$$

The force has to be divided per unit of distance, so the mass of the structure will be transformed into the linear density ($\lambda$) of the structure. This will be computed by the program, which calculates the mass of the structure once it knows the density of the materials and the size of the structure, and then it divides it by the total length.

$$F = \lambda\omega^2 d \tag{21}$$

In the figure 53 one can see that the distance d, the distance in y and the distance in z build a rectangle triangle where d is the hypotenuse. Well, this is not exactly true, since the origin of y is displaced 1 meter, because the center of rotation has to be at the center of the structure. Then:

$$d^2 = (y-1)^2 + z^2$$

$$d = \sqrt{(y-1)^2 + z^2} \tag{22}$$

$$F = \lambda\omega^2\sqrt{(y-1)^2 + z^2} \tag{23}$$

Now, the value for the force at any node in the structure is known. But it is still not possible to put it in the integrals of the equation 33. To do that it has to be speared into its components (y and z, since x is always zero). And the expression has to be converted from global coordinates to local coordinate, otherwise it will not be possible to integrate the expression.

$$F_x = 0 \tag{24}$$

$$F_y = \lambda\omega^2(y-1) \tag{25}$$

$$F_z = \lambda\omega^2 z \tag{26}$$

The conversion from global to local coordinates is the following:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x_e^{(1)} \\ y_e^{(1)} \\ z_e^{(1)} \end{bmatrix} + \frac{1}{h_e}\begin{bmatrix} x_e^{(2)} - x_e^{(1)} \\ y_e^{(2)} - y_e^{(1)} \\ z_e^{(2)} - z_e^{(1)} \end{bmatrix} x' \tag{27}$$

Which lead to the following expressions of the force in local coordinates:

$$F_x(x') = 0 \tag{28}$$

$$Fy(x') = \lambda\omega^2\big[y_e^{(1)} + (y_e^{(2)} - y_e^{(1)})\frac{x'}{h_e} - 1\big] \tag{29}$$

$$Fz(x') = \lambda\omega^2\big[z_e^{(1)} + (z_e^{(2)} - z_e^{(1)})\frac{x'}{h_e}\big] \tag{30}$$

Now it is possible to integrate and know all the values of the internal forces for every element e:

$$[f_e] = \frac{\lambda\omega^2}{h_e}\begin{bmatrix} 0 \\ \int_0^{h_e}(h_e - x')\big[y_e^{(1)} + (y_e^{(2)} - y_e^{(1)})\frac{x'}{h_e} - 1\big]dx' \\ \int_0^{h_e}(h_e - x')\big[z_e^{(1)} + (z_e^{(2)} - z_e^{(1)})\frac{x'}{h_e}\big]dx' \\ 0 \\ \int_0^{h_e} x'\big[y_e^{(1)} + (y_e^{(2)} - y_e^{(1)})\frac{x'}{h_e} - 1\big]dx' \\ \int_0^{h_e} x'\big[z_e^{(1)} + (z_e^{(2)} - z_e^{(1)})\frac{x'}{h_e}\big]dx' \end{bmatrix} \tag{31}$$

When the integrals are solved the following result is obtained:

$$[f_e] = \frac{\lambda\omega^2}{h_e}\begin{bmatrix} 0 \\ \frac{1}{6}h_e^2(2y_e^{(1)} + y_e^{(2)} - 3) \\ \frac{1}{6}h_e^2(2z_e^{(1)} + z_e^{(2)}) \\ 0 \\ \frac{1}{6}h_e^2(y_e^{(1)} + 2y_e^{(2)} - 3) \\ \frac{1}{6}h_e^2(z_e^{(1)} + 2z_e^{(2)}) \end{bmatrix} \tag{32}$$

$$[f_e] = \begin{bmatrix} 0 \\ \frac{\lambda\omega^2 h_e}{6}(2y_e^{(1)} + y_e^{(2)} - 3) \\ \frac{\lambda\omega^2 h_e}{6}(2z_e^{(1)} + z_e^{(2)}) \\ 0 \\ \frac{\lambda\omega^2 h_e}{6}(y_e^{(1)} + 2y_e^{(2)} - 3) \\ \frac{\lambda\omega^2 h_e}{6}(z_e^{(1)} + 2z_e^{(2)}) \end{bmatrix} \tag{33}$$

Now one only has to compute the values of the coordinates of the nodes for every element and put them in the expressions and go through every element.

**Centrifugal Force**

If Starship was hanging from the structure on Earth, calculating its force would be as simple as multiplying its mass times the acceleration of gravity, which is constant. But when the system is rotating in space, every section of Starship pulls with a different force, because every section has a different distance to the center of rotation. In order to find the total force that Starship makes, the contribution of every surface differential of Starship has to be taken into consideration by solving an integral.

$$F = ma = m\omega^2 r \tag{34}$$

$$m = \rho A dr \tag{35}$$

Where A is the area of every section of Starship. This is not a constant value along the ship so an equation to express A as a function of r has to be found:

$$dF = \rho A(r) dr \omega^2 r$$

$$dF = \rho\omega^2 A(r) r dr \tag{36}$$

When we find an expression for A(r), the value of the total force will be:

$$F = \rho\omega^2 \int_{Rstructure}^{Rstructure+50} A(r) r dr \tag{37}$$

Note that the origin is considered to be at the center of rotation, so in order to integrate the Starship domain, it is needed to integrate from the end of the structure to the end of Starship (wich is the length of the structure plus the length of Starship, 50 meteres).

Now it is necessary to find an expression that models the surface of Starship as a function of the distance to the center of rotation. Starship has a radius of 4.5 meters and a length of 50 meters (starting form the end of the structure). First, an equation to express the radius of the ship as a function of the distance to the center of rotation has to be found:

$$Rstshp(r) = \frac{4.5(r - Rstructure)}{\sqrt{(r - Rstructure)^2 + 15}} \tag{38}$$

If this equation with an Rstructure of 10 meters (which is very low but its just an example) is represented, the following plot is obtained:

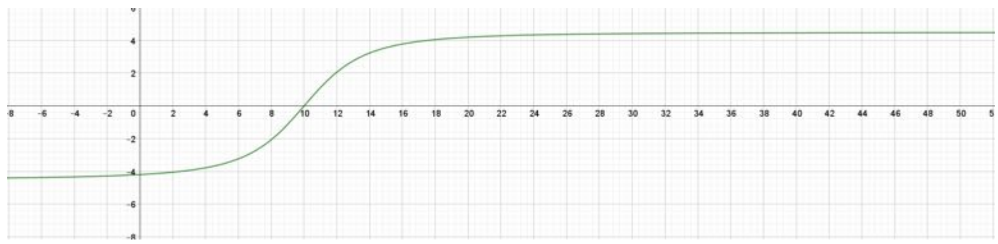


Figure 54: Representation of the Radius of Starship as a function of its distance to the center of rotation.

AS one can see, the plot matches approximately the shape of Starship from 10 meters to 60 (50 of the ship plus 10 of the structure). Now the area has to be known:

$$A(r) = \pi\left[Rstshp(r)\right]^2 \tag{39}$$

$$A(r) = \frac{4.5^2\pi(r - Rstructure)^2}{(r - Rstructure)^2 + 15} \tag{40}$$

Now, the expression for A(r) has been obtained, and it is possible to calculate the force. But before doing that, the entire volume of Starship will be calculated in order to know its density. For that, it is needed to perform a revolution volume integral around the x axis (r axis in this case). To calculate the volume it will be supposed that the Rstructure is zero, since the volume will be constant for any Rstructure:

$$V = \pi \int_0^{50} \frac{4.5^2 r^2}{r^2 + 15} = 2812.88m^3 \tag{41}$$

When the volume is obtained one can calculate the density, but first it is needed to determine the total mass of Starship. In the program, the percentage of fuel will be put as one of the input variables, but the fuel percentage for the rotation of the system should never be over 50%. This is because the three ships will always perform the acceleration burn to its destination (thus burning half or more of the fuel) before docking to the structure and starting the rotation. Expression for Starship total mass:

$$Mstshp = EmptyMass + MaxPayload + MaxFuelMass * Fuelpercentage \quad (42)$$

The empty mass is 120 tons, the maximum payload capacity is 100 tons, and the maximum fuel mass is 1200 tons. This values are taken from SpaceX website and the Starship user's guide. For a 50% of propellant, the following value for the mass is obtained:

$$Mstshp = 120Tons + 100tTons + (1200tTons * 0.5) = 820Tons = 820000kg \quad (43)$$

Finally, the density of Starship is:

$$\rho = \frac{Mstshp}{V} = \frac{820000kg}{2812.88m^3} = 291.52kg/m^3 \quad (44)$$

Now it is possible to calculate the centrifugal force as a function of the length of the structure (Rstructure):

$$F = \rho\omega^2 \int_{Rstructure}^{Rstructure+50} \frac{4.5^2\pi(r - Rstructure)^2}{(r - Rstructure)^2 + 15} rdr \quad (45)$$

Solving the integral the following expression is obtained for F as a function of Rstructure:

$$F(Rstructure) = \rho\omega^2 \left[ -\frac{582541102(2Rstruct(\sqrt{15}tg^{-1}(10\sqrt{\frac{5}{3}}) - 50) + 5(3ln(\frac{503}{3}) - 500))}{18313935} \right] \quad (46)$$

Now this expression has to be put into the program and it will calculate the centrifugal force for any given Rstructure.

**Tangential Force**

The tangential force is produced due to the angular acceleration. In order to accelerate the rotation up to the desired angular velocity we have to produce a force tangential to the structure. This force is done by the RCS (Reaction Control System) of the two outer Starships at the same time. The RCS is compund by a series of lateral thrusters used to maneuver in space.

The two outer ships activate the RCS and make a Moment of Force to the system. That is proportional to the force and to the distance of the point of application (bottom of Starship) to the center of rotation (longitudinal axis of central Starship).

$$\vec{M} = I\vec{\alpha} = I\frac{d\vec{\omega}}{dt} \tag{47}$$

$$M = I\frac{\Delta\omega}{\Delta t} \tag{48}$$

$$M = Fstshp1 * (Rstructure + 50) + Fstshp2 * (Rstruct + 50)$$

$$M = (Fstshp1 + Fstshp2) * (Rstructure + 50) \tag{49}$$

We know that the two Starships have to do the same thrust:

$$M = 2 * Fstshp * (Rstructure + 50) \tag{50}$$

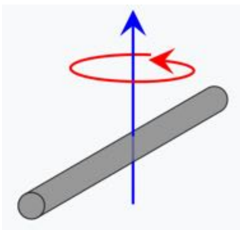
$$2 * Fstshp * (Rstructure + 50) = I\frac{\Delta\omega}{\Delta t} \tag{51}$$

$$Fstshp = \frac{I\omega}{2 * (Rstructure + 50) * \Delta t} \tag{52}$$

Now we have the expression of the tangential force of one Starship, but the Moment of Inertia of the whole system has to be determined. To ease the calculations, Starship has been considered to be a perfect cylinder with the same mass, diameter and length of Starship. Starships 1 and 2 are the outer Starships, and number 3 is the central. 1 and 2 are perpendicular to the axis of rotation, while number 3 is aligned. And the structure has been considered to be a long cylinder with the lenght of the two structures (one on each side) with the central ship in the middle.

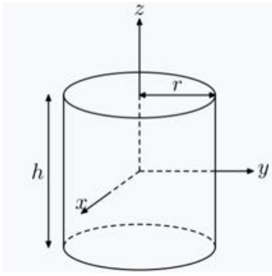
$$I_{TOTAL} = Istructure + 2 * Istshp_{1,2} + Istshp_3 \tag{53}$$

The cylinder for the structure has the axis of rotation passing through its middle:



$$Istructure = \frac{1}{12}Mstructure(2 * Rstructure)^2 \tag{54}$$

The cylinder for the central Starship (3) has its axis of rotation along the longitudinal axis of the cylinder:




$$Istshp_3 = \frac{1}{2} Mstshp * 4.5^2 \tag{55}$$

The outer Starships are not tangent to the axis of rotation, so to determine their moment of inertia we have to use the Steiner theorem of parallel axis. The theorem allows to determine the moment of inertia or the second moment of area of a rigid body about any axis, given the body's moment of inertia about a parallel axis through the object's center of gravity and the perpendicular distance between the axes. So we will determine a parallel axis to the axis of rotation that passes thorugh Starship's center of mass (which we will consider to be in the middle of the ship, at 25 meters form the tip). The formula of the Steiner theorem is the following:

$$I = I_{cm} + md^2 \tag{56}$$

Applying the formula to one of the outer ships:

$$Istshp_{1,2} = \frac{1}{12} Mstshp * 50^2 + Mstshp * (Rstructure + 25)^2 \tag{57}$$

Now we have the expression for the inertia for the center and outer ships, and for the structure. We only have to apply equation 53 to get the total moment of inertia of the system, and then put that value in equation 52 to get the tangential force.

## 8.3 Results of the Simulation

Once the code was finished, the final design point (or design points) had to be selected for the structure. As has been stated before, the input variables were the following:

- Number of bays
- Diameter of bars
- Diameter of cables
- Gravity level at Starship
- Duration of the angular acceleration
- Fuel percentage of Starship

For a given set of values for the input variables, the program returns:

- Factor of Safety (FOS)
- Radius of rotation (at Starship's lowest deck)
- Length of the Mast
- Angular Velocity
- Plot of the Stress of every element

Now, an explanation of every input variable wil be done to describe its range of possible values and discuss which would be the optimal value. The minimum value wanted for the Factor of Safety is 3, since the structure is critical for mission success and security we need a reasonable safety margin. But a FOS too high will elevate the costs excessively.

**Fuel percentage of Starship**

This one is pretty straightforward. The value can vary from 0 (a Starship without fuel) to 1 (a fully fueled Starship). The value chosen for the simulation is 0.5 as has been stated before. This value can vary between missions, depending on the destination, the desired trajectory, and other factors that can alter the amount of fuel after the acceleration burn to the destination. This is a calculation that would be given by the propulsion team for every mission, but for now 50% will be selected, since it is a good approach.

**Gravity level at Starship**

Starship is planned to have many decks, as shown in the figure 55. The variable is the value for the G that a person standing on the lowest deck would feel (22 meters below the nose tip). This is because if the value is set at the upper deck, the decks below would have a gravity level greater than 1g, and this is uncomfortable for humans. If 1g is selected at the bottom deck, the decks above will be feeling a little bit less than 1g, which is perfectly comfortable.

The minimum value for this variable would be about 1/6g, as it was mentioned in section 5.3.1, the study [14] found that less of that value makes it difficult for humans to establish a sense of up and down. The maximum value would be 1g.

Rotating artificial gravity has the advantage that it is possible to accelerate or decelerate the rotation to change the gravity levels. For example, in the trip to Mars, 0.4g of gravity could be set. Like this the passengers would be adapted to the low gravity at the martian surface. And for the return trip to Earth, it would probably be a good idea to select values close to 1g, so when the astronauts arrive back at home they are physically fit and perfectly healthy.

For the simulation I will select a value of 1g. Even though in some phases of the mission 1g would not be necessary, the structure should be able to resist 1g.

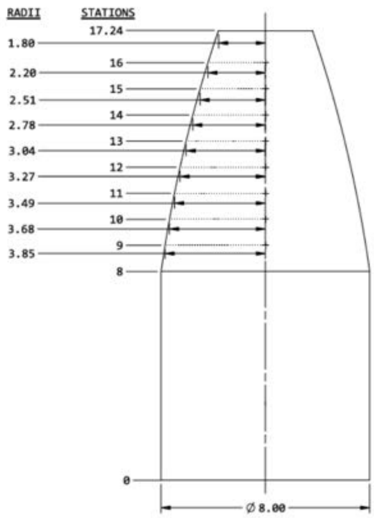



Figure 55: Starship distribution of decks. Image: SpaceX

**Duration of the angular acceleration and Diameter of Cables**

The value of the duration of the angular acceleration depends on many things. Its maximum and minimum value are imposed by the characteristics of the RCS of Starship (by its max and min thrust). But as I explained at the beginning of this section, it has been considered are considering that SpaceX would have to switch from their current RCS which has very low thrust, to a Methalox RCS, with higher thrust. There is not much information about Methalox RCS, since they have never been used before. After some research, it was found that 50 kN is the average value of maximum thrust. The minimum is harder to guess but for this case the thrust will be closer to the maximum so it is not critical to know the value of the minimum thrust.

If the acceleration takes a short amount of time, the passengers will be forced into their seats in an uncomfortable way, and they will experience an abrupt change in gravity. But it can not take too long either, since the passengers would have to sit down for a lot of time.

Due to the characteristics of the structure, the tangential force will directly affect the stress of the cables, while the axial force will affect the stress of the bars. So the duration of the acceleration is related to the other variable "Diameter of cables". We know that the minimum value of the FOS is 3, so we can try to establish which combination of duration of acceleration and diameter of cables gives values of FOS between 3 and 4.

It is needed that the diameter of the cable to be the minimum possible, like this it will be easier for the entire structure to retract. The minimum value of the diameter of the cables is 2mm (from the Certex website). If the diameter of the cables is set to 2mm, to get a FOS of 3, 2 hours of acceleration time are needed. This is not terrible, but seems a little bit too long. A good duration of the acceleration could be half an hour. This would require a diameter of 4mm for a FOS of 3. Which is a good value.

**Number of bays and Diameter of bars**

This two variables are linked. The more bays, the greater will be the centrifugal force and the greater will have to be the bars. Again, a FOS of 3 or more is the aim.

The maximum number of bays is 40, since that makes for a length of 80 meters of mast. The maximum stowing capacity of the mast is 1/20th of its max length and if the radius of Starship is 4 meters, then 4 times 20 is 80 meters. The maximum length of the mast would mean maximum comfort for the passengers, and the most Earth-like experience, but it would also rise the cost of the project significantly.

### 8.3.1 Final design points

As can be seen there are a lot of variables involved in the problem, and it is hard to choose an optimal value for all of them that would make the perfect Artificial Gravity structure. For this reason I am going to select three design points, with different approaches. One looking for maximum comfort, the other looking for minimum cost, and the other will be a point in the middle looking for a good compromise between cost and comfort. If this project was to become a reality some day, there would be the need for further research to determine the limits of comfort, and an economical study would also be required to set the correct values.

**DESIGN POINT 1 (Yellow Star)**

- Number of bays = 40
- Diameter of bars = 17 cm
- Diameter of cables = 4 mm
- Gravity level at Starship = 1g
- Duration of the angular acceleration = 30 min
- Fuel percentage of Starship = 50%
- Factor of Safety (FOS) = 3
- Radius of rotation (at Starship's lowest deck) = 102 m
- Length of the Mast = 80 m
- Angular Velocity = 3 RPM

Now the plot of the deformed structure will be shown. The color code shows the stress of every bar/cable.

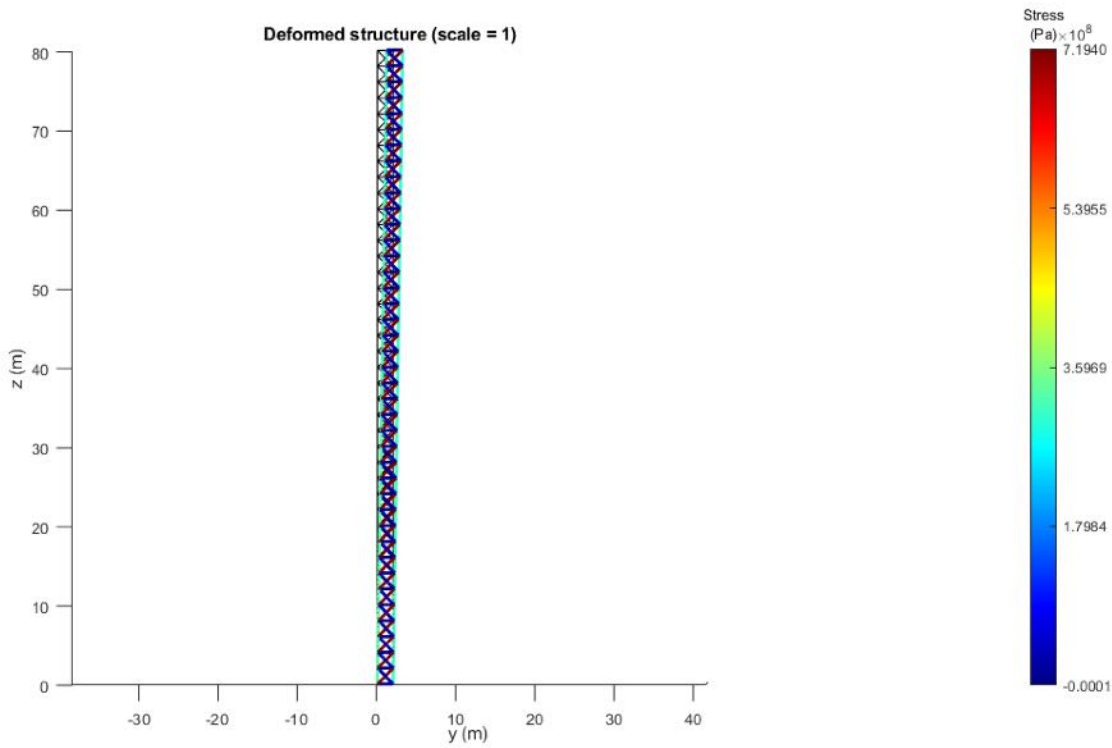



Figure 56: Plot of the deformed structure (2D).

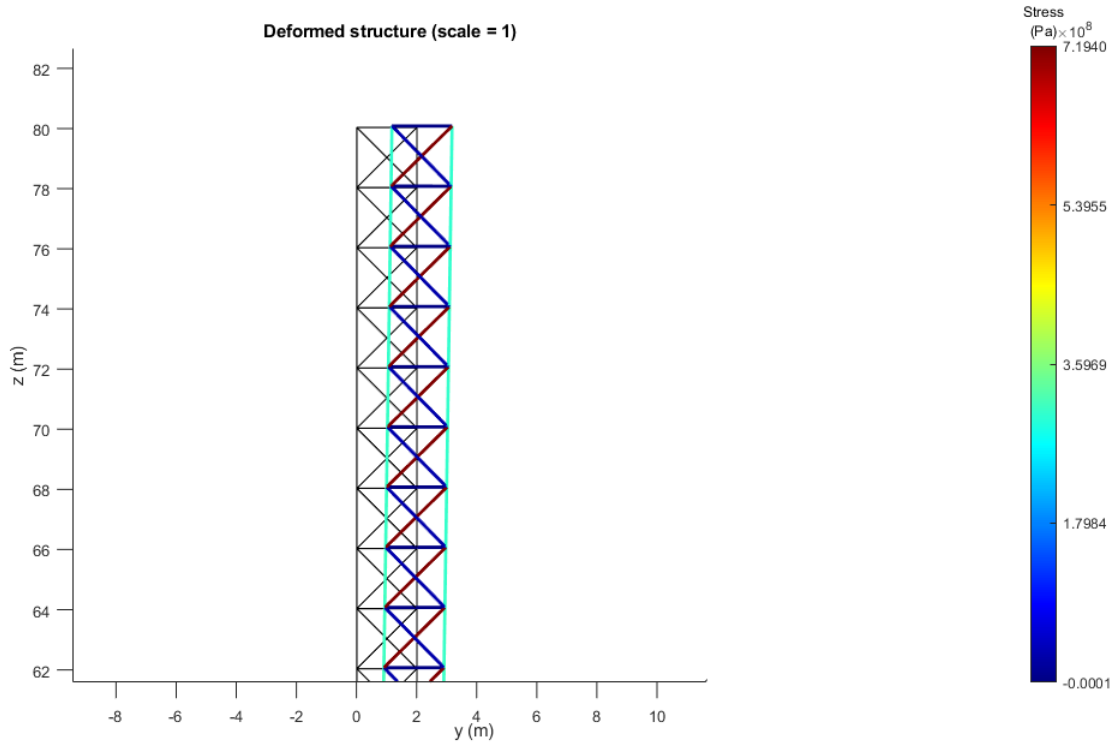



Figure 57: Plot of the deformed structure, zoomed to the last 20 meters of the structure (2D).

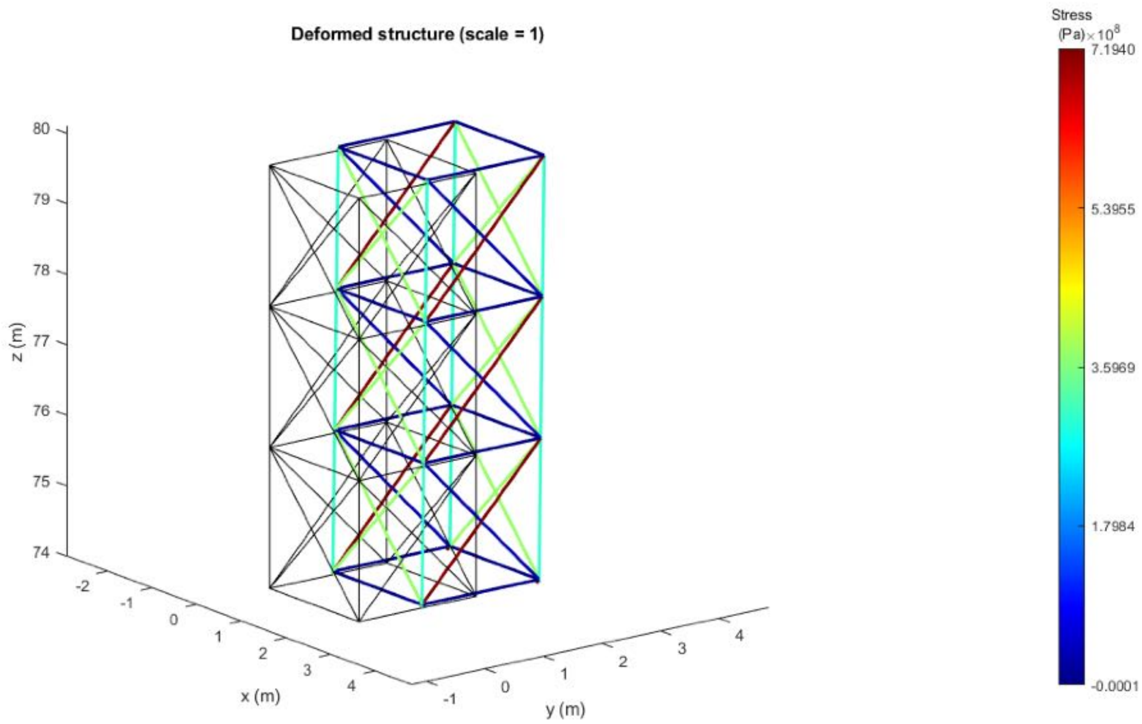



Figure 58: Last 3 bays of the deformed structure (3D).

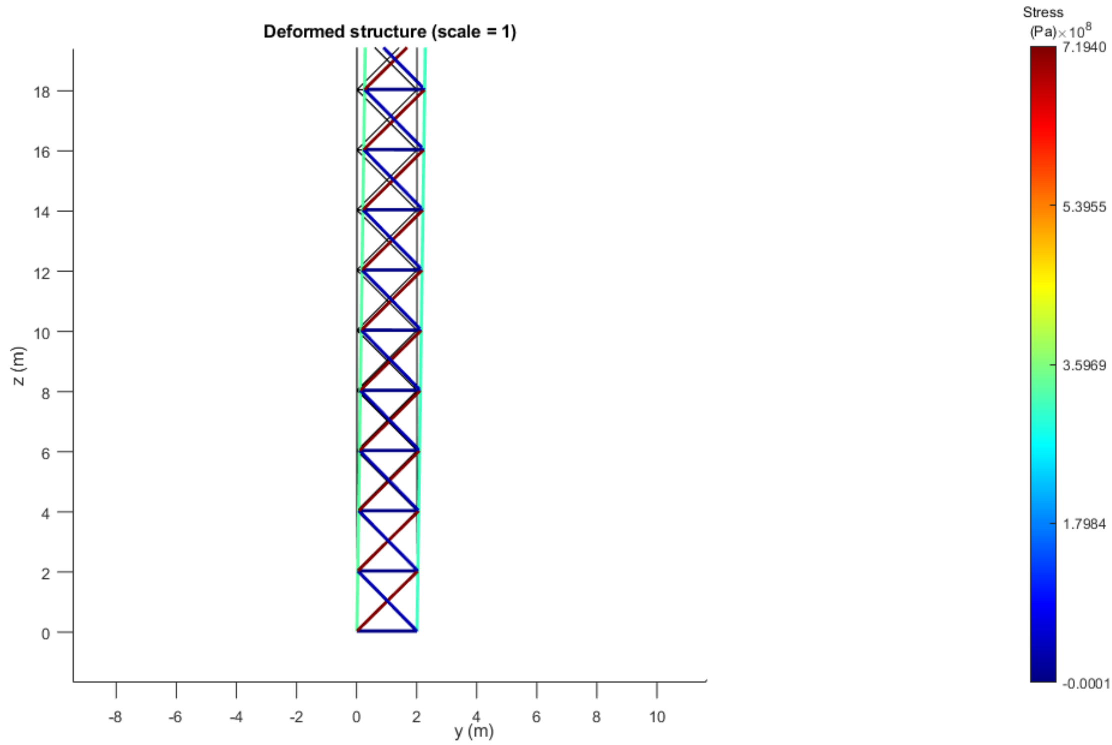



Figure 59: Plot of the deformed structure, zoomed to the first 20 meters of the structure (2D).

In the plots above we can see different views of the deformed structure. The maximum displacement for this case is 1.17 meters (1.4% of the total length of the mast), and it happens at the tip of the structure. In this case, the most stressed elements are the diagonal cables with a maximum stress of $7.2 * 10^8 Pa$. The factor of safety for the cables in this case is 3 meanwhile the FOS of the bars is 3.6, which are less demanded than the cables with a maximum stress of $3.3 * 10^8 Pa$. As we can see, the battens are the less demanded elements of the structure.

**DESIGN POINT 2 (Black Star)**

- Number of bays = 10
- Diameter of bars = 13 cm
- Diameter of cables = 3 mm
- Gravity level at Starship = 1g
- Duration of the angular acceleration = 31 min
- Fuel percentage of Starship = 50%
- Factor of Safety (FOS) = 3
- Radius of rotation (at Starship's lowest deck) = 42 m
- Length of the Mast = 20 m
- Angular Velocity = 4.6 RPM

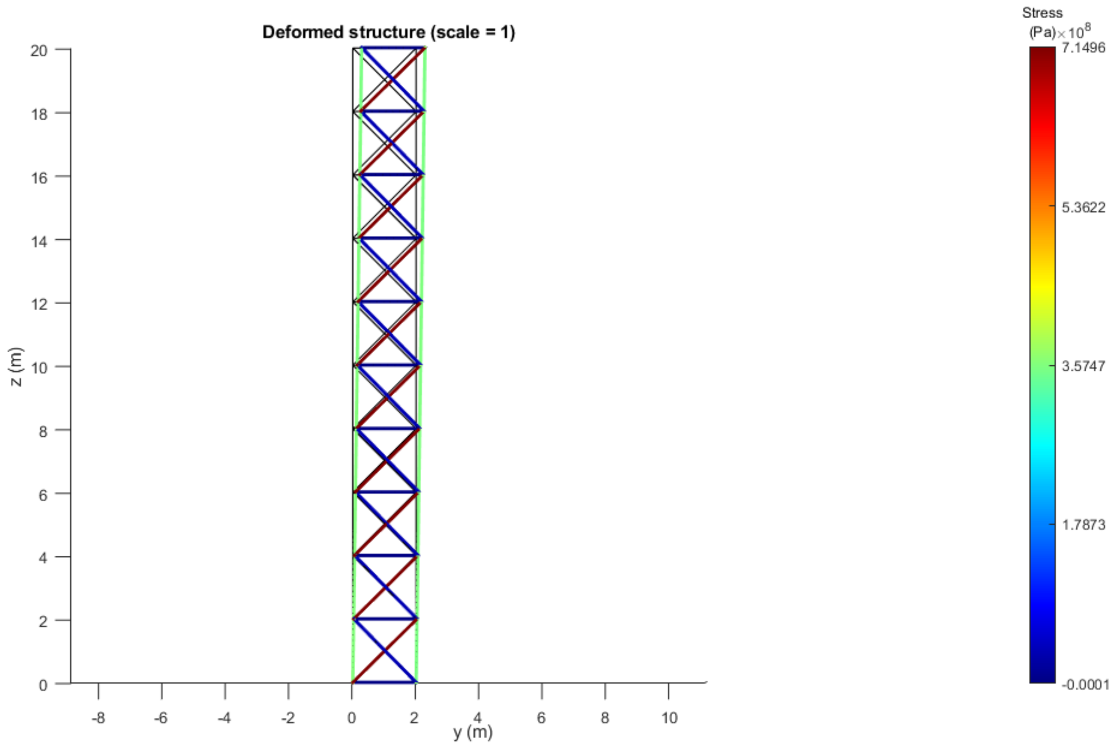



Figure 60: Plot of the deformed structure (2D).

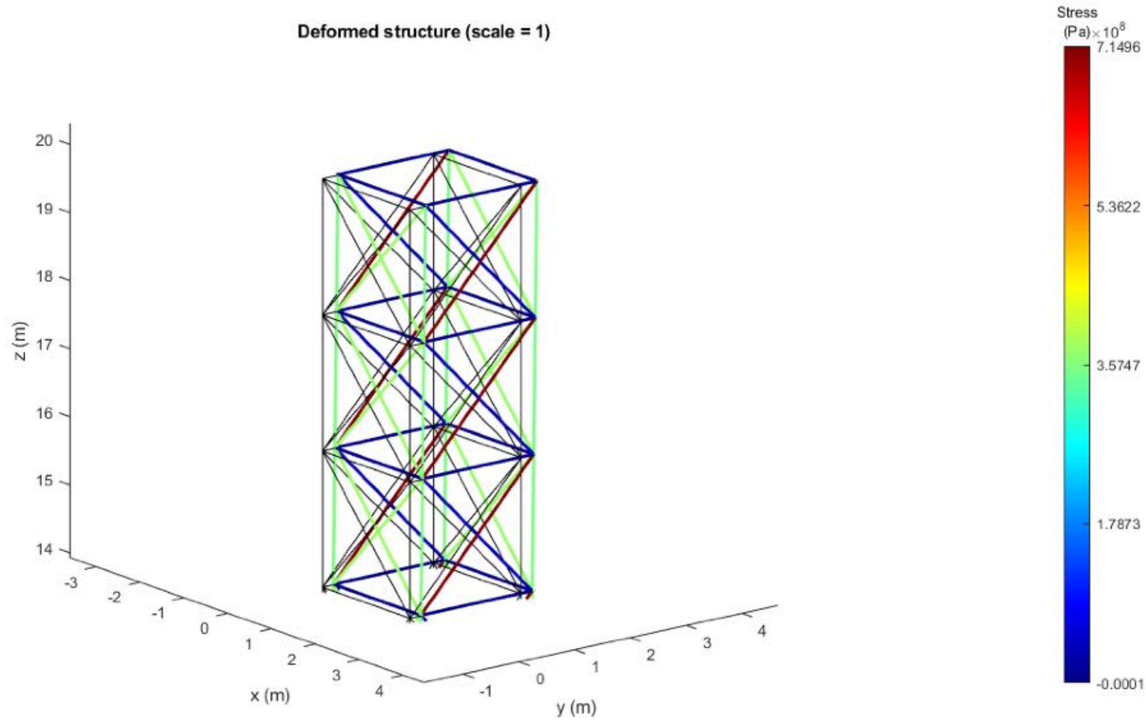



Figure 61: Last 3 bays of the deformed structure (3D).

As one can see, the displacements for this structure are significantly smaller than in the first case. The maximum displacement here is 0.28 meters (again, 1.4% of the total length of the mast). In this case, the cables are the most demanded elements also with a FOS of 3, compared with the FOS of 3.3 for the bars.

**DESIGN POINT 3 (Blue Star)**

- Number of bays = 30
- Diameter of bars = 15 cm
- Diameter of cables = 4 mm
- Gravity level at Starship = 1g
- Duration of the angular acceleration = 27 min
- Fuel percentage of Starship = 50%
- Factor of Safety (FOS) = 3
- Radius of rotation (at Starship's lowest deck) = 82 m
- Length of the Mast = 60 m
- Angular Velocity = 3.3 RPM

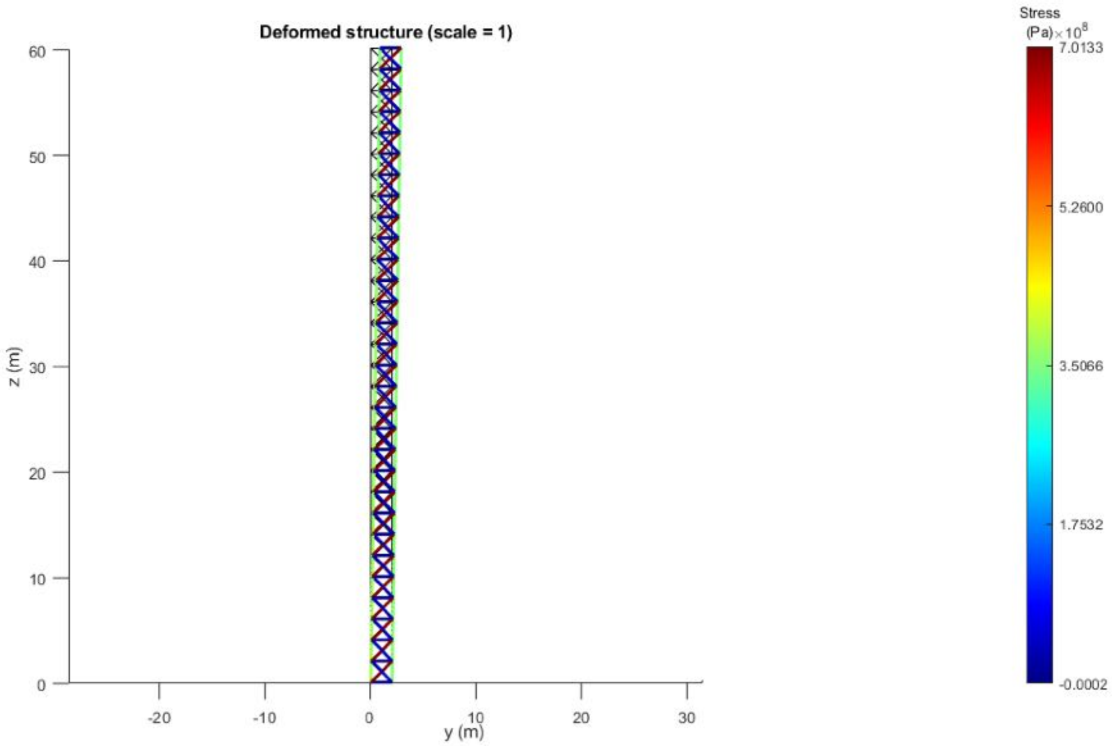



Figure 62: Plot of the deformed structure (2D).

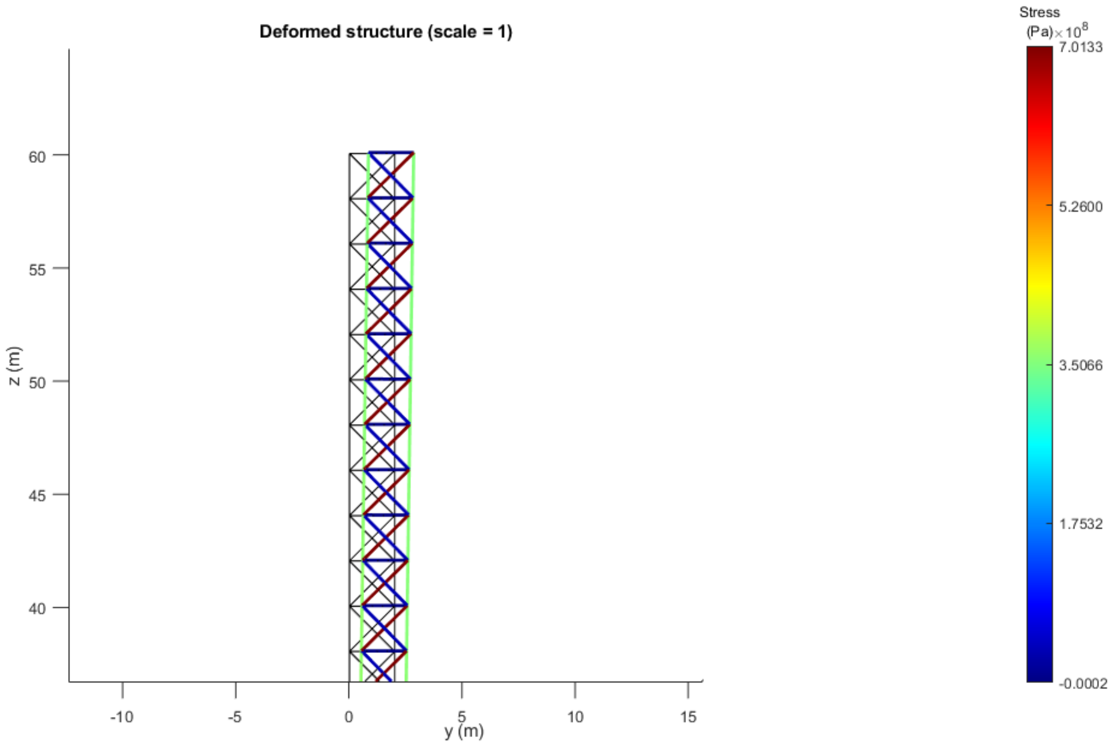



Figure 63: Plot of the deformed structure, zoomed to the last 20 meters of the structure (2D).

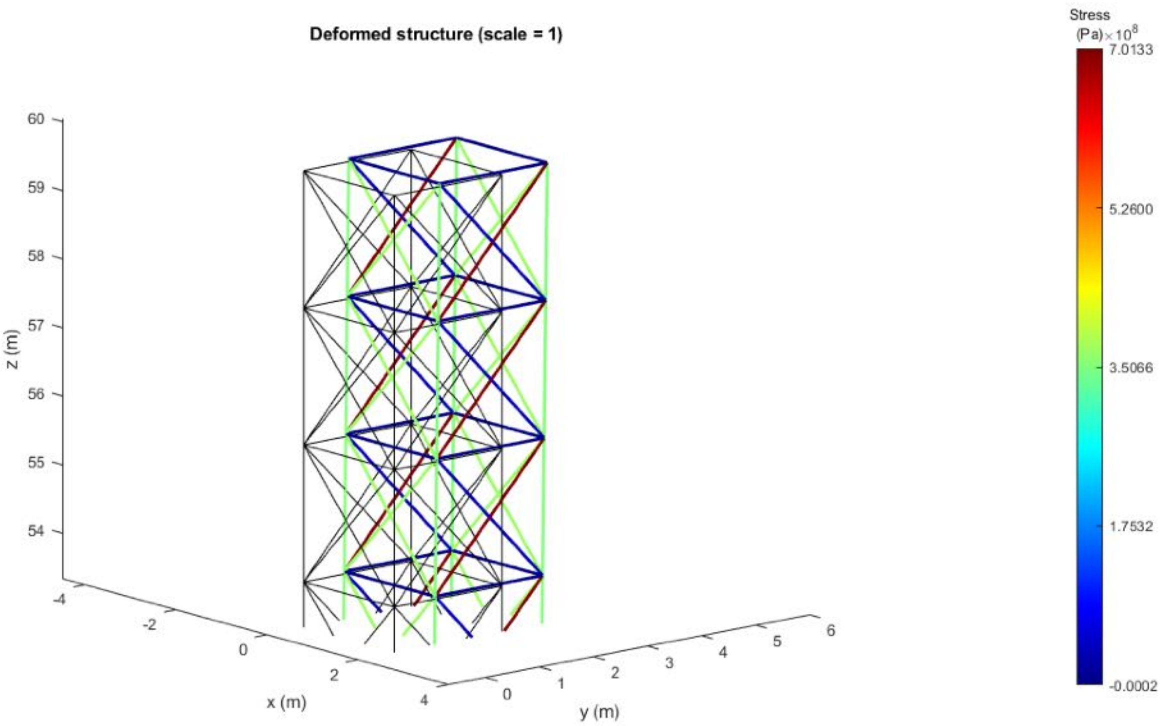



Figure 64: Last 3 bays of the deformed structure (3D).

This structure is 60 meters long, the exact same length of the original ADAM mast. Compared to ADAM, this one is wider 2 meters in size, and has wider bars. The maximum displacement for this case is 0.84 meters (as happens in the last two cases, 1.4% of the total length of the mast). Notice that if we aim for a FOS of 3 for the cables, the maximum displacement remains at 1.4% of the total length for any given length of the mast. Again, the most demanded elements are the cables with a FOS of 3. The FOS of the bars is 3.3.

**Artificial Gravity design chart**

Now, the three selected points are going to be represented in the artificial gravity design chart explained in section 5.3.1. This chart shows the rotational radius vs. the angular velocity of the structure and sets regions for the comfort zones according to the research studies about how humans deal with rotation.

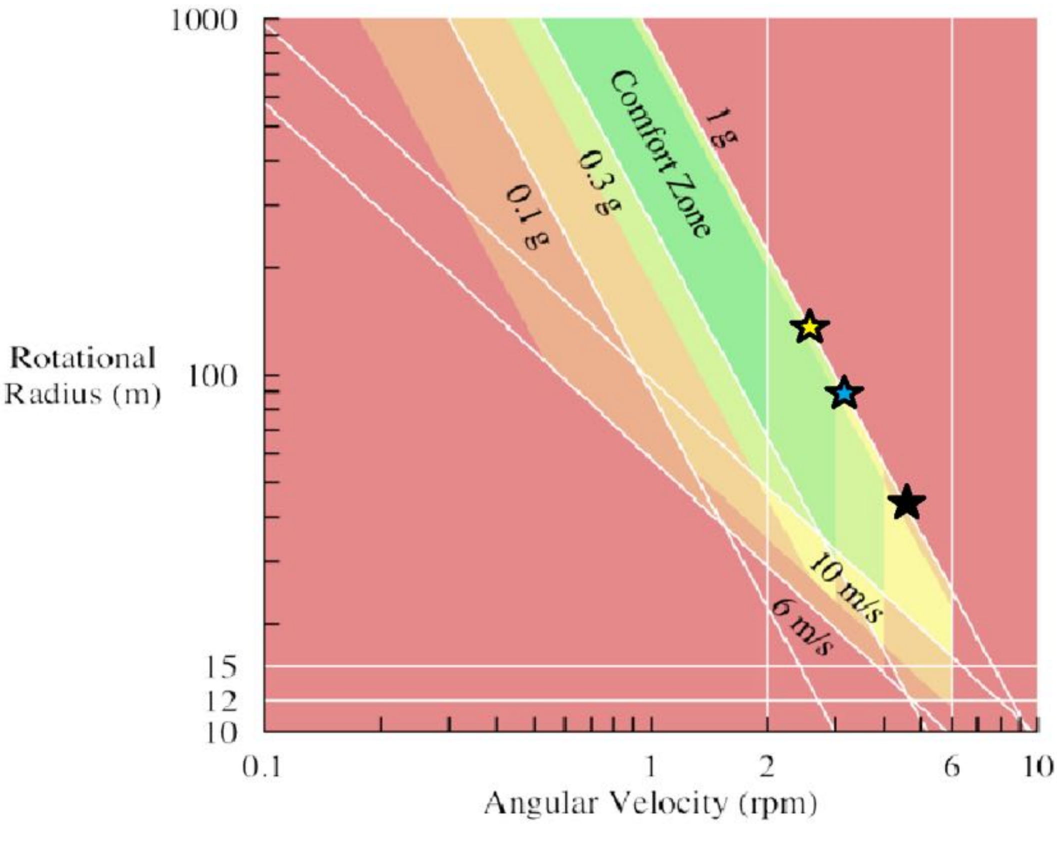



Figure 65: Three design points represented in an Artificial Gravity comfort display chart. Chart taken from [8].

As can be seen in the graphic above, the three design points are over the line of 1g of acceleration. The yellow star represents the point that offers more comfort. It is still not in the maximum comfort zone. This is because complete Earth-like experience with no need of adaptation time occurs below 2 rpm. I must note that if the level of gravity was 0.38g (Mars gravity), for a trip to Mars, the design point would be well inside the maximum comfort zone. 3 RPM is still a good value and requires little adaptation time according to research.

The blue star represents the third design point. It is slightly into the light green zone (above 3 rpm). This means that the passengers would require a little bit more adaptation time, but in a 6 months trip it would be worth to feel a little slightly sick for some hours to get gravity for the long journey. If the level of gravity was set at the martian gravity, the structure would still not be in the max comfort zone by a bit, but it would be in the green zone below 3 RPM.

The black star represents the minimum cost option, this one offers low comfort for the crew. It is in the yellow zone of the chart, over 4 RPM indicating that the time it would require the passengers to adapt could be long, some of them may not be able to adapt at all. This option would be good if the Starship is crewed by trained astronauts in the first crewed missions to Mars. If this structure were to be chosen as the final design it would be wise to not accelerate to 1g during the long trip, to stay below 4 RPM.

# 9 Environmental Impact

The environmental impact of this project is relatively low. The main negative impact would come from the manufacturing of the structure itself, the emissions related with the production of the materials. The engineering hours and the necessary energy to run the computers and the offices would also play a part.

Taking the whole Starship project into account, this modification adds low emissions comparet to how it would be in the first place. Yes, it will require one more launch for every two Starships, and this means more CO2 to the atmosphere. But rocket emissions suppose a marginal percentage of global CO2 emissions.

# 10 Budget Analysis

This project focuses on the technical viability of the proposal, but it also looks to reduce the costs of the project and the extra operational costs for SpaceX if it would become a reality.

Starship is set to be the cheapest rocket to ever fly. When it starts scale production, SpaceX has stated that the cost per kg to orbit could be as low as 20 to 30 $ per kilogram. This would be a revolution for the space industry making space accessible for many people or companies. As a comparison, the Space Shuttle had a cost per kg to orbit of 5000 $ per kilogram. This means that carrying the mast for Starship's gravity to space would cost about 620000 $ (Given that the mass of a 60 meter mast is 15500 kg, and Starship would carry 2 of them). Comparing this to the cost of launching ADAM in the Space Shuttle, ADAM's mass was 4000 kg, and the Shuttle would carry only one. This means that the cost is 20000000 $.

A part from the reduced launch costs thanks to Starship, the cost of engineering and manufacturing the mast would be reasonable, since the technology to develop such a mast has already been proven. There are facilities in the US where this mast could be constructed and this would also reduce the logistics cost.

# 11 Planification of the next phase

The next phase of the project would start by performing a deeper structural analysis about the mast. It would be necessary to simulate more precisely how the mast would retract and deploy, and how it would endure long operations of months or maybe years resisting the forces of artificial gravity and the roughness of the space environment. It would also be necessary to determine the nature of the joints of the structure and the docking system with Starship.

A part from further studying the mast, the next step would be studying the changes that Stasrship would require in order to make the system functional. Maybe a reinforced nosecone to resist the force of artificial gravity. The redesign of the RCS that was explained during this project. It would be interesting to analyse if the current RCS are enough for the angular acceleration or if they would need to bee re-engineered.

# 12 Conclusion

Artificial Gravity has a place in the future of space exploration. Its importance in future missions will be critical if we want to be in space for long periods of time. Missions like asteroid mining, planetary and lunar colonies, big space stations derive from the growth predicted for the industry in the near future. It is a good time to do space science and engineering. Companies will be willing to spend money in new technologies to improve habitability and comfort for space, because nowadays space is uncomfortable. If the number of people going to space will rise to historical records in the coming years, space can't be uncomfortable. Spacecrafts should feel like home away from home.

One of the companies that is set to be the giant in the space industry is SpaceX. They have an extraordinary vision and extremely ambitious goals. If things go their way and they achieve the goal of transporting hundreds of ships to Mars to start a colony, they will need to have artificial gravity solved.

With this proposal I have tried to solve the problem in the easiest possible way for SpaceX, minimizing the changes to the current design of their ship, and using technology that is available today and that it has been used in space before (ADAM Mast). Bringing this concept to reality would certainly be a challenge for SpaceX, and they would need support from NASA and other entities (NASA has used deployable space booms before). But SpaceX and NASA are not competitors, they have demonstrated that they work together very well. NASA has financed SpaceX with their contracts to resupply the ISS, they have given technological advice and SpaceX would not be where they are today without NASA.

Further research on how the human body reacts to artificial gravity would be needed if this project was to become a reality. Deeper analysis on how passengers would feel, what movements they could or could not do, etc. The interior design of Starship would also have to be re-considered. For example, the floor of the decks would have to be slightly curved so the body of the passenger is always aligned with the centrifugal acceleration.

Finally I have to state that this project is not thought for the present of SpaceX, but for its (hopefully) brilliant future. Starship is still under construction and testing, but it looks very promising. Even though this project is not for the today, we must start now to create the technologies that will change the future. Like the famous quote from Abraham Lincoln says: *The best possible way to predict the future is to create it.*

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