



Humanity and Space

Societal and Technical Challenges of a Martian Colony

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Abstract

Space exploration has provided many benefits to humanity and has the potential to continue delivering technological advancements to society. In this paper, a rationale for human space exploration is presented that includes preserving the human species, developing innovative technologies that are applicable to Earth, and increasing our understanding of the universe. The technical challenges of establishing a Mars colony are evaluated, and solutions are proposed to overcome these obstacles in order to provide recommendations for the future colonization of Mars.

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1. Executive Summary

Space exploration has had a profound impact on humanity, an influence that is often overlooked or understated by scientists, engineers, and civilians. This IQP works to understand the relationship between humanity and space through identification of space travel's extensive past and future benefits, in order to provide a rationale for this endeavor. Space travel has directly and indirectly produced many innovative technologies that have improved life on Earth, and it holds vast potential benefits that may save humanity in the future. A human colony on another planet would ensure the survival of the human species in case of an event that destroyed Earth, such as the asteroid that altered Earth's climate and led to the dinosaurs' extinction. Specifically, Mars provides a reliable site for colonization because of its similarities to Earth and the availability of resources that can be extracted and used to sustain humans, such as oxygen, water, and methane. A station on Mars would also provide a gateway to exploring the outer planets such as Saturn and Jupiter, other stars, and potentially exoplanets. Traveling to Mars would provide a deeper understanding of the universe we live in and teach us about Mars' potential for life, and thus the potential for life outside our solar system.

After evaluating the benefits human space exploration provides, this paper focuses on the primary technical challenges that must be overcome for Mars colonization, including radiation exposure, food and water, low gravity, and Mars robotics. Radiation is one of the most significant obstacles for long-term human space exploration, but may be mitigated with methods such as passive shielding, active shielding, and human gene alteration. Food and water production on Mars is another challenge for Mars colonization, as enough food and water cannot be brought from Earth to sustain a large human colony. This paper explores the challenges plants may face on the Mars surface and proposes innovative ways to overcome these obstacles. Lower gravity on Mars poses a challenge for humans, systems, and plants, but studies are being performed in space and on the ISS that can lead to potential solutions, such as artificial gravity. Robots will greatly help a Martian colony; however it is critical that the integration of robots and humans is properly utilized to leverage the talents of both in an advantageous manner.

An evaluation of potential locations for a Mars colony is then performed for areas that may be a suitable outpost location. Finally, recommendations for future work are proposed to continue overcoming the societal and technical challenges of a Mars colony.

2. Introduction

Space exploration has provided humanity with great benefits which justify the time, effort, and risk that has been invested. This IQP will identify and evaluate these advancements in order to justify why space exploration is important to society. In the last century, deploying space systems has advanced the quality of human life in many areas, such as in human health, weather predictions and disaster response, and various innovative technologies. The demanding nature of space exploration requires top-tier developments and innovations that are more environmentally friendly, longer-lasting, more reliable, and more self-sustaining than current systems on Earth. This push for new technologies, which has been driven by the desire to discover our universe, has led to the development of innovative technologies that have potential applications on Earth.

Informing the public of the vast benefits space travel provides is essential to gaining their interest and approval, which is ultimately what provides the money and resources to pursue space missions. As we explore the past benefits space travel has had on humanity, potential benefits an extraterrestrial colony would bring, the challenges associated with this feat, and potential solutions for these challenges, we will better understand the technical and societal impacts of an extraterrestrial colony on society, both positive and negative. This interaction between science, engineering, technology, and humanity makes this an excellent IQP topic, as it evaluates the ways in which these different areas interact to affect society.

As an aerospace engineering student who is deeply passionate about the advancement of human space exploration, particularly the mission to Mars, one of the most common questions I am asked is “why explore space?” Truthfully, I have always had a difficult time answering this question beyond the justification that it is intriguing and interesting to me. Justifying even to myself why human space exploration is necessary and why the work I do every day is valuable has always been a challenge. This IQP has given me the opportunity to further understand the tangible and potential benefits that space exploration provides. This has allowed me to gain an understanding of why this work is important and why the general public should care about space travel. Bridging the gap between my technical work and the effects it has on humanity has enabled me to become a more well-rounded engineer.

3. Benefits of Space Travel to Humanity

3.1. Human Health [1]

Technologies developed for applications on the International Space Station (ISS) have led to advancements in medical fields on Earth. NeuroArm is a medical technology that enables the completion of surgeries previously thought to be impossible and makes difficult surgeries easier. More precise and tremor-free than the human hand, NeuroArm has saved many lives by successfully performing brain surgery and other operations that were too difficult for doctors. Another medical technology arose from the Eye Tracking Device experiment, which studied how humans' reference frames are altered in space with the absence of gravity. This device is now used on Earth to track the eye's movement during laser eye surgery, which has led to surgical improvements. NIOX MINO® controls and monitors nitric oxide levels for humans living in space, which is essential because elevated levels can cause inflammation of the airways, decompression sickness, and other adverse health effects. Nitric oxide is also an important indicator for people with asthma, and monitoring nitric oxide levels can help provide more accurate dose requirements, leading to fewer asthma attacks and a better quality of life. Technology from NIOX MINO® was utilized to monitor asthma patients' nitric oxide levels and minimize their attacks.

3.2. Earth Observation and Disaster Response [1]

The ISS monitors environmental conditions all over the globe to help resolve environmental problems that threaten our planet. RapidSCAT measures the ocean's surface wind speed and direction, and this data is used for determining weather patterns and performing weather predictions. The Cloud Aerosol Transport System (CATS) takes vertical profiles of the clouds and aerosols in our atmosphere. Clouds and aerosols are significant in the way that they reflect the sun's radiation differently, and more knowledge about how these clouds and aerosols exist in the atmosphere allows us to better model the atmosphere, climate, and air quality of Earth.

Water resupply is not an option for long-term space travel, so water must be cleansed and recycled in space. In 2006, the first NASA ground-based water filtration system was put in Iraq in a town that had no access to clean drinking water. A 2000-liter water tank was delivered to the village and was cleaned and iodinated regularly. Similar systems have been used in India,

Mexico, Central America, and South America that have provided clean water to these developing areas.

3.3. Innovative Technology

There are other space technologies in development with potential applications on Earth. Robotic systems are being developed to perform mining, determine composition of the atmosphere and regolith, and discover other important features. These autonomous systems have the potential to improve life on Earth and reduce exploration risks by automating processes and performing dangerous excursions, such as exploring sites of radiation accidents, gas leaks, or other dangerous areas where human health could be at risk.

In addition, power systems need substantial improvement to become sufficient for a Mars mission. Power methods that utilize fuel with a limited supply are not an option for space systems; therefore, scientists and engineers are forced to develop more viable power solutions. Specifically, for human exploration missions, the power systems for long-term habitats, rovers, and other systems have to be designed to be robust, self-reliant, and long-lasting. Earth systems will soon need to shift towards these more sustainable power methods as time progresses and finite resources diminish. Learning how to produce more efficient power for space systems can help improve the power systems on Earth, such as car batteries, by making them more environmentally friendly, longer-lasting, more reliable, or more self-sustaining. Similarly, systems deployed to space have to be extremely reliable since astronauts will have limited tools, time, and knowledge to make critical repairs. Specifically, planetary systems often will need to remain dormant for long periods of time, withstand significant radiation and micrometeorite orbital debris (MMOD), and function without being regularly serviced. The progress and solutions made through overcoming these challenges for planetary systems can be applied to systems on Earth, such as cars and airplanes, to make them more reliable.

4. Benefits of Mars Colonization

Establishing a human presence on Mars is an expensive and time-consuming endeavor that comes with many benefits, risks, and challenges. In order to justify spending the time and money to pursue this feat, the benefits should have a significant impact to people on Earth. Three of the primary benefits of a Mars mission include utilizing Mars as a backup planet safe haven to ensure the survival of mankind, developing technologies that can be used to improve the quality of life on Earth, and gaining a better understanding of the universe based on the chemicals and potential lifeforms found on Mars.

Mars is the most Earth-like planet in our solar system. It has a similar length day to Earth, an atmosphere that provides some protection against radiation, an adequate amount of sunlight to harness for energy, and a relatively moderate temperature range. Most importantly, Mars has resources that humans can utilize to live on Mars for long periods of time. The Martian atmosphere is composed of 95% carbon dioxide, as well as smaller amounts of nitrogen, argon, oxygen, and carbon monoxide [2]. Although humans cannot breathe this chemical composition, these elements are also found on Earth and can be turned into breathable air. MOXIE (Mars Oxygen ISRU Experiment), which will be on the Mars 2020 rover, will take carbon dioxide from the Martian atmosphere and turn it into oxygen that can be used by future astronauts [3]. It is a 1/100 scale model of what one day may be deployed to Mars to produce breathable air [4]. In addition, water has been proven to exist on Mars. Studies and projects are being pursued that strive to develop autonomous systems that can extract this water from the Martian soil. Since water is such an important element to the survival of mankind, an environment with water is crucial to attaining Earth independence and sustaining a human colony on another planet.

Similarly, the presence of methane on Mars makes it suitable for in situ resource utilization (ISRU) propellant production. Methane and oxygen can be produced from Martian carbon dioxide and hydrogen to be used for LOX/Methane propellant [5]. This will enable astronauts to leave Mars and travel back to Earth or to other destinations in space without having to bring as much propellant from Earth.

4.1. Ensure the survival of the human species

As the fate of Earth becomes increasingly unknown, having a second planet to escape to may become necessary for the survival of humanity. Earth may be destroyed by events such as an asteroid hitting Earth, nuclear war, a global pandemic, overpopulation, boiling of the Earth's oceans, or a massive fire. Similarly, an event may occur that damages the genes of the human species or animal population, and having a DNA bank on Mars may be critical to restoring the damaged or destroyed areas of Earth. The sun's solar flares could also cause the Earth's destruction, as they have already knocked down power grids and communication networks, destroyed electronic devices, and increased radiation dose amounts for airline passengers. These are just some examples of catastrophes that may occur to Earth, which is why a backup planet is advantageous and necessary. Becoming a multi-planet species will help ensure the long-term survival of the human population.

4.2. Gateway to exploring the outer solar system

Mars is in a premier location to observe and explore the outer solar system, as Mars is relatively close to Jupiter, Saturn, and the other outer planets. In addition, Mars is very close to the asteroid belt, so putting a telescope or base on Mars would allow for great astronomical observations. Moreover, spacecraft could be deployed from Mars to explore the asteroid belt, which could facilitate the use of asteroids for resources. Mars is a gateway to exploring these outer planet gas giants and eventually leaving the solar system.

4.3. Understanding the origin of the universe and discovering life on Mars

Another critical reason to explore Mars is to better understand the universe by determining Mars' potential for life, learning about its current and ancient climate, and discovering its geology and geophysics [5]. Mars is the most probable location that scientists believe may sustain life. If life is proven to exist on Mars, it would greatly change how humanity views our world and the solar system, as the possibilities would be endless for what exists in the universe. If humans are serious about fulfilling the desire to know more about the world in which we live, a Mars mission is the clear-cut next step to uncovering the truth of our solar system and the universe.

4.4. Technological advancements that improve the quality of life on Earth

Technological advancements have greatly improved the quality and productivity of life on Earth. Computers are a primary example of a technology that has revolutionized society, as they allow people to perform calculations and acquire information more easily than any previous generations. For example, programs such as Maple and Matlab enable mathematicians and scientists to execute calculations rapidly, whereas primitive calculators were the primary method for calculations less than a century ago. Similarly, libraries and books were necessary to gather information, and now information can easily be accessed by simply typing a question into a cellular phone. In addition to scientific uses, robots now assist humans with chores, such as the Roomba which can clean households. Helping humans with monotonous tasks, such as cleaning, has led to increased time for more analytically challenging tasks that only humans can accomplish.

5. Technical Challenges

5.1. Mars Habitat

The Mars habitat is one of the most important systems for a Mars mission, as it is what will sustain the crew for hundreds of days on the Martian surface. During this time, it will be exposed to harsh Martian surface conditions and will need to survive micrometeorite orbital debris impacts and high radiation levels. There are several methods being considered to protect against MMOD. One of these methods suggests using bulletproof Kevlar as a sacrificial wall by placing it between the outer wall and the spacecraft so the actual spacecraft will not be damaged [7]. Although this works, it is not practical in the long-term because after a shield is damaged its ability to shield the spacecraft is compromised. A similar study looked at a thermal and micrometeorite protection system for an unmanned lunar cargo lander, which utilized a multilayered thermal insulation blanket [8]. This blanket has layers of Mylar, which act as a bumper wall to dissipate MMODs. The needed thickness of this MMOD protection blanket can be calculated [8]. First, the diameter of a one-gram micrometeorite can be found, using a micrometeorite density of 0.5 g/cm^3 :

$$D_m = 2 * \sqrt[3]{\frac{3m}{4\pi\rho}} = 2 * \sqrt[3]{\frac{3 * 1\text{gram}}{4\pi * \frac{0.5\text{g}}{\text{cm}^3}}}$$

$$D_m = 1.56 \text{ cm}$$

The bumper thickness for aluminum can be calculated by:

$$t_b = 0.04 * D_m = 0.04 * 1.56 \text{ cm}$$

$$t_b = 0.0625 \text{ cm}$$

This bumper thickness of 0.0625 cm gives a mass per unit area of 0.175 g/cm^2 for aluminum. However, MLI protects as well as aluminum, but has only 13.3 percent of the mass per unit area. This gives a MLI bumper thickness of 0.023 g/cm^2 , equating to a bumper thickness of 2.3 millimeters [8].

A newer technology currently being developed is a self-healing shield, which is a multilayered shield that uses a liquid monomer between two solid polymers [9]. After being

punctured, this middle liquid layer of the shield flows into the gaps and solidifies due to an interaction with oxygen [9]. One specific example of this self-healing shield uses polyethylene as the middle liquid layer [10]. Polyethylene was considered as a potential heat shielding material since ancient times, but was not used because it liquefies in the ablation process. This liquefaction can be beneficial for repairing damage from MMODs, as polyethylene is an ideal material for the middle liquid monomer layer of the shield.

Radiation

The crew's exposure to radiation is another major concern for a long duration human space exploration mission. Normally the Earth's magnetosphere protects the Earth from radiation, but interstellar space lacks that protection. There are two types of radiation that can threaten astronauts and equipment. Galactic cosmic radiation (GCR) consists of ionized atoms coming from outside the solar system that emit a constant background radiation. This will not harm astronauts immediately, but rather will build up and cause problems if exposed to for long periods of time. Solar particle events (SPE) are the second type of space radiation, which consist of solar particles produced by the sun during solar flares. If exposed to this, astronauts would likely immediately acquire radiation sickness that could kill them. Although deadly, solar particle events can be detected, do not happen frequently, and would likely only last for a few hours. They are also much easier to protect against with simple radiation shielding methods, so astronauts could hide in a shelter until the event passes. Contrarily, GCR radiation poses less immediate danger, but is deadly if built up over time, and it is much more difficult to protect against.

In order to preserve astronaut health, NASA standards limit radiation exposure to a 3% REID (Risk of Exposure Induced Death) value based on gender and age [9]. A 3% REID value means that astronauts cannot be exposed to an amount of radiation that would make them greater than 3% more likely to develop cancer as a result of the radiation exposure. Galactic cosmic radiation levels are about 0.67 mSv and 1.8 mSv per day on the Mars surface and in interstellar space, respectively. These radiation levels will not allow for a long-duration human space exploration mission according to NASA Health Standards, unless they are drastically mitigated.

Career Exposure Limits for NASA Astronauts by Age and Gender*				
Age (years)	25	35	45	55
Male	1.50 Sv	2.50 Sv	3.25 Sv	4.00 Sv
Female	1.00 Sv	1.75 Sv	2.50 Sv	3.00 Sv

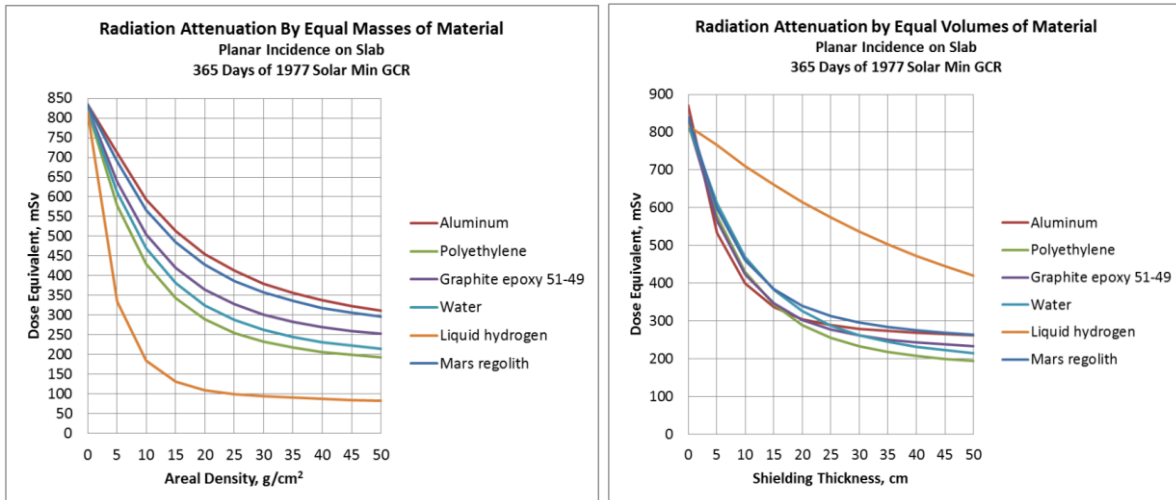
There are several passive radiation protection methods that could help reduce radiation dosage given to astronauts and the systems. Polyethylene has a high hydrogen content, which is effective for deflecting radiation. It is a lightweight fabric, which makes it a good option for spacecraft that need to minimize mass and have complex shapes [12]. RFX1 is a specific type of polyethylene composed of lightweight carbon and hydrogen atoms. It is 50% and 15% better at shielding SPE and GCR than aluminum, respectively [13].

Water is another material that is very effective at shielding radiation. It has a high hydrogen content and is relatively dense and cheap, but it is much heavier than polyethylene. Unlike polyethylene which would primarily just be used for radiation shielding, water has many other applications so contingency water can be used to make a radiation shield. Moreover, lunar or Martian water produced through ISRU production could be used for shielding, which would reduce the water mass launched to Mars.

Regolith can also provide protection against radiation, which would be beneficial since it is already on Mars. However, a great deal of regolith would be needed to provide adequate radiation protection, so robots to move the regolith would be needed. Researchers are currently searching for a polymer binder to combine with regolith for a thinner radiation shield [14]. In this case, only the polymer would need to be launched from Earth for the radiation protection.

An innovative idea is to use plastic packaging from recycled trash to make tiles that will shield radiation. NASA Ames developed a compactor that turns a day's garbage into an 8-inch diameter tile half an inch thick [15]. It compresses the trash to at least ten times smaller than its original size, and the high hydrogen content provides a good radiation shield. This would help solve the radiation exposure problem, as well as provide a use for trash. However, it may be difficult to bring the compactor to Mars and to make it operate properly in the Martian environment.

Below is a set of graphs that compare different radiation shielding materials by areal density and shielding thickness, respectively [16]. Polyethylene, water, and regolith all provide comparable radiation shielding, so a material should be chosen based on what is most convenient for the mission.



Finding or formulating astronauts who are more resistant to radiation is also being considered. Potential astronauts can be tested and chosen based on who is more genetically predisposed to radiation. In addition, techniques to modify and improve the human ability to handle radiation may also be used, such as genetic editing, gene therapy, cryopreservation, and biobanking [17]. There is also research being done to develop medications that can reduce the effects of radiation [18]. For example, the University of California, San Francisco found a drug, PLX5622 developed by Plexxikon, that can be used to mitigate memory loss from cosmic radiation [19]. PLX5622 was tested on mice and proved effective; mice exposed to radiation that received the drug did not show cognitive deficits, while the control group did [19].

Active radiation shielding is another method that could protect a Mars colony. Active radiation shielding creates an electromagnetic field around a spacecraft or habitat to protect from radiation like Earth's magnetosphere [20]. Rather than mitigate the impact of radiation, the field diverts particles so that they never hit the spacecraft. A key aspect of this concept is making sure the field can divert the particles, but also not harm the astronauts. Electrostatic shielding creates a large electric field around a habitat. It is relatively lightweight, and there are no major physiological issues from humans in electrostatic fields. However, their voltage is limited, which

limits the energy level of particles that can be deflected. Magnetic shielding generates a large magnetic field around the spacecraft, which produces no current and can protect against all radiation levels. Unfortunately, negative physiological affects exist for humans in strong magnetic fields. To counteract this, the design would have to contain a “habitable area” within the magnetic field where the field is weak so that astronauts could live in that area. Plasma shielding consists of a mass of ionized particles in electromagnetic fields that deflect charged particles. This shielding is the most lightweight and uses the least power; however, it is still in the experimental phase and needs significant research and testing before it could be considered for a Mars mission.

5.2. Food and Water

Previous human space exploration missions have been short in duration or close to Earth, which eliminated the need for long-term independent food and water solutions. Trips to the moon only lasted about a week, so adequate consumables could be brought in the spacecraft without adding too much mass. Although astronauts live on the ISS for long durations of time, it is close enough to Earth that it can be resupplied with food and other necessities several times per year. Contrarily, a crewed mission to Mars would be long in duration and far from Earth, so bringing all needed food or performing frequent resupply are not viable options.

Humans generally need between 1500 and 2000 calories per day; however, this varies based on metabolism, exercise level, temperature, and other factors [21]. Some people estimate that each astronaut should be allocated approximately 3000 calories a day due to the intensive responsibilities of crew members and different environment of Mars [21]. Currently on the ISS, each meal (including packaging) weighs about 0.83 kilograms [41]. At this level, a four-crew three-year mission to Mars where astronauts eat three meals a day would require over 10,866 kilograms of food to sustain them [41]. Even if packaging and calories could be somewhat decreased, the mass is still unreasonably high. It would cost an estimated one billion dollars per person per year to send food from Earth to Mars, which is unsustainable, especially for a large human colony [22].

However, for initial missions, some food will need to be brought from Earth until a sustainable food system is implemented. Astronaut food must be nutritious, and a major concern is that food sent from Earth will lose its nutritional value over time [23]. NASA has partnered

with the US military to evaluate how to preserve the nutritional value of foods over time, as this is a problem with food storage for both astronauts and military troops. In addition to nutrition, another important aspect of an astronaut's diet is diversity of the menu. "Menu fatigue" is a studied phenomenon that occurs when people become bored with their food options because the menu lacks variety [23]. This causes people to eat only enough to survive, which will make them weak and unable to perform necessary job functions. On the ISS there are 200 menu options; however, not all of these options can survive the duration of a Mars mission. Because of the cost it would take to send food from Earth to Mars, as well as the shortcomings in nutrition and variety, it is essential for the long-term presence of humans on Mars that astronauts learn to grow their own food.

Many challenges come with farming on Mars, which researchers are currently working to overcome. Mars only receives about half the sunlight that Earth does, which presents problems for many plants [21]. Two potential solutions are to provide extra artificial lighting for the plants, or choose plants that are able to grow with less sunlight. The Martian atmospheric pressure is another problem for plants, since it is extremely low at only .6% of Earth's atmospheric pressure. Pressurized greenhouses can be used; however, it is difficult to contain high pressures, so growing plants in a lower pressure is a more practical option [21]. Plants can grow regularly in one tenth of Earth's atmospheric pressure, but considerations must be made for the Martian farmers that will be exposed to these conditions. Wearing a spacesuit while farming is not ideal, and preferably farmers will not need any protection in the greenhouses, so an appropriate atmospheric pressure should be chosen. The Armstrong limit is the lowest pressure the human body can withstand before our blood starts to boil, and it is about 6.6% of normal atmospheric pressure (6.3 kPa) [21]. Some recommendations say that an atmospheric pressure 50% of Earth's, which is about that of Mount Everest, would be a good compromise. This would make the greenhouse's pressurization closer to Mars' atmospheric pressure, enable plant success, and provide enough pressure for farmers to work comfortably, however research is still being conducted to find the optimal atmospheric pressure [21].

Controlling the carbon dioxide (CO₂) levels in a greenhouse also pose a problem for Martian farming. In a closed greenhouse environment, plants deplete CO₂ levels, so CO₂ constantly has to be added. Fortunately, the Mars atmosphere consists of 95% CO₂, so this CO₂

can be harnessed and added to the greenhouse as needed. For reference, normal CO₂ levels on Earth are 300 – 500 parts per million (ppm) [21]. However, studies have shown that plants grow better with increased CO₂ levels. A graph from a paper studying how potatoes grow in different CO₂ levels is shown below [24], which reveals that potatoes have the highest stomatal conductance at a CO₂ level of 10,000 ppm followed by 400 ppm and then 100 ppm.

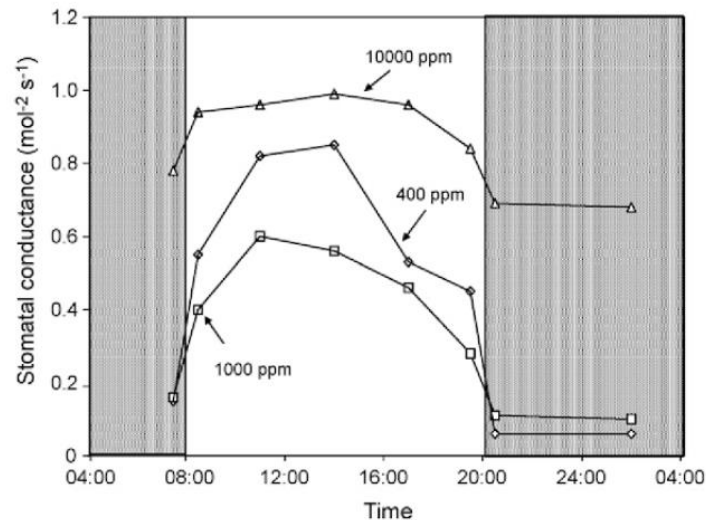


Figure 17.12: Stomatal conductance of potatoes grown at 400, 1000, and 10 000 ppm carbon dioxide. Conductance and transpiration were lowest at 1000 ppm and highest at 10 000 ppm. Super-elevated concentrations like 10 000 ppm might can occur in closed environments in space (source: Wheeler et al., 1999).

Although elevated levels of CO₂ increase plant performance, consideration must be shown for the farmers who will work in these greenhouses. Humans can handle CO₂ levels of up to 10,000 ppm (1% CO₂) before they start feeling dizzy or lightheaded, and up to 20,000 ppm (2% CO₂) before they experience difficulty breathing [21]. Concentrations of CO₂ become completely toxic at 50,000 (5% CO₂) [21]. These are upper bounds for what humans can survive in, so levels should be kept lower than 10,000 ppm. This paper suggests that 1500 ppm is a reasonable level for the plant life to thrive and farmers to survive [21]. However, farmers spending long durations of time in the greenhouses should still use breathing gear to prevent negative long-term effects of increased CO₂ exposure [21]. Oxygen levels in greenhouses are also a concern, not only because they can gradually kill humans, but also because they increase fire risk [21]. The Apollo 1 fire was a result of the pure oxygen environment in which the ground test was conducted, which led to future ground tests being conducted in a nitrogen-oxygen mixed

environment [25]. According to OSHA, air composition should have between 19.5 and 22% oxygen [21]. When higher oxygen levels are present, more nitrogen is needed to counter these levels, which may not be available in large quantities on Mars [21]. A potential solution is to filter out the oxygen; however, currently oxygen cannot be filtered out without also losing nitrogen [21].

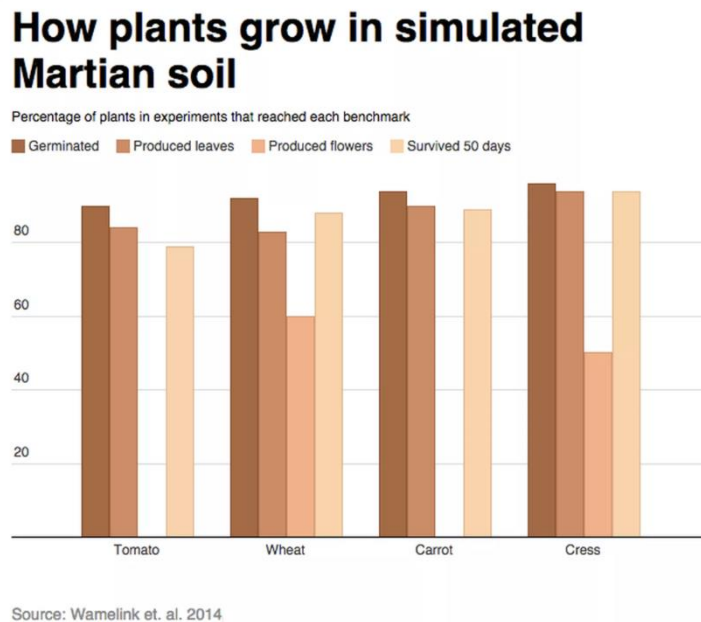
Growing plants in Mars' gravity, which is 38% of Earth's gravity, also poses a problem for Martian farming. On Earth, plants use gravity to orient themselves, so some plants may be unable to grow correctly if they cannot orient themselves under Mars' lower gravity [26]. Studies are being performed on the ISS to determine how plants grow in microgravity, although we have not been able to test how plants grow in the 38% gravity on Mars. However, the German Aerospace Center (DLR) has developed a greenhouse satellite, Euglena and Combined Regenerative Organic-Food Production in Space (Eu:CROPIS), that will be deployed in 2018 to study how plants grow under different gravity conditions [27]. Eu:CROPIS will simulate a different gravity by rotating about its longitudinal axis while orbiting in LEO at 600 km. It will simulate the moon's gravity, 16% of Earth's, for the first six months, and for the latter six months it will simulate Mars' gravity, 38% of Earth's. Inside Eu:CROPIS, microorganisms will fertilize, protect, and provide oxygen to tomato seeds, which will be grown in Earth's atmospheric pressure under LED lights with a day/night rhythm [27]. Scientists are hopeful that data from this experiment will help them better understand the future for farming on Mars.

Plants grown on Mars will most likely need to be contained within a greenhouse, because no known plants can survive the Martian cold temperatures, low pressures, and radiation exposure [28]. Even within a greenhouse, a major problem is the absence of a soil with organic materials on Mars. Instead, Mars contains regolith, which consists of volcanic rock and some toxic chemicals [29]. Since it would be too expensive to bring soil from Earth, research is being conducted to evaluate how plants can grow in Mars regolith, or how this regolith can be enhanced to better support Martian farming [29].

North Carolina State University wants to utilize gene splicing to add genes from extremophiles to plants, in order to make them better able to survive the Martian environment [28]. These researchers performed a proof of concept experiment by inserting a microbe into tobacco cells, and next they want to provide plants a gene for cold tolerance. Making plants more

resistant to adverse conditions such as cold temperatures and draught can also benefit plants on Earth. NASA Kennedy Space Center and Florida Tech Buzz Aldrin Space Institute performed a 30-day experiment on how crops grow in Martian soil [29]. They tested how lettuce grew in Earth potting soil (control group), Martian-like soil (simulated group), and Martian-like soil with added nutrients (enhanced simulated group). The simulated group grew some of the lettuce, but only half as many survived as in the control group. The lettuce tasted the same, but had longer germination rates and weaker root systems. The study is now looking at what added nutrients will yield the best results.

Researchers published a paper in journal PLOS ONE in 2014 that studied how plants can grow in simulated Martian soil, simulated lunar soil, and Earth nutrient-poor soil [30]. Simulated Martian soil was produced from Hawaiian volcanic ash, based on information from the Viking lander and Pathfinder rover. The study grew tomatoes, wheat, cress and mustard in simulated Martian soil for 50 days. Of the plants grown in the Martian simulated soil, 79% of each were still alive after 50 days. Of the plants grown in lunar simulated soil, the majority were dead after 50 days. Below is a graph of the performance of crops grown in Martian soil [18].



Although many other problems still need to be solved before food can be grown on Mars, the success of crops in Martian regolith proves promising for future Martian farming.

A certain type of life, methanogens, have the potential to live in Martian conditions without a greenhouse. Methanogens are microorganisms that produce methane from carbon dioxide, hydrogen, and water. They do not need oxygen, organic nutrients, or light to survive, which is why scientists believe they may be the ideal species to live underneath the ground on Mars [31]. The University of Arkansas performed a study in 2002 that demonstrated three of four tested strains of methanogens successfully grew in Martian simulant with the presence of water [32]. A more recent study by the University of Arkansas tested methanogens in the low pressure that they would experience on Mars, and the methanogens survived after being in low pressure [33]. The University of Arkansas has also previously found that certain species of methanogens survived in Martian freeze-thaw cycles [33].

Other creative ideas for farming include putting astronauts on Phobos, one of Mars' moons, prior to Mars in order to assist with the Mars mission³⁴. Phobos is easier to land on because it does not have an atmosphere. A Martian surface station could be constructed while the crew is on Phobos and has a great view of Mars' surface. Another idea is to place many inflatable greenhouses on Phobos that will grow crops for the Mars astronauts. When needed, this food could be deployed down to the Mars' surface. Similarly, greenhouses could be deployed in interstellar space, much like Eu:CROPIS, to begin growing plants on the journey to Mars. Growing food in space would reduce the mass needed to launch from Earth, since only seeds would need to launch rather than full-grown crops. Another idea is to integrate greenhouses into the crew's habitat. This would add scenic and familiar views to help with psychological stresses, as well as provide oxygen for the astronauts.

A more aberrant idea to enable Martian farming involves terraforming Mars or compressing the Martian atmosphere to create a friendlier environment for plants. Heating up the atmosphere would release carbon dioxide that could increase the atmospheric of Mars and create atmosphere. The terraforming process can be modeled and explained with the following equations [35].

First, the mean temperature of the Mars surface can be represented as a function of its atmospheric pressure where S is the solar constant, T_{BB} is the black body temperature of Mars 213.5K, and P is the pressure of Mars in bar:

$$T_{mean} = S^{0.25} * T_{BB} + 20 * (1 + S) * P^{0.5}$$

Next, we can find the temperature at the pole where ΔT is the difference between the mean temperature and the temperature at the pole, which is about 75K for $S=1$:

$$T_{pole} = T_{mean} - \frac{\Delta T}{1 + 5P}$$

A rough approximation can be made for the maximum temperature on Mars:

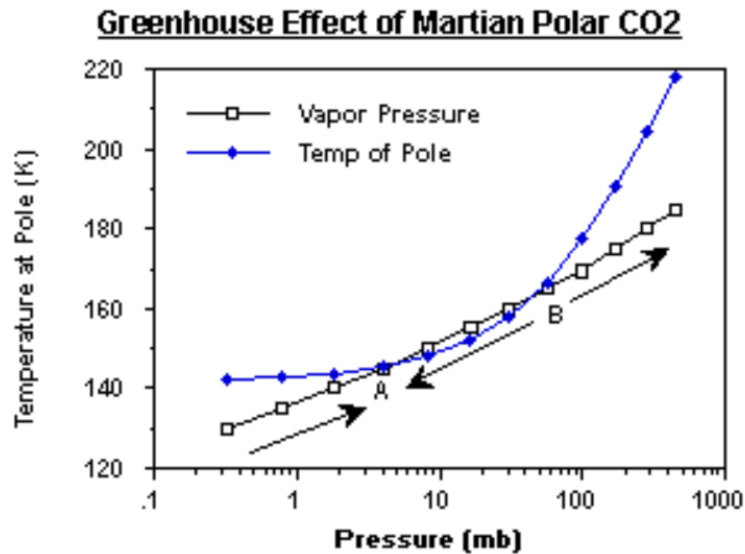
$$T_{max} = T_{equator} = 1.1 * T_{mean}$$

The global temperature distribution can then be given, where L_{at} is the latitude:

$$T(L_{at}) = T_{max} - (T_{max} - T_{pole}) * \sin^{1.5} L_{at}$$

To represent the CO_2 pressure as a function of the temperature, we can use the approximation of the vapor pressure curve for CO_2 . The results are shown in the graph below [35].

$$P = 1.23 * 10^7 * e^{-3168/T_{pole}}$$



The current state of Mars is represented by point A, which has a 6 mbar pressure and 147K temperature at the pole. The other equilibrium point is represented by point B, however it is unstable. If the temperature of Mars were increased just 4°K, points A and B would move closer together until the pole temperature curve would lie entirely above the vapor pressure curve. Once this occurs, Mars would experience runaway greenhouse heating that would cause the pole to evaporate and create an atmosphere. The current atmospheric pressure on Mars is 6

mbar, and it is estimated that the atmospheric pressure of Mars could reach about 400 mbar, which is much closer to Earth's 1013.25 mbar atmosphere.

In order to produce this 4°K temperature increase, Elon Musk suggests dropping thermonuclear weapons on the Martian poles, which would release the carbon dioxide ice to thicken the atmosphere and warm up the planet [13]. Another method involves using solar sail orbiting mirrors, which would increase the light that hits Mars and thus increase the temperature on Mars. However, a mirror on the order of a 100 kilometer diameter would be needed to accomplish this level of heating [36]. Finally, redirecting the path of an ammonia asteroid to hit Mars is another suggested way to increase Mars' temperature. The outer solar system is thought to have many of these ammonia asteroids with a mass large enough to release up to 10TW of energy if impacted with Mars [35]. Although mathematically feasible, there is much uncertainty in if ammonia asteroids are actually prevalent in the solar system and how difficult it would be to redirect their orbit into Mars. Moreover, all these options are drastic measures that would cause much destruction to Mars that would likely damage its unique environment and geology. Much consideration should be taken before deciding to perform one of these actions that can likely not be reversed.

Water

Since the discovery of water on Mars in 2012, Mars has been viewed as a probable home for past life, present life, and future life. Many robotic missions to Mars have suggested or confirmed the presence of ice on Mars, and it was previously believed that ice was only present far beneath Mars' surface. However, 2018 NASA images show an abundance of underground bands at mid-latitudes that begin only three to six feet under the surface, which scientists believe to be ice [71]. Similarly, data from the Mars Reconnaissance Orbiter showed the presence of a water ice reservoir larger than New Mexico at Utopia Planitia [76]. This ice is not bound to minerals like much of the Martian ice is, so it should be relatively easy to access and utilize. Extracting this ice for use by humans could enable mankind to have a sustained presence on the red planet by providing the resources to make drinking water, breathable air, and methane.

Although valuable, this ice still needs to be extracted and produced into these useful resources which presents a challenge. Water cannot be stable in the liquid form because of the low temperatures and low pressures on Mars, making its production and storage a challenge. It

either exists as ice on or under the surface, or as water vapor in the atmosphere, and this H₂O also contains many toxic perchlorates [37]. Many researchers are finding ways to extract and purify the water from Martian soil, ice caps, or atmosphere to make it usable for humans. However, this is a difficult, timely, and costly process, so it will be necessary to recycle the extracted water in order to meet the water needs of humans.

One method to extract the water from Martian soil, although not very efficient, is to compress CO₂ and put it over the Martian soil [38]. The gas will collect some of the water, and once it is allowed to expand it will release clean and purified water [38]. Another method is to collect saturated soil and heat it to 500 degrees Celsius, and the water will then convert to steam. This steam could be collected and condensed, producing clean and purified water. In addition, colonists can desalinate, potentially through reverse osmosis, the areas on Mars that are predicted to have seasonal flows of liquid water. In this scenario, the Mars colony would need to be close to one of these water flows. Another way to retrieve water is from the Mars ice caps, where significant reservoirs of water exist; the northern ice cap has about 1.6 million cubic kilometers of ice [38]. Studies suggest mining the ice at the poles and transporting it with autonomous vehicles to the colony, where it can be purified and turned to liquid for human colonists [38]. Mars One plans suggest extracting water from the soil by evaporating and condensing it. They allot 50 liters of water for each astronaut per day and recommend that most water be recycled to reduce the amount of water extraction from the soil [40].

Regardless of how water is retrieved on Mars, the water will need to be recycled efficiently in order to support a large human colony. Currently ECLSS systems on the ISS are only 80% efficient, which will not be sufficient for a Mars mission. Many studies are looking to bring this efficiency closer to 99%, which is what will be needed for a long-term space exploration mission [39]. To ensure astronauts will have ample water, water can be stored in tanks from old rockets sent down to the Martian surface, and a certain amount of purified water may be required to be on the surface before the crew arrives. Moreover, water from mining of asteroids near Mars could prove useful if it is harder than scientists expect to mine water from the Martian soil.

Although much research needs to occur prior to farming on Mars and extracting water through ISRU capabilities, many important steps are underway, including evaluating plant

growth in Mars soil, determining how plants will grow in partial gravity environments, and developing drills to mine water. The potential solutions researchers around the world are working on may one-day enable space farming to become reality.

5.3. Lower Gravity

Microgravity presents many problems to astronaut health, which makes it a significant danger for the transit from Earth to Mars. Bone loss and bone demineralization are known problems for astronauts, as bone loss in space occurs at a rate of over 1% per month [42]. This causes a decrease in bone density and strength and can lead to osteoporosis. Bone demineralization increases the risk of bone fractures and kidney stones.

Cardiovascular changes are also a significant risk to astronauts [43]. The presence of gravity causes blood pressure to be lower above the heart and higher below the heart. Without gravity, bodily fluids are disrupted and blood pressure remains about the same throughout the whole body, which causes changes in cardiovascular physiology. For example, increased blood pressure to the eyes can cause vision problems for astronauts [43]. The neurovestibular system controls the human balance, vision stabilization, and orientation. Microgravity prevents the body from knowing its orientation and direction, which can disrupt the neurovestibular system and lead to disorientation [43]. Finally, circadian rhythms will be affected because there is no day and night cycle on the transit to Mars. Sleep loss may lead to fatigue and decreased performance of crew [43].

Artificial gravity presents a solution to the dangers that a microgravity environment poses to the crew and systems. Artificial gravity can be generated by providing the transit vehicle with an acceleration equal to Earth's gravity [44]. If the linear acceleration of the spacecraft equals 9.8 m/s^2 , the astronauts would experience a force equal to that of Earth's gravity. However, such a high linear acceleration cannot be maintained for a long duration spaceflight. Spinning the spacecraft to generate a centripetal acceleration can provide the artificial gravity by spinning at a constant rate, which is a more reasonable task. The force centrifugal force generated on an object can be displayed as a function of the mass of the object, linear velocity of the object, and radius of the motion [44]:

$$F_c = \frac{mv^2}{r}$$

Linear velocity can be written in terms of angular velocity (radians per second) and the radius of the curve:

$$v = \omega r$$

Then, the centrifugal force can be written as:

$$F_c = m\omega^2 r$$

By setting this force equal to the force of gravity, the relationship between the rate of rotation, radius, and gravity can be found:

$$F_g = mg$$

$$F_c = F_g$$

$$m\omega^2 r = mg$$

$$\omega = \sqrt{\frac{g}{r}}$$

In this equation, the angular velocity is expressed in radians per second. However, revolutions per minute is a more convenient way to measure angular velocity. Radians per second can be converted to rotations per minute using simple conversions.

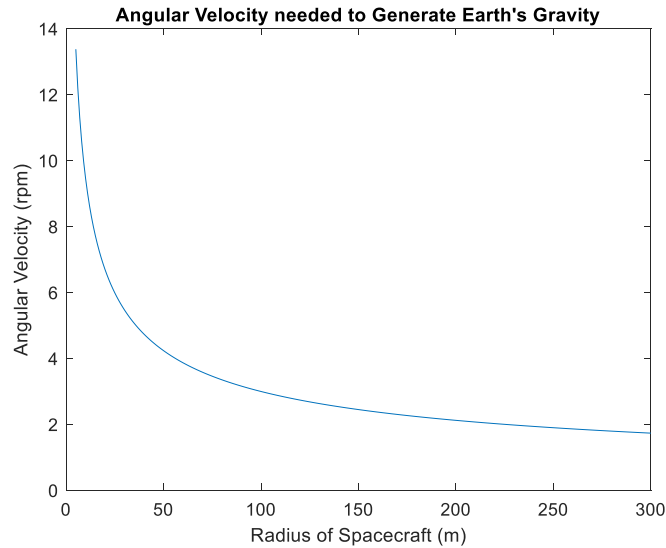
$$1 \text{ rpm} = \frac{1 \text{ rad}}{s} * \frac{1 \text{ rev}}{2\pi \text{ rad}} * \frac{60 \text{ s}}{1 \text{ min}} \approx 9.55 \frac{\text{rad}}{s}$$

Angular velocity in rotations per minute (rpm) can be expressed as Ω , and the equation can be rewritten as:

$$\Omega = 9.55 \sqrt{\frac{g}{r}}$$

$$r = 91.2 \frac{g}{\Omega^2}$$

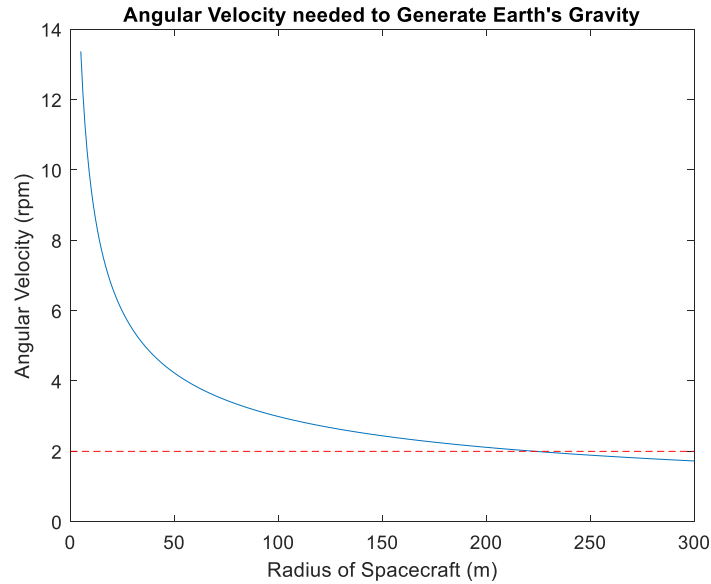
Substituting in Earth's gravity for g , the relationship between the radius of the spacecraft and angular acceleration can be shown.



This graph shows the angular acceleration that is needed to generate Earth's gravity, as a function of the spacecraft radius, ranging from 5 meters to 300 meters. At 5 meters, the angular velocity of the spacecraft would need to be about 14.5 rpm to generate 9.8 m/s^2 , and at 300 meters it would need to be just under 2 rpm. Based on this graph, a reasonable size spacecraft would be about fifty meters. Fifty meters corresponds to a reasonable angular velocity, and it has a good return on investment compared to higher radius spacecraft.

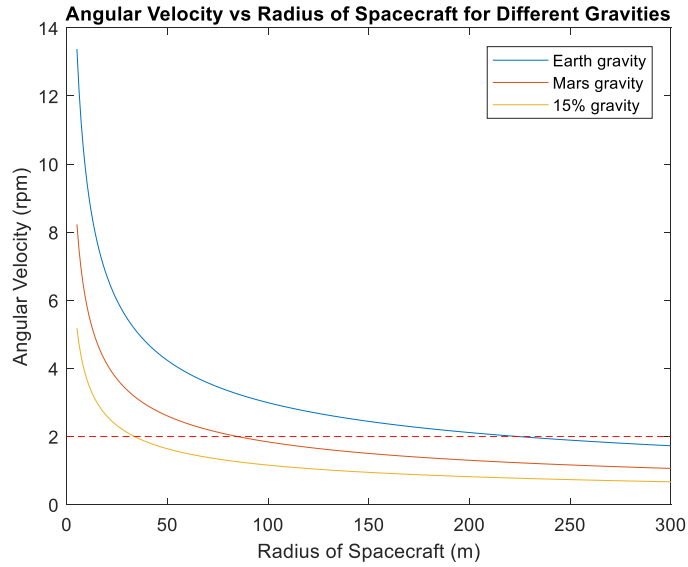
Centripetal acceleration will produce gravity that is not entirely Earth-normal. Using a higher rpm distorts the path of objects dropped much more than lower rpm levels of the same radius [45]. In addition, some studies suggest that the rpm needs to be below 2 (.21 rad/sec) in order to prevent the crew from getting dizzy and sick [46]. This still needs to be confirmed, but the case where this is true is shown below:

$$r = 91.2 \frac{g}{\Omega^2} = 91.2 * \frac{9.81}{2^2} = 223.7 \text{ m}$$



Using regular centripetal acceleration to achieve Earth's gravity, a spacecraft that has a 223-meter radius would be needed. This size spacecraft is extremely large, and most likely unfeasible with current technologies.

However, studies have shown that only about 15% of Earth's gravity is necessary for astronauts to properly orient themselves and to prevent many of the physiological effects that come with microgravity [47]. A particular study from PLOS One performed extensive studies on ten people with pristine health in order to find the lowest gravity that would be acceptable for humans. The 15% they found is very close to the moon's gravity of 16%; however, it is far below Mars' 38%, which is promising for the upcoming Mars missions. In order to limit the difficulty transitioning from transit to the Mars surface, Mars' gravity could be generated in transit so that the astronauts are already accustomed to it upon arrival. Using Mars' gravity and 15% gravity in the angular velocity equations, the relationship between angular velocity and spacecraft radius can be shown for different gravity levels:



Mars' gravity:

$$r = 91.2 \frac{g}{\Omega^2} = 91.2 * \frac{3.711}{2^2} = 84.6 \text{ m}$$

15% of Earth's gravity:

$$r = 91.2 \frac{g}{\Omega^2} = 91.2 * \frac{1.472}{2^2} = 33.5 \text{ m}$$

A spacecraft that has an 84.6-meter radius and 33.5-meter radius would be needed to generate Mars gravity and 15% gravity, respectively. However, these are still very large spacecraft.

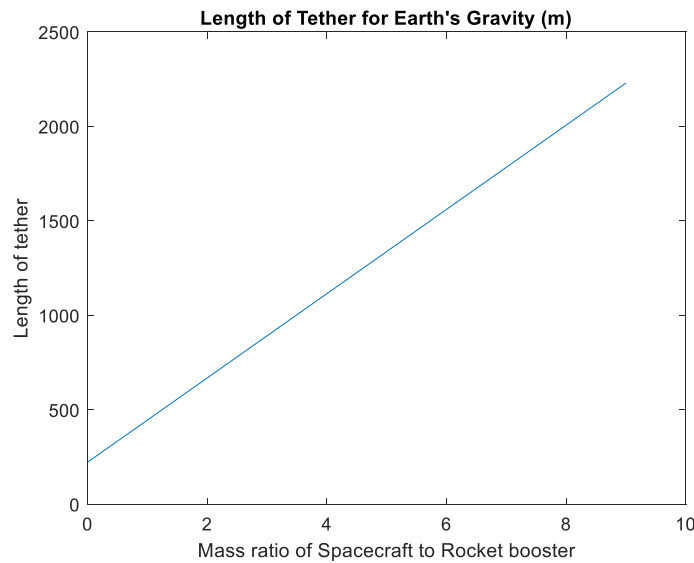
A solution that can lower the spacecraft radius without increasing the rpm is to connect the spacecraft to a large counterweight, such as a rocket booster or second spacecraft [46]. The relationship between the masses of the systems and the distance between them can be observed. The center of mass of the system must be at a radius r of 223 meters from the spacecraft. The system relationships can be defined in terms of the mass of the spacecraft (M_{sc}), mass of the counterweight (M_{cw}), the length of the tether (L), and the radius of the spacecraft orbit (r)³.

$$M_{sc}r = M_{cw}(L - r)$$

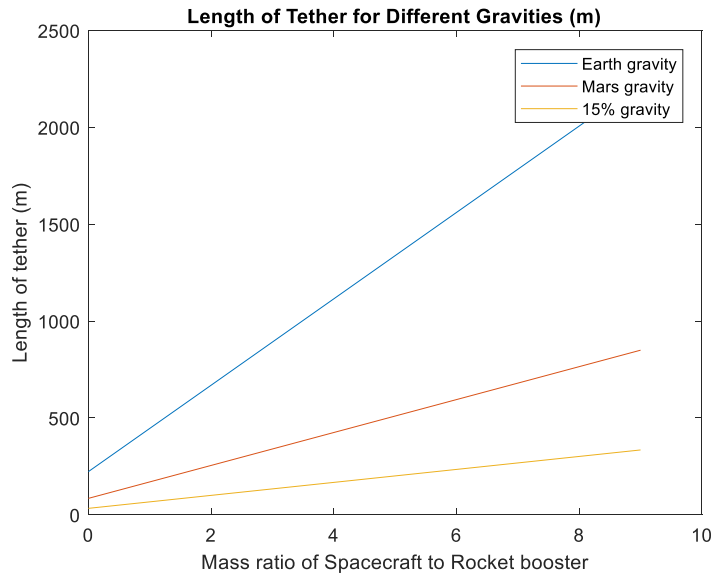
To rewrite in terms of the unknown, L:

$$L = r \left(\frac{M_{sc}}{M_{cw}} + 1 \right)$$

Below is a graph of the length of the tether needed to generate Earth's gravity, as a function of spacecraft to counterweight mass ratio. It can be observed that as the counterweight mass approaches infinity, the length of the tether approaches 223 meters, which is the distance from the spacecraft to the axis of rotation. It linearly increases as the mass ratio increases, and when the masses are equal the tether length is equal to exactly twice the radius. The larger the counterweight mass, the shorter the tether.



For Mars' gravity, the tether is 85 meters as the counterweight approaches infinity, and it is 170 meters when the masses are equal. For 15% gravity, the tether is 33 meters as the counterweight approaches infinity, and it is 66 meters when the masses are equal. Again, these options provide much more feasible options for artificial gravity.



Artificial gravity provides a solution to many of the problems of microgravity; however, it presents problems of its own. Therefore, only the necessary level of artificial gravity should be used in order to prevent astronauts from experiencing negative side effects. Before artificial gravity can be seriously considered for a human exploration mission, work needs to be done to verify exactly how many rpm humans can handle and what gravity level is acceptable for humans. Moreover, for the tether and counterweight option, research should be done on how to initiate the spinning motion, how to prevent orbital debris from disrupting the spin, and how to choose a tether that is strong but also light. As researchers work to solve these problems, artificial gravity will become more practical and may one day be a key aspect of human space travel.

5.4. Robots on Mars

Robots are a critical aspect of space exploration that continue to create the path for future human space travel. There are many reasons why sending robots to space is advantageous for society. Robotic missions cost significantly less than human missions, so they provide valuable information for a lower cost and lower risk than a crewed mission. This information is then used to advise scientists what types of missions are worth pursuing. Robotic missions to Mars during the last century have informed scientists of Mars' atmospheric composition, regolith composition, pressure, temperature, and many other qualities that have allowed researchers to

more accurately determine the accommodations that need to be made to facilitate human survival on Mars.

The Mariner Missions were the first attempts to learn more about Mars, beginning with flybys of the planet. Mariner 4 mission, launched in 1964, provided the first close up photos of Mars, as well as information on the solar wind environment [48]. Mariners 6 and 7, launched in 1969, analyzed the Martian atmosphere and surface with remote sensors, and recorded and sent to Earth hundreds of pictures [49]. Mariner 9 was the first artificial satellite to enter Mars' orbit, instead of performing a flyby as previous missions. It observed that a dust storm was encompassing the planet, and after the dust storm it captured photos of the Martian surface that revealed volcanos, a Grand Canyon, and the relics of ancient riverbeds, as well as close up photos of Phobos and Deimos [50].

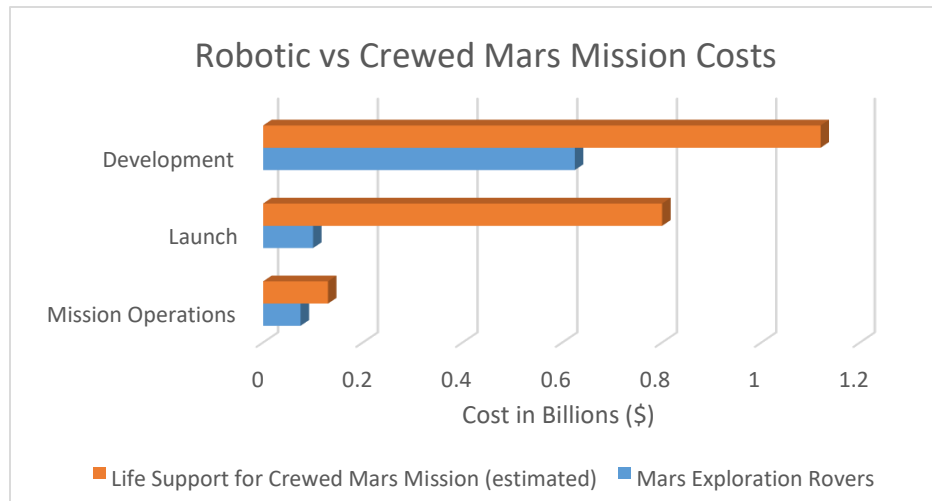
The Viking Project, launched in 1975, was the first US mission that safely landed on Mars and relayed images of the surface [51]. The landers conducted biology experiments to search for the possibility of life on Mars, and they found interesting and unexpected results about the nature of the soil and its possibility for life. Rover missions, including Pathfinder, the Mars Exploration Rovers, and Mars Science Laboratory, have greatly advanced our knowledge of the Martian environment, which has allowed scientists to predict what locations of Mars may contain water or life and are thus the most promising to explore [52].

Less than half of missions sent to Mars have been successful (23 out of 54) due to many risks such as launching, navigation, and most dangerously entry, decent, and landing (EDL) [53]. Robotic missions do not jeopardize human life, which is why they have been able to push the boundaries of space exploration through low cost and high risk missions. Robots can scope out dangerous situations that are deemed too dangerous for humans. In addition, they require much less maintenance and resources than do humans, so they are less expensive missions. Nevertheless, now that there is reason to believe Mars is potentially habitable for the human species and there is a better understanding of Martian dangers, we are ready to leverage human capabilities to deepen our understanding of the Red planet.

Humans versus Robots

Humans have talents that robots do not, such as advanced thought-processes, innovation, adaptability, and versatility. Robots can be programmed to perform functions and react to certain circumstances; however, they will not be ready for what they do not anticipate. Humans have the unique ability to make quick decisions, which will prove especially critical for a Mars mission where the roundtrip communication time lag is up to forty minutes. Rovers generally need to wait for commands from JPL that are based on information the robot relays to NASA, which adds to the sluggishness of robotic surface missions. Humans' ability to analyze a situation and think quickly will enable faster and more frequent exploration, and it could also save a mission that is experiencing a time-sensitive failure. Because of both robots and humans' special skillsets, they will both play a critical role for a Mars mission.

For a round-trip journey to the surface of Mars with six crew, the estimated consumable mass is over 100T, up to 200T [54]. Great energy and fuel savings result from robotic missions that do not require consumables, which results in a significant cost difference between a robotic and crewed Mars mission. The graph below compares the total cost of the two Mars Exploration Rovers (MER) Spirit and Opportunity, with the estimated cost of solely the life support system for a crewed Mars mission. This estimation was made in a published paper from NASA Ames Research Center and was based on ISS life support costs [55]. The total cost of the MER program was \$800 million, while this study predicts it would cost over \$2 billion just for life support on a three year crewed Mars mission. This puts into perspective how costly it is to keep humans alive in outer space versus the cost of a robotic mission. Therefore, robotic capabilities should be used where possible in order to reduce the number of astronauts to sustain.



As in any space mission, it is important to evaluate the risks and consequence for the overall mission and its divisions. For missions or activities with a high risk or high consequence, it is advantageous to send robotic missions so there is the lowest loss in the event of a failure. As demonstrated by the Colombia and Challenger accidents, losing human life is a traumatic experience for the entire nation, and it can cause major setbacks for human space exploration programs. Therefore, careful consideration should be given as to whether or not a mission should involve humans. Activities with risks that have a high likelihood or consequence should be performed by robots rather than humans.

My recommendation for a crewed Mars mission is that robots should be used for the following occasions:

1. Activities with risks that have a high likelihood and/or consequence
2. Exploring new areas
3. Routine activities

Humans should primarily monitor, repair, and give direction to the robots based on information they receive and their own critical thinking abilities. Human lives should not be endangered to explore new areas, since unknown risks of indefinite danger may be present. Instead, robotic lives can be expended to gather information that will let scientists know if an area is safe to pursue and whether or not it is worth pursuing. In addition, there is no need for humans to perform functions that are routine, such as farming, performing ISRU functions, or transporting materials. Although these are most likely not high risk endeavors, it is not necessary

for astronauts to expend energy or risk an accident doing monotonous tasks that can be easily performed by robots. The optimal use of robotic and human abilities on Mars will create an optimal robotic-human interface that minimizes risk, reduces cost, and makes great discoveries, which will facilitate the success of a Mars mission.

Proposed Notional Architecture

Finding the right balance of human and robotic talents that has the optimal cost and benefit will be a critical part of the Mars mission. Robots and humans each have a unique role to play in space exploration. Utilizing the right attributes of each will enable the safest, most efficient, and most cost effective way to explore space, make discoveries, and uncover our past. Analyzing the surface architecture and its components can help reveal where robotic and human talents can best be used and show the unique interaction between them. Below is a notional idea of the unique roles robots and humans may perform for a Mars mission. This idea aims to provide a cost-effective solution by utilizing robots where possible to minimize cost, and using humans in areas where robots are insufficient, either due to cost or the inability to replace unique human qualities. Note that in all of these systems humans will be responsible for monitoring the systems and performing regular maintenance in order to enable the robots to last as long as possible.

i. Habitat

Ideally, the Mars habitat should be constructed prior to the crew's arrival on Mars. The construction of the habitat can be performed by a swarm of robots moving pieces of the habitat into place, or it may be an inflatable habitat deployed after landing on Mars. It may also be a combination of those options, with inflatable habitats that are covered in Mars regolith or another material for radiation shielding.

To enable the greatest expansion of the Mars colony, there should be small modular habitats that can easily be assembled by robots. Ideally, the robots would not need the guidance of humans to perform this assembly. One robotic development that would be ideal for this construction are "Termes," which are a swarm of robots developed at Harvard University [57]. The key idea behind this design is that there is no one leader; rather Termes observe the behavior of each other and place blocks where they observe a vacant space in the structure. Termes are

each programmed to follow a set of traffic rules, and they can perform their individual functions without knowing the overall plan or state of the structure. This is also beneficial because if one stops working, the others can execute the structure as planned without fear of losing the lead Terme.

Similar to other recent robotic developments, Termes were developed as a proof of concept without regard to their efficiency or lifetime [57]. The battery can only last for two to three minutes, which would evidently not suffice for a Mars mission. In order for swarm robots to be utilized for Mars habitat construction, their power lifespan needs vast improvement. Small robots for swarms will likely not be large enough to contain solar cells that could harness the sun's energy, so an efficient power system needs to be developed.

ii. Transportation

Several types of robots will be used to facilitate movement of materials and crew members on Mars, including unpressurized rovers, pressurized rovers, and innovative robotic developments. Robots can move heavy materials during setup operations, either operating autonomously or with crew direction. In addition, rovers or robots can be used to perform setup operations prior to the crew's arrival, including installing the power system, assembling the habitat, initiating water production, wiring the surface infrastructure, and planting seeds.

Many unpressurized rovers have been used on the lunar and Martian surfaces, and would prove beneficial for transporting materials. For example, the Apollo Lunar Roving Vehicle could carry a 490-kilogram payload on the lunar surface, and it traversed up to 20.1 kilometers [66]. Improvements should be made to minimize weight and cost for a future Mars mission. Unpressurized rovers also have the ability to advance scientific exploration by performing their own scientific missions to gather data, such as Mars rovers have for decades. It would be beneficial to have astronauts on Mars to send commands to these rovers since it would eliminate the communication lag time that there is on Earth. It currently takes upwards of forty minutes for rovers to send data from Mars to Earth so that scientists can analyze the data and then send back instructions for the rover's next movement. Humans on Mars could provide almost immediate direction for the rovers.

Pressurized rovers will be utilized on Mars as well, in order to transport astronauts over long distances. Specifically, NASA's Space Exploration Vehicle (SEV) can support astronauts for up to two weeks in a pressurized rover and can bring astronauts more than 125 miles [65]. This would enable humans to travel much further than they could in an EVA suit.

In addition to rovers, a four-pound Mars helicopter is currently in development that will travel to the red planet on the Mars 2020 rover [70]. It will autonomously begin flight and send back images and data to scientists on Earth [53]. Flying a helicopter on Mars is vastly different than on Earth for two primary reasons: The Martian atmosphere is only 1% of Earth's atmosphere, which makes gaining lift difficult, and Mars' gravity is 38 percent of Earth's, so less force is required to overcome the downward gravitational pull. The force from a helicopter can be modeled below [70]:

$$F_{thrust} = \frac{\rho * A * v^2}{2} = m * g$$

Where:

ρ = air density

A = rotor area

v = speed the air is pushed down

m = mass of the helicopter

g = Mars' gravitational acceleration

Because the Martian atmosphere is so thin, the rotor area and/or air speed must be high to compensate for the low air density. The Mars helicopter's blades will rotate at 3,000 rpm, which is ten times faster than the typical blade rotation rate of helicopters on Earth. This experiment is a proof of concept to determine whether or not helicopters on Mars are a viable technology. If successful, helicopters may be the next robotic systems to conquer Mars, and they could facilitate in a human Mars exploration mission.

In addition, robotic devices can assist humans by improving their strength, agility, and overall athletic ability. The "Exoskeleton" is a development for the Army that allows soldiers to carry much more weight with less energy [58]. Soldiers are up to twenty-seven times more productive using this technology, and it allows them to carry more loads for longer periods of

time. This could enable astronauts on Mars to carry more supplies, thus helping the transportation robots. Humans are more agile and adaptable than robots, so they can reach areas the robots may not be programmed to reach. Leveraging this unique human ability with robotic strength can create a superhuman with the ability to excel on Mars. Similar to the Termes and other recently developed robotic devices, the power system of the Exoskeleton needs to be refined before it is suitable for a Mars mission.

iii. Power System

Thorium and uranium are both viable power systems for a Mars colony because of their great energy yield per mass and low waste production. Uranium is a fissile isotope that yields large amounts of energy when split. Nuclear reactors on Earth are made from uranium, and there is an abundance of it on Earth. However, uranium produces harmful radiation as well as dangerous waste from which bombs can be made. It also has to be enriched prior to use for a nuclear reactor.

Thorium presents a safer option than uranium because its fuel is more stable than uranium-based fuels, and it does not produce as much nuclear bomb waste [59]. However, thorium reactors have not been explored and developed nearly as much as uranium reactors, primarily because uranium reactors produce waste that is used to make nuclear weapons [59]. In addition, they are not a fissile material so they need U-233, U-235 or another fissile material to ignite, which makes designing them difficult [61]. Nevertheless, thorium is still an appealing option; it has a longer half-life and is much more abundant, and it is estimated that the nuclear energy that can be made from all the thorium on Earth is greater than that of all the oil, coal, and uranium in the world combined [60]. Thorium nuclear technology needs to be greatly developed and tested prior to use during a Mars mission.

Regardless of the specific type of nuclear power, the first system that should be deployed on the surface is the power system, as it is the source of energy for all the other systems. Robots should be entirely responsible for the setup and maintenance of the nuclear reactor because of the harmful effects and dangers it poses to humans. Robots can autonomously dig a hole and bury the nuclear reactor in it, or build up a wall around it to help protect crew members from nuclear radiation. Then, robots can connect wires to the other systems on the surface, such as the greenhouse, water production, and habitat. RoboClam is a device developed after razor clams,

which work by contracting their bodies to develop a vacuum that fluidizes the soil thus making it easier to dig through [67]. MIT and the University of Maryland believe that these clam-like digging devices can help with laying down submarine data cables [67]. Devices such as the RoboClam could potentially assist with digging through Mars regolith and laying down power cables for a Martian surface architecture. However, studies would have to be done on how the RoboClam would behave digging through Mars regolith in the Martian environment and how well it could handle radiation exposure. These unknown dangers could prove fatal to small robots that function flawlessly on Earth.

iv. Food

Farming on Mars is a challenge that is best suited for both robots and humans. Similar to Earth, much of the Martian farming can be automated including the planting, watering, and lighting of the plants. There is no need for astronauts to waste time performing these tasks. However, botanists will be greatly needed on Mars to ensure successful farming, particularly because it will be so new on Mars. Humans will be responsible for monitoring the plant growth and making necessary adjustments to soil nutrition, water levels, light levels, and other important variables that affect plant growth.

Harvest CROO Robotics is an excellent example of what may one day govern farming on Mars. Their robot can pick eight acres of strawberry plants in a single day, which would normally require 30 human pickers [62]. Tons of food will be needed for a large Mars colony, so robots dominating farming will allow the humans to focus on more important colony roles. Similarly, Vision Robotics has developed several farming robots with functions including thinning, weeding/spraying, mapping, and estimating crop loads [63]. These robots can help maintain the greenhouse instead of humans. In addition, the mapping and estimating robots can assist astronaut farmers in determining how to improve the performance and efficiency of the farm [63].

v. Water

Water from the soil will be extracted and purified using ISRU capabilities. Recently, water was estimated to be within a few feet of the Martian surface, which would make water mining a viable option [64]. Drilling may be performed by instruments such as the Tartan Ice

Drilling System developed by Carnegie Melon students, which autonomously drills for ice, vaporizes it, and condenses it so that it is clean and ready for astronauts to consume [64]. This water will then be stored in tanks and delivered to the habitat, greenhouse, and other areas needing water. The water used in these systems will then be recycled to decrease the amount of water that needs to be drilled.

vi. Science

Science exploration studies have only been performed by robots thus far, but human talents can be leveraged to accelerate and advance these discoveries. Robots should make preliminary findings and excursions on Mars. A swarm of Martian robots could be sent out, and the information could be relayed back to the astronauts in the habitat. The astronauts can then analyze the information and take note of areas that may be scientifically interesting so that astronaut EVAs can be planned to these areas. Places that are dangerous will also be noted, so that they can then be further explored by robots suited for the environment.

“Humanoid” Robots

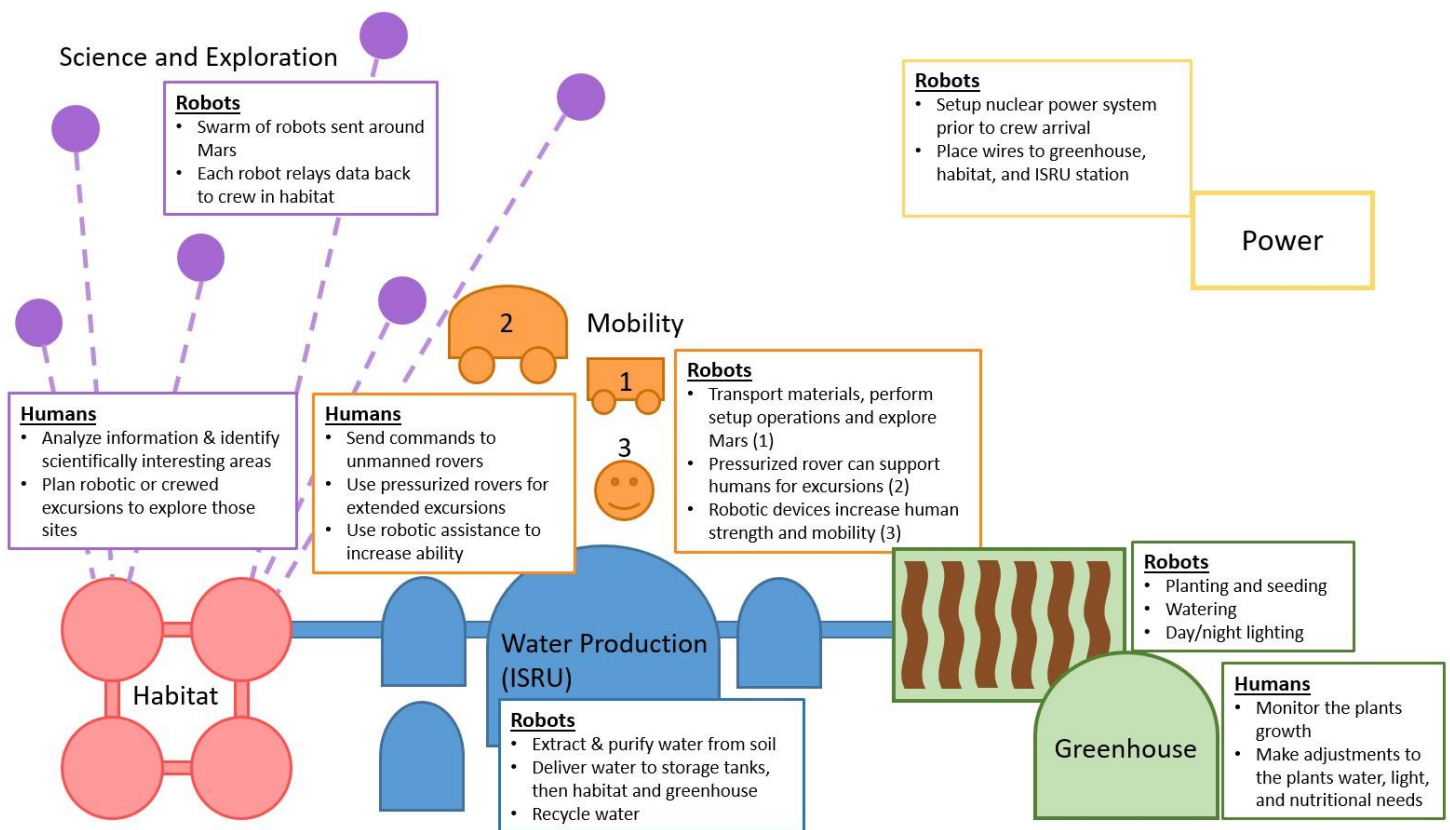
Robots are increasingly gaining human abilities, such as ones produced by Boston Dynamics, which developed a Humanoid robot called Atlas. Atlas is six feet tall, weighs 330 pounds, and has the ability to run, jump, and do backflips [68]. Applications of Atlas include performing dangerous tasks, such as going to a nuclear reactor during a meltdown, shutting off an oil spill, or putting out wildfires [68]. A robot like Atlas designed to investigate dangerous areas would be greatly beneficial for a Mars mission. However, a lighter robot with the ability to make quicker movements and decisions without direction from humans is what is needed next to be sufficient for a Mars mission.

In 2017, Worcester Polytechnic Institute (WPI) was a finalist for the NASA-sponsored Space Robotics Challenge (SRC), which aimed to develop robotic capabilities of a humanoid robot to help astronauts during the Mars mission. To qualify, WPI developed a rover that could accurately report lights in a simulated environment and could press a button to open a door and go through that door without falling. For the virtual competition, teams had to perform tasks that would help save a Mars mission: align a communications dish, restore a solar array, and fix a habitat leak [69]. The WPICMU team received seventh place in the finals with their robot

WARNER (WPI's Atlas Robot for Nonconventional Emergency Response). Much work like this is being done to develop robots capable of performing dangerous and emergency procedures, but refinements in their autonomy and translation from an Earth to Martian environment need to be made prior to traveling to Mars. In addition, the power systems of many of these robots need to be developed and tailored for Mars to make them more self-sustaining or longer lasting.

Graphical Depiction

Below is a graphical representation of the roles humans and robots may play in a Martian surface architecture.



6. Mars Outpost Location

The location of the Mars outpost is an important aspect of the mission that will determine the landing characteristics, access to resources, and proximity to scientifically interesting features. Over the past few years, scientists along with members of the community have performed trade studies of potential colony locations where humans may first live on Mars. The first obstacle to living on the Martian surface, and arguably the most dangerous aspect of space travel, is entry, descent, and landing. Therefore, a landing site should be chosen that facilitates the EDL process. A flat, 25 square-kilometer area is desired to provide enough landing area for other spacecraft to land supplies and future missions [72]. The terrain should not be rocky or it could damage the spacecraft, and it should not be too soft since the spacecraft could descend into soft Mars regolith and become stuck [72]. In addition, a landing site low in altitude is considered advantageous because there is more time and atmosphere for deceleration. Another important characteristic of a landing site is its resources, specifically water access. Water has a wide range of uses, such as drinking, radiation shielding, oxygen production, methane production, so close proximity to a water source is high priority.

Proximity to scientifically interesting areas is also another important aspect, as the goal is to learn more about Mars and the universe. Close to water sources is thought to be the best place to discover past, present, or future potential for life. Other scientifically interesting areas include near craters, canyons, and outcrops [72]. Another debate is whether to settle near the equator or at a higher latitude. Water is more easily accessible at high latitudes; however, cold winter temperatures and absence of sun during winter months would make living in these areas very difficult [72]. Finally, scientists are inquiring as to whether it is better to settle in a location that rovers have already explored or an entirely new area. Sending humans to an area where robots have been would mitigate risk and increase probability of success; however, the argument can be made that exploration should occur in a new area of the planet to achieve a more complete understanding of the Martian environment. Potential colony locations on Mars have been assessed based on these criteria.

Southern Meridiani Planum

The Meridiani Planum, site of the Opportunity rover, is appealing for many reasons. It is a large and flat surface that would be perfect for landing and establishing a human settlement

[73]. The possibility for water lies in mining sulphate-rich sediments and heating them to release water to be used by the settlement⁷⁴. The Meridiani Planum is also scientifically interesting; it is home to very old Martian rocks that date back to a time when Mars and Earth were similar [73]. Moreover, there are ancient salt lake deposits, various craters, and river valleys that are of interest to scientists [73].

Gale Crater

Gale Crater, home to the Curiosity rover, is another potential location for a human outpost. Similar to the Meridiani Planum, scientists are familiar with the area from data and images Curiosity has relayed to Earth. The landing site would be at the center of the landing ellipse for Curiosity, which has already been thoroughly assessed and analyzed, as well as proven through Curiosity's successful landing [75]. This landing site is located at a very low altitude, which is advantageous for entry, descent, and landing operations due to the increased atmosphere to help decelerate the spacecraft. It is located at an equatorial altitude, so the temperatures would be moderate and the sun pattern would be similar to Earth's. Gale crater has many scientifically interesting areas including evidence of a lake, indigenous Martian carbon, and confirmed habitable environments [75]. Unfortunately, water will most likely not exist near the surface as in other Martian locations; however, water could be extracted from minerals and the atmosphere.

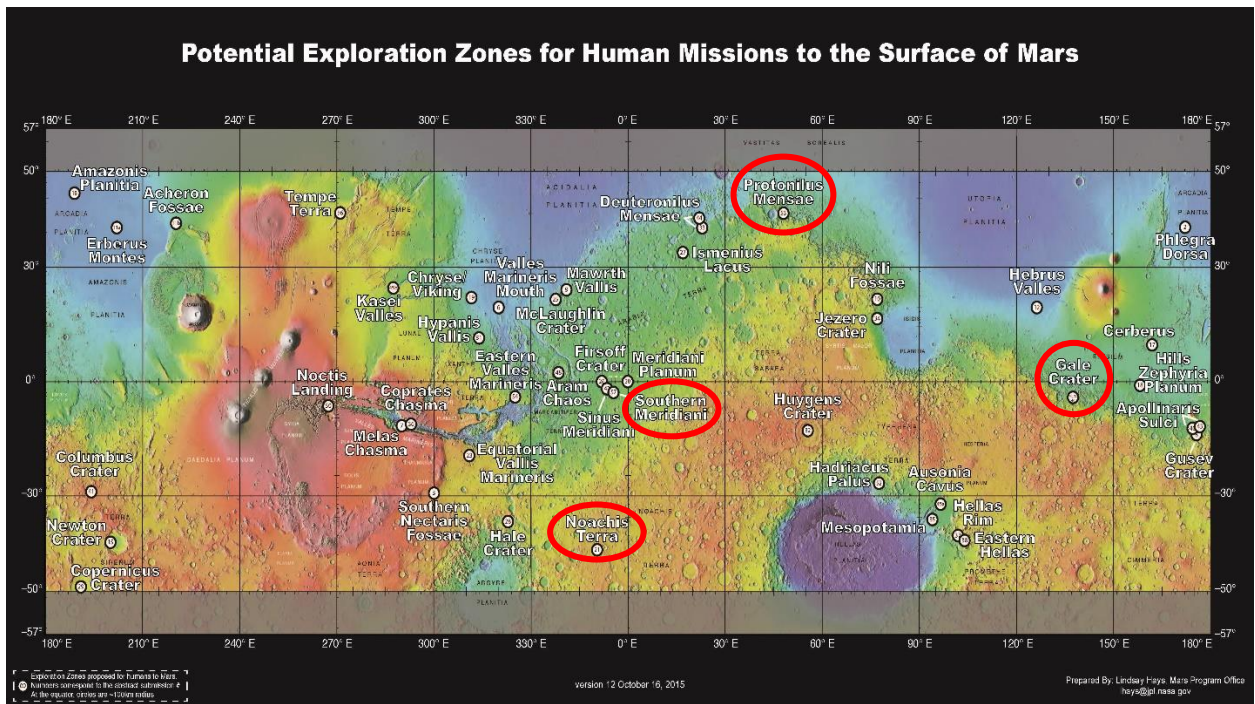
Protonilus Mensae

Protonilus Mensae is a high-latitude area not previously explored with rovers that has an abundance of ice in glacier [72]. This water could be home to past or present life on Mars, and it would also be beneficial for sustaining the astronaut colony. Protonilus Mensae is very close to Moreux Crater, an area that holds scientifically interesting geology [75]. Although there is an abundance of resources and regions of interest, it would be challenging for astronauts to survive in this high latitude. The sun would be absent for months during the winter, and the cold temperatures would threaten the survival of the astronauts and space systems. A trade study would need to be conducted as to whether or not the area is worth designing the mission to survive these harsh conditions.

Noachis Terra – Russell Crater

Russell Crater, located inside Noachis Terra, is a scientifically interesting area that could provide a suitable landing site on Mars. Russell Crater is home to linear gullies, a feature first observed by the Mars Reconnaissance Orbiter that has puzzled scientists for over a decade [78]. Linear gullies are paths with raised banks along the sides, similar to water flows on Earth. Some gullies end with a pit at the end, which scientists believe may be due to a block of ice traveling down the gully and sublimating at the end [78]. Sending humans to the Russell Crater would provide insight about what causes linear gullies. If ice does exist in these gullies, it could be used to supply water for a human colony. Russell Crater is about 134 kilometers in diameter and is at a low altitude, which would provide a sufficient landing site for spacecraft [79].

The Southern Meridiani Planum, Gale Crater, Protonilus Mensae, and Noachis Terra are circled in the figure below [77].



7. Conclusions/Moving Forward

Human space exploration has evidently provided many benefits to society, and space travel continues to offer novel advancements for humanity. These advancements are in areas such as atmospheric modeling, medical technologies, and household chores. A Mars colony would produce many other technologies with profound applications here on Earth. However, many technical challenges must be overcome before a human Mars colony is feasible. These challenges include equipping humans and systems for radiation exposure, overcoming the lack of plant necessities on Mars, surviving in a low-gravity environment, integrating robotic and human capabilities to complete tasks and solve problems, and choosing a Mars outpost location. Ideas such as artificial gravity, in-space gardens, and a human-robotic interaction were analyzed and assessed as potential solutions for these challenges. Moreover, factors for choosing a landing location were identified and potential landing sites were assessed. Engineers and scientists continue to undertake these challenges, and many advancements have been made prove these obstacles are surmountable. Based on this progress, further research and recommendations can be made that will help further prepare for the journey to Mars.

There is still much work to be done in preparation for a journey to Mars. Future IQP teams may propose solutions for additional challenges a Mars mission will face, such as dust mitigation and long-lasting power systems. They may wish to delve deeper into one specific challenge and develop a well-thought out and detailed solution for the chosen issue. In addition, a more detailed plan of how ISRU capabilities will assist in the Mars mission, such as through asteroid mining, should be completed.

The great benefits to humanity that space exploration has provided justify the time, effort, and risk that have been invested. Overcoming the challenges that hinder long-term human space exploration is not an easy feat, but has the potential to deliver great advancements to society. By building on the significant work that has already been accomplished, the scientific community can continue to solve the challenges space colonization presents in order to bring humanity closer to Mars.

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