A REVIEW OF STRUCTURAL AND SYSTEM DESIGN OF MARS ROVER CURIOSITY AND PERSEVERANCE

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Abstract

This review paper aims to gather currently available information on the Mars rover Perseverance and Curiosity, and attempt to analyze them in terms of structure and system. The Mars Rover Perseverance and Curiosity are the latest Mars exploration rover from the National Aeronautics and Space Administration (NASA). The Mars rovers have the ability to explore, collect and analyze samples themselves, while being remotely controlled from Earth. Three components of the rover are analyzed, the body, wheel, and arm. The purpose, design principle, structure, mechanics, and thermal analysis of each part is reviewed based on available research. A review and discussion of possible improvements to the rover are also reviewed. From the analysis, the rovers' body can provide structural support, while providing sufficient thermal requirements for its systems. The rover's wheel is rigid, providing resilience and structural support, while utilizing the Rocker-Bogie mechanism. Lastly, the arm and turret systems have the capability to support its equipment load by utilizing several systems such as the Caging mechanism and flex cable systems, while also accounting for thermal conditions.

Keywords: **Mars rover curiosity; Mars rover persévérance; Mars rover; Mars exploration; Space engineering**

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Introduction

In the vast and ever-expanding universe, perhaps one of the most intriguing places for the humans to research and explore are the planets, especially ones that could potentially be habitable. Enter Mars, the planet that is both reachable and is the most similar to earth in the entire solar system.

Although Mars is relatively similar to earth, there are some major limitations that make human exploration on Mars extremely difficult: (Learn, 2023) long traveling time, major environmental differences, etc. Moreover, to aid human exploration on Mars, we must use rovers instead. Rovers are a type of vehicle designed to be operated on a surface of any solid-surfaced celestial body, or planet. Generally designed to operate autonomously or with minimal input from humans, however, some rovers were designed to operate as a land vehicle for the crew members. Most rovers, especially Mars rovers, are designed to explore and collect samples to further examine and experiment with.

Mars rovers (Mars Exploration Rover, MER) are essentially rovers that operate on Mars to explore the Mars terrain and obtain samples to experiment with. There has been a total of 6 rovers on Mars, 5 being American, and with one being Chinese. As of 2023, 3 rovers are active: Curiosity, Perseverance, and Zhurong. The other 3 are retired: Sojourner, Spirit, and Opportunity (NASA, 2021). There have been a total of 5 (successful) American Mars rovers, which are listed chronologically as follows: (Sojourner 1997; Spirit 2004; Opportunity 2004; Curiosity 2012) and the (Perseverance 2021; Urbain, 2023).

Figure 1. From left to right shows MER: Spirit & Opportunity; Sojourner; and Curiosity (Varga, 2021)

History & Mission

Sojourner was the first ever rover to land & operate on a foreign planet. It was a part of the Mars Pathfinder mission, which was established to serve as a demonstration that sending instruments to Mars can be done inexpensively and effectively (NASA, 2013). The mission also required the rover to return geological & atmospheric data and soil properties as well. The rover landed along with the Pathfinder lander on Mars on 4 July 1997 (Siddiqi, 2018). The rover was the lightest, weighing only 10.5 kg, and traversing just over 100m on the Martian surface.

Spirit & Opportunity were the next two rovers up. They were a part of the Mars Exploration Rovers mission. The mission was established to find evidence of water on Mars (NASA, 2019). The two rovers were significantly more significant than the Sojourner, weighing in at 185 kgs. They both fulfilled their missions of finding evidence of water on Mars.

Curiosity was a part of the Mars Science Laboratory mission. Its objective was to determine the climate & geology conditions, and determine the habitability on Mars, past and present (NASA, 2009). Curiosity's mission was to explore the Gale Crater, in which the mission is ongoing. It found that Mars once had the ability to support microbial life (NASA, 2014). The rover is significantly larger than the previous rovers, being car-sized. It weighs almost 900kg, and so far, has traveled just under 30 km.

Perseverance is the latest rover to land on Mars to date. It was a part of the Mars 2020 mission. The main objective of the mission was to find further details of habitability of Mars in the past, collect rock samples, and test oxygen production for future manned missions (NASA, 2021). Its mission was to explore the Jezero crater, in which the mission is ongoing. The rover also had the "Ingenuity" helicopter with it. Perseverance weighs a little more than its predecessor, coming in at 1,025 kg, having a similar structure to the Curiosity (NASA, 2020).

It can be observed that in each iteration of the rover, each rover has its own designated missions and duties, along with different landing sites on the Mars, and consequently, each rover was fitted with different tools and equipment necessary to fulfill its designated mission. The rovers in each iteration were also larger and heavier.

In this review paper, we will be diving into the two latest iterations of the NASA rovers: The Curiosity and The Perseverance for their practical and engineering design considerations of their general designs, rover bodies, wheels, and their robotic arms. The review paper's structure can be seen in Figure 2 below.

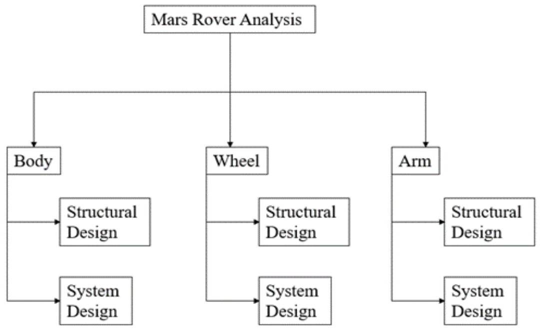

Figure 2. Overview of the paper's structure

Curiosity and Perseverance Comparisons

The two rovers have many similarities among them. They are similarly sized, have similar tools, and are designed with similar principles to withstand similar environments due to them both being Mars rovers. However, they still have some differences among them due to their different designated missions and duties, along with the technological advancements between both the rovers' iterations.

First difference: their designated missions. As mentioned in the History & Mission section, the Curiosity was sent to assess whether the Mars environment could support microbial life by analyzing for organic molecules in the collected rock and soil samples, while the Perseverance, the newer generation of the two, was sent to do similar objectives but with additional tasks of collecting rock samples, caching them for future missions (as opposed to on-board analysis by the Curiosity) and testing for the oxygen production.

Second difference: their mission sites. While both were sent to Mars, Curiosity was sent to the Gale crater, and Perseverance was sent to the Jezero crater.

Third difference: Technological upgrades to their tools and equipment. Although the design and equipment of the two rovers are similar, the Perseverance, as a newer iteration of the rover, was equipped with upgraded versions of the equipment used in the perseverance, such as the cameras and power systems. The Perseverance was also equipped with entirely new equipment in the Ingenuity helicopter as well.

Fourth difference: size and weight difference. Although Perseverance's design was based off the Curiosity, both being described as "car-sized" (shown in Figure 1), its size and weight are slightly higher than that of the Curiosity. With more equipment and tools, the Perseverance's weight comes up a little higher than the Curiosity, at 1,025 kgs as opposed to roughly 900 kgs.

In the sections below, we will go into the details of the design considerations of each component of the rovers (rover body, rover wheels designs, and the arms.) i.e., what systems are in the aforementioned components, what materials they are made of, what considerations were taken into the material and design selection, etc.

Body

The body's primary functions are to transport and preserve the rover's computer, electronics, and instrument system. The protected rover's essential components and temperature controls are thus kept in the rover's strong outer layer (NASA, 2020). Due to the unique Mars environmental surroundings, the atmosphere, and the geographical characteristics, various materials must be studied and analyzed for Mars missions. Figure 3 shows the main body of the rover.

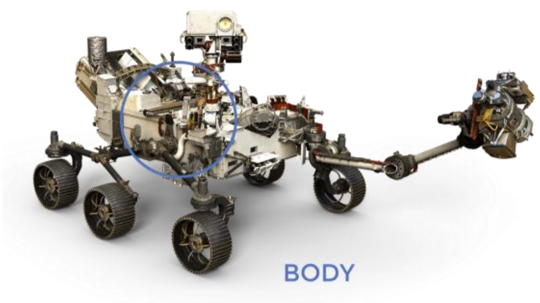

Figure 3. The rover's main body (circled) (NASA, 2017)

Structural Design

Design Principles

The Perseverance rover's design is inspired by the concept of NASA's Mars Science Laboratory rover, the Curiosity. The latest advancement of technology has allowed for the improvement of exploration (NASA, 2020). The ability to sample and cache minerals are the top priority of the new design. As a result, new coring drills are added to collect samples, seal them in tubes, and place them on Mars' surface (Novak *et al.*, 2022). On top of the electronic box is a piece known as the Rover Equipment Deck (RED). It is designed to resemble the appearance of a convertible car, letting the rover mast, allowing cameras to sit outside and take clear pictures of Mars' terrain (NASA, 2020).

The chassis is designed to improve the mobility range and duration of Mars rovers by redesigning specific aspects of the previous Mars rover concept (Michaud *et al.*, 2002). Due to the concept of rigid wheels, which do not contain any motor or spring elements, the loads on which the wheels with actuators are placed must be well distributed. It is also necessary to preserve the rovers' linkages in order to transverse on uneven terrain on Martian surfaces (Ellery *et al.*, 2005). Furthermore, to withstand the impacts and absorb shock when the rover is traveling over rocky terrain, the chassis of the body should be designed according to the required specifications (Michaud *et al*., 2002; Michaud *et al*., 2004).

The structure is divided into several sections: the chassis frame is located at the bottom and sides; the Rover Equipment Deck is placed at the top; the bottom section is called the belly pan and is for the new Sampling and Catching inner workspace, which is released shortly after the rover lands. This workspace is thus exposed to the Martian atmosphere to make more space for sample handling operations (NASA, 2009, 2020).

Material Selection

The atmosphere of Mars consists of 95.32% carbon dioxide, 2.70% nitrogen, 1.60% argon, 0.13% oxygen, and 0.08% carbon monoxide, as well as trace amounts of water vapor, nitrogen oxide, neon, hydrogen-deuterium-oxygen, krypton, and xenon (Williams, 2023). The greenhouse effect does not have a large impact on the red planet due to the immensely thin atmosphere, which causes extreme temperature fluctuations. The average temperature is approximately -63°C, with daily temperatures ranging from -89°C to -31°C. Furthermore, a temperature difference of -10°C within 1.5m of distance exists. As a result, a dust storm forms between the hotspots and their surroundings, eventually leading to the name Dust Devils (Sharma *et al*., 2021).

Magnetic airborne dust is induced by minerals such as hematite. The salinity of the soil, signs of riverbeds, the appearance of water bodies, sharp teeth-like rocks, cements, volcanoes, and crates are commonly discovered as geographical characteristics on Martian surfaces (Sharma *et al*., 2021). As a result, the following factors should be considered when selecting materials: Mars has a different atmosphere condition, this means it has a different ambient temperature; the rover must have a minimum temperature range (Sharma *et al*., 2021); the atmosphere also has a lower pressure than Earth, which is considered when attempting to preserve sensitive scientific instruments(Williams, 2023); due to the possibility of corrosion, the material must be resistant to corrosion to a certain degree; with the presence of magnetic dust, the material must not be ferromagnetic to a certain level; the radiation level must also be considered as Mars (Sharma *et al*., 2021); lastly, weight optimization is an important factor, as the structure must be sturdy, while having the lightest weight possible (Sudnik, 2020). The rovers such as Curiosity or Perseverance usually use metals as the main material (stainless steel, aluminium, copper, titanium, tin, and zinc) (Sudnik, 2020; Sharma *et al*., 2021). From our assumption, the material of the body is likely to be a combination of metal alloys, such as stainless steel and aluminium.

System Design

Hardware (Kempenaar *et al*., 2018)

The Perseverance rover’s design is based on the MSL rover. The Perseverance rover is slightly bigger and heavier than the MSL rover, Curiosity. The Multi-Mission Radioisotope Thermal Generator (MMRTG) has been moved back, and its chassis has been stretched longer. The rover’s mass is higher from the 899 kg flown on MSL to roughly 1,025 kg on Perseverance. In table 1 below, technical comparisons of the two rovers are shown.

Table 1. The Rover’s Body Technical Specification (NASA, 2009, 2020)

Tech Specs	Curiosity	Perseverance
Length	3 meters	3 meters
Width	2.7 meters	2.7 meters
Height	2.2 meters	2.2 meters
Weight/Mass	899 kilograms	1025 kilograms
Structure	The chassis frame is at the bottom and sides; the Rover Equipment Deck is at the top.	The chassis frame is at the bottom and sides; the Rover Equipment Deck is at the top; the bottom section is called the belly pan and is for the new Sampling and Catching inner workspace.

Figure 4 depicts the rover and engineering hardware that is mounted externally. Most of the external hardware is the same or similar to what was flown on MSL, with the exception of the new SCS. The Remote Sensing Mast (RSM) on the Perseverance is similar to the MSL in that it employs the same actuators and mechanisms. The two most obvious modifications to the RSM are the addition of sensors for the Mars Environment Dynamics Analyzer (MEDA) instrument mounted along the mast and the reduction of Navigation Cameras (NavCams) on the MSL to two units.

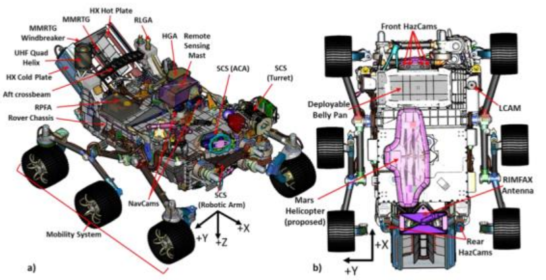

Figure 4. External hardware of Perseverance Mars rover in (a) isometric view and (b) bottom view (Kempenaar *et al*., 2018)

The interior of the rover is divided into two distinct enclosures: a sizable, fully enclosed area in the back and a smaller, partially enclosed area in the front with the Adaptive Caching Assembly (ACA). The rover's Heat Rejection System (HRS) regulates the rear enclosure's temperature, which contains electronics and instruments that would otherwise need survival heaters to withstand the extremes of the Martian environment.

Thermal Design Driver (Kempenaar *et al*., 2018)

The external Mars environments and the rover's hardware are the two main factors affecting the temperatures of both internal and external hardware. The thermal designs were to be designed with the most extreme environments as guidelines. Eight potential landing sites were identified with the Environmental Requirements Document (ERD), with Holden Crater having the most severe temperatures. The thermal systems were therefore designed based on Holden Crater environments.

After the majority of the thermal design was completed, the candidate landing sites were narrowed down to Columbia Hills, North East Syrtis, and the Jezero Crater. The thermal environments used for design were not updated despite Columbia Hills having the most extreme thermal environment of the remaining candidate landing sites. As Columbia Hills is not much different than Holden Crater.

The general thermal design methodology of Perseverance is the same compared to MSL. The simplest zone is that of uncontrolled hardware, where thermal control is entirely passive. The typical Allowable Flight Temperature (AFT) ranges for uncontrolled hardware are -128°C to +50°C, though they may require heaters to function.

Due to its low resistance to the harsh Martian environment, some hardware may rely on the Heat Rejection System (HRS) for thermal control. Additionally, it may rely on independent survival heaters with hardware-specific set points. The HRS provides thermally controlled hardware with AFT ranges of -40°C to +50°C. The battery is a special case; even though it is mounted to the RAMP, AFT range is not acceptable, so the battery is thermally isolated from the RAMP and uses heaters to reduce its AFT range to -20°C to +30°C for the surface phase of the mission.

Like most external hardware, the MMRTG thermal control is entirely passive during the surface phase of the mission, but because of the MMRTG's high thermal dissipation, its AFT range is increased from +65°C to +200°C. It is important to note that the MMRTG initially performed hotter than anticipated during the MSL mission, increasing the maximum AFT for the Perseverance rover from +191°C to +200°C. The heat received from the MMRTG has increased the AFT range of the heat exchangers on the back of the rover, which are located relative to other external hardware, from -90°C to +100°C.

Perseverance represents a significant advancement over Curiosity, being slightly larger and heavier to accommodate additional scientific instruments. Its revised chassis ensures better navigation and a longer operating duration by improving mobility and endurance on Martian terrain. Perseverance also has more plutonium dioxide than Curiosity and a redesigned Multi-Mission Radioisotope Thermal Generator (MMRTG) location, which ensures continuous power generation for longer exploration missions. This new design feature enables Perseverance to collect and preserve geological specimens with precision.

Wheels

The main function of wheels is to provide traction for rovers to travel across the Martian terrain, mostly consisting of sand, sharp rock, and gravel (NASA, 2022). Figure 5 depicts the wheel of the Perseverance rover.

Figure 5. The Mars rover's wheel (Kooser, 2020)

Structural Design (Haggart and Waydo, 2008)

Wheels are one of the most essential parts of rovers because they provide the ability for rovers to travel across the planetary surface. Without the wheels, rovers will only be stationary electronic boxes on another planet. To design wheels, there are several requirements and limitations to take into account in order to make them function properly.

First, the wheels' size and diameter cannot be too large because of the space limitation of their transport vehicles from Earth to Mars. In other words, the wheels must have the appropriate size in order to fit inside the rocket and aeroshell during a launch phase, as well as a descent-landing phase.

Second, the weight of the wheel should be optimized so that the minimum weight is achieved, and the strength also meets the criteria. The wheels should be able to handle the load during the landing phase. Also, the wheels should be able to support the weight of a rover without significant structural failure.

Third, the wheels of a rover should be able to bring a rover across various Martian terrain which mostly consists of sand, sharp rocks, and gravel. These types of terrain could make serious problems for the wheels such as dents, punctures, slip, and sink. Therefore, the wheels should be designed in order to handle these harsh terrain conditions. With all requirements mentioned in the previous part, special structural features have been added to rover wheels which are grousers, wheel geometry, flexures, and stiffening rings.

Grousers' design

Grousers are a feature that protrudes from a wheel skin. Their primary function is to provide traction for the wheels when moving across Martian terrain, especially in loose soil. Moreover, they give some additional strength to the wheel structure (Haggart and Waydo, 2008). Figure 6 shows the grousers' pattern. There is a study about the effect of grousers when the wheel moves on loose soil, and the result, Figure 7, clearly shows that the wheel without grousers experiences a large slip when moving on loose soil with just only a little slope. So, this result clearly elucidates that grousers are necessary for the traversing of Mars rovers since the sandy terrain can also be found on Mars (Iizuka *et al*., 2011).

The slip ratio can be calculated by (Iizuka *et al*., 2011):

$$\text{Drive; } \lambda = 1 - \frac{V\omega}{r\omega} \quad (1)$$

$$Brake; \lambda = 1 - \frac{r\omega}{V_\omega} \quad (2)$$

When designing grousers, there are many parameters that can be changed such as the pattern of grousers, the height of grousers, and the number of grousers. Modifying these parameters will directly affect the traction performance of the wheels.

Figure 6. Grouser's pattern at different angles (NASA, 2021)

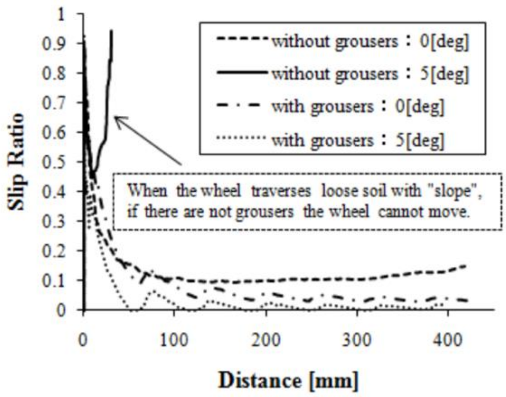

Figure 7. Line graph showing the relationship between slip ratio and distance (Iizuka *et al*., 2011)

Grousers' pattern (Iizuka *et al*., 2011)

There are various patterns of grousers that can be used on the wheel surface, for example, parallel, slanted, chevron, and offset V - shapes. Figure 8 shows some of the different grousers patterns. These patterns help to prevent side slips when the rover travels up the inclined terrain by increasing the lateral forces (F_y). Figure 9 shows the forces on a wheel when on an incline. However, some patterns can also add drawbacks to the wheel, especially the pattern with sharp edges. Having sharp edges causes high-stress areas which can severely damage the wheel surface, like the chevron pattern in Curiosity Rover. For Perseverance, the pattern of grousers has been changed to a slightly curved pattern to reduce the stress concentration while keeping good traction performance.

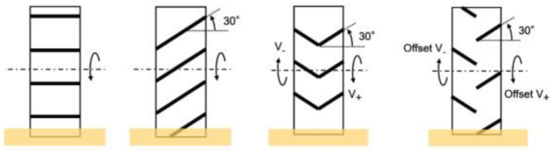

Figure 8. Diagrams of different patterns of grousers (Nagaoka *et al*., 2020)

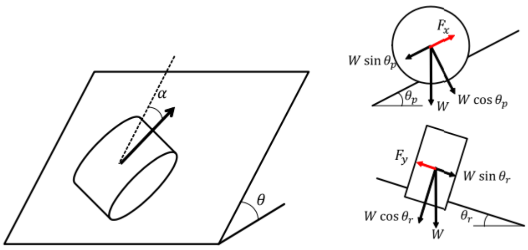

Figure 9. Diagram showing FBD of a wheel traversing incline (Inotsume *et al*., 2019)

Grousers' height (Ding *et al*., 2011)

Increasing the height of grousers can improve the drawbar pull of a wheel. Long grousers are suitable for traversing on soft and sandy terrain. On the other hand, short grousers are suitable for traversing on hard and flat terrain. Grousers also help to increase the radius of the wheel by their height when the soil is fully packed between them. However, there are limitations and constraints for choosing their height, for example, the wheel radius/grousers height ratio.

Number of grousers (Lawton, 2020)

To find the minimum number of grousers, the Bekker relationship and grouser equation are used, as well as Martian soil properties which can be obtained from ESA.

Bekker pressure-sinkage relationship:

$$Z = \sqrt[\left(n-\frac{1}{2}\right)]{\frac{3W}{bk\sqrt{D}(3-n)}} \tag{3}$$

Where:
Z = sinkage(cm)
n = sinkage index
W = weight of the rover(N)
b = wheel width(cm)
k = coefficient of proportionality

Grouser equation:

$$\phi = \frac{1}{(1-i)}\left(\sqrt{\left(1+\hat{h}\right)^2 - (1-\hat{z})^2} - \sqrt{1 - (1-\hat{z})^2}\right) \tag{4}$$

Where:
i = wheel slip
$\hat{h}$ = grouser height normalized by wheel radius
$\hat{Z}$ = sinkage normalized by wheel radius

Figure 10 depicts the wheel geometry.

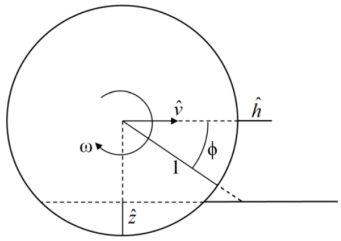

Figure 10. Diagram showing geometry of a wheel (Skonieczny et al., 2012)

The minimum number of grousers, g_n, is:

$$g_n = \frac{2\pi}{\phi} \tag{5}$$

Flexures are a structure that connects the tire and the drive source together. They provide strength for a wheel when the combination of loads acts on it. The geometry of the flexures is designed so that they can handle the load in all 6 degrees of freedom. Figure 11 shows the wheel flexure. Moreover, the stiffness in each degree of freedom of the flexures can be tunable. Another structural feature, the stiffening ring, is located at the mounting plane of flexures. It helps to distribute the loads and restore hoop stress when the tire deforms (Haggart and Waydo, 2008). Figure 12 depicts the Curiosity's wheel components.

Figure 11. Photograph of a wheel flexure (Haggart and Waydo, 2008)

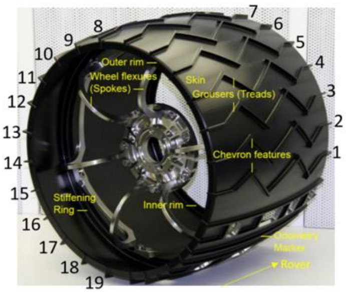

Figure 12. Photograph of the wheel, with components labeled (Haggart and Waydo, 2008)

Tires' material

Since Mars' surface environment is different when compared to Earth, although similar. On Mars, it has volcanic craters and dust that could create dust storms (Dunbar, 2023). As a result, the Mars rover will require strength and resistant wheels to navigate the rocks and trenches it will encounter. The current-generation rover's wheels, the Perseverance, consist of three wheels on each side, each measuring 20.7 inches in diameter, and are made of aluminium (NASA, 2009). Aluminium is an excellent material for wheels since it is lightweight yet maintains strength and is ductile even at low temperatures (Raj *et al.*, 2021). The temperatures on Mars were low, reaching -153 degrees Celsius (NASA, 2022).

Flexures' material (Lawton, 2020)

This part is what carries the overall weight of the tire by welding on all six sides of the tire. Thus, titanium alloy is the material to be utilized, and the beta-alpha kind of titanium is known as Ti-6Al-4V. The selected type of titanium alloy has higher strength and durability than others and is relatively light in weight compared to other materials, as shown in Table 2. In the flexures, it is necessary to choose a high-strength material to withstand the impact when the wheel touches the surface of Mars.

Table 2. Mechanical Properties of Metal Alloys (Lawton, 2020)

Name	Density (g/cc)	UTS (MPa)
Al 2014-T6	2.8	483
Al 2024-T6	2.78	427
A-286	7.92	620
Al 7475-T7651	2.81	531
ASTM 310	7.89	550
Al 5456-H343	2.66	435
5Al-2.5Sn-Ti	4.48	861
Ti-6Al-4V	4.43	950

Legs' material

Connecting the wheels to the rover's body are legs, which can help propel the wheels over obstacles such as rocks or holes. It has the capacity to navigate through rock up to 40 centimeters high and a hole up to 25 centimeters in diameter (NASA, 2020). The rover's legs must support the weight of the wheels and other parts that may be attached to the rover, whether it's body or arms.

Therefore, the material used is titanium alloy, which is expected to be Ti-6Al-4V, as it is the strongest, as seen in Table 2. Titanium is also highly resistant to corrosion, making it suitable for the diverse environments encountered on Mars. When compared to other materials in Table 3. It can be seen that titanium can withstand corrosion higher than others. In addition, titanium has a very low thermal conductivity, which can make the wheel legs withstand Martian temperatures well and maintain the internal temperature well to avoid damage(Veiga *et al*., 2012).

Table 3. Comparison of material properties (Veiga *et al*., 2012)

	Ti	Al	Fe	Ni
Corrosion resistance	High +	High	Low	Medium
Thermal conductivity [W/mK]	15-22	221-247	68-80	72-92

Structural Comparisons

The current rover data, Perseverance, was created using the design data provided above. Figure 13 demonstrates the modification in the picture on the right, which will be in the present one utilized. The diameter of the two designed wheels, the current rover named 'Perseverance', is 20.7 inches in size, whereas the previous one was 20 inches, smaller and weighs 150 kilograms lighter (Light, 2023). Perseverance is designed with bigger wheel size since the wheels have to support more load from the rover's weight compared to Curiosity. The current rover's weight is increased due to the addition of foil coating on top to avoid static electricity (UC RUSAL, 2023). From Figure 13 it can be seen that the tire treads of the wheels are different in terms of spacing and appearance. The Perseverance rover has twice as many grousers, 48 grousers, as the old one, 19 grousers. The increase in the number of grousers reduces the chance that the rocks will be stuck between the grousers, as well as improve the mobility of the rover. Additionally, the grousers of Perseverance has a slightly curved shape (Light, 2023; UC RUSAL, 2023) compared to the chevron grousers in the Curiosity rover. The new grousers in Perseverance provide a better grip on sandy terrain and allow the wheel to withstand pressure from rocky surfaces (Lawton, 2020). Also, they reduce the stress concentration effect which can be found at the sharp edges of the Curiosity rover's wheels with chevron grousers.

Figure 13. Visual comparison between the Perseverance and Curiosity's wheel (NASA, 2020).

System Design

Suspension

NASA has begun installing this system on the sojourner rover. The installation was carried out in a 6-wheel rocker-bogie suspension system. The system's design is used by many spacecraft to explore whether it's spirit, opportunity, or curiosity until today's rover called Perseverance still uses this system in the form of six wheels. The rocker-bogie suspension system was used for missions to explore the rugged Mars terrain. As an important part of the rover, the system allows the rover to climb over obstacles that are higher than the height of the wheels while still maintaining a relatively stable weight distribution across all six wheels (Chinchkar *et al*., 2017).

This system has three components: differential, rocker, and bogie. Firstly, the differential is a pivot in the middle of the upper deck of the rover, connecting it to the left and right rockers as well as the rover's body. Secondly, It's the part that connects the front wheel to the differential and the back of the bogie. This part is a rocker, there will be one on the left and right side. Lastly, the bogie that's what connects both the front and the back wheels to the rocker. (Haggart and Waydo, 2008; Kempenaar *et al*., 2018) Figure 14 shows the rocker-bogie mechanism.

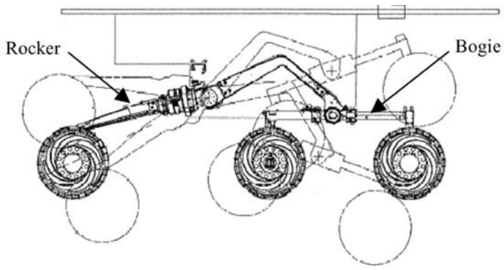

Figure 14. Diagram of the Rocker-Bogie mechanism (Maimone *et al*., 2006)

In this system, the main components are bogie and rocker. The bogies consist of a pair of wheels on each side so that in one rover, there are four wheels in the bogie, each of which has a freewheeling mechanism. Then the bogie is connected to the rocker by the connection in a V shape. As for the rockers, there will be wheels on each side. This works in that when the rover's wheels encounter an obstacle, the wheels that will be hit first are the two front wheels. The middle and back wheels are the wheels that provide support or thrust to the front wheels, which allows the front wheels to lift themselves over those obstacles. (Vishwas and Satish, 2017)

The rocker-bogie mechanism will distribute the weight of the rover equally for each wheel. To determine the dimensions of this mechanism, the following formulas can be used, assuming that the ground is smooth. (Nuñez *et al*., 2021) Figure 15 shows the diagram of the Rocker- Bogie mechanism.

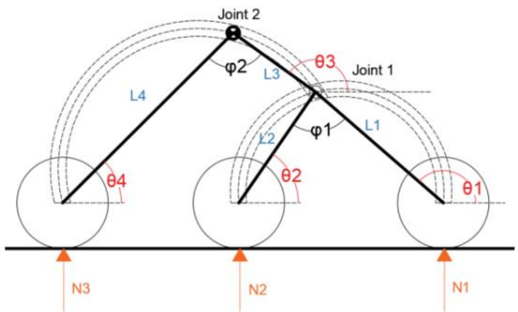

Figure 15. Diagram showing dimensions of Rocker-bogie mechanism (Nuñez *et al*., 2021)

$$\theta_1 = \theta_2 + \varphi_1 \quad (6)$$

$$\theta_3 = \theta_4 + \varphi_2 \quad (7)$$

$$\theta_1 = \sin^{-1}\frac{r_2 - r_1 + h_2 - h_1}{\sqrt{(l_1 - l_2\cos\varphi_1)^2 + (l_2\sin\varphi_1)^2}} - \tan^{-1}\frac{l_2\sin\varphi_1}{l_1 - l_2\cos\varphi_1} \quad (8)$$

$$\theta_3 = \sin^{-1}\frac{r_3 - r_1 + h_3 - h_1 - l_1\sin\theta_1}{\sqrt{(l_3 - l_4\cos\varphi_2)^2 + (l_4\sin\varphi_2)^2}} - \tan^{-1}\frac{l_4\sin\varphi_2}{l_3 - l_4\cos\varphi_2} \quad (9)$$

$$N_1 = \frac{Mgl_2l_4\cos\theta_2\cos\theta_4}{2(l_1\cos\theta_1 - l_2\cos\theta_2)(l_3\cos\theta_3 - l_4\cos\theta_4)} \quad (10)$$

$$N_2 = \frac{-l_1\cos\theta_1}{(l_2\cos\theta_2)}N_1 \quad (11)$$

$$N_2 = \frac{Mg}{2} + \frac{l_1\cos\theta_1 - l_2\cos\theta_2}{(l_2\cos\theta_2)}N_1 \quad (12)$$

Arm (Moeller *et al*., 2021)

The robotic arm is perhaps one of the most crucial components of the Perseverance rover. It serves as a mobility medium for the many-equipped instruments of the rover for the Mars rock sampling and caching task of the Mars 2020 mission. The Robotic Arm (RA) itself is a subsystem of the "Sampling and Caching Subsystem (SCS), which comprises two smaller subsystems: the RA & tools turret assembly and the Adaptive Caching Assembly (ACA.) The two subsystems (RA & turret) + the ACA work together to perform Mars rock sample sampling and caching duties. Figure 16 below shows the arm components (SCS) of the Perseverance.

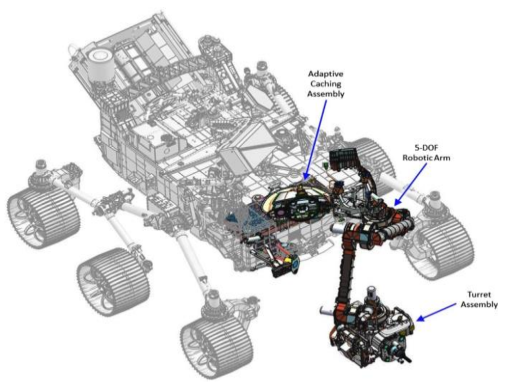

Figure 16. The Mars 2020 rover (Perseverance) with the SCS components highlighted (Moeller *et al*., 2020).

While the Robotic Arm (RA) and the tools turret assembly of the Perseverance are almost identical in design to the older Mars Scientific Labs (MSL) rover (the Curiosity) with slight adjustments due to slightly heavier load on the tools turret assembly, the ACA system is a completely new system installed on the Perseverance to serve the sample-caching duties of the Mars 2020 mission. In this section, we will be focusing mainly on the design principles & materials of the Robotic Arm (RA) and the turret assembly.

Structural Design

Design Principles of RA & Turret Assembly (Moeller *et al*., 2021)

The responsibilities of the Robotic Arm (RA) are to position the tools turret assembly to its desired position, maintain that said position during the operation of the tools on the turrets, and return & dock the samples obtained to the ACA for processing, sampling, and also drill bit exchange. The Robotic Arm & turret assembly design must consider the stated responsibilities.

When talking about the desired position of the tools turret assembly, the term "Primary workspace" is then introduced. The term refers to the optimal positioning target for the tools turret through the RA. The workspace is a cylindrical volume, with a base diameter of 80 cm, and height of 100 cm, and is located 120 cm in front of the main rover body & 20 cm below the flat surface the rover is positioned on. Note: the turret itself has a rough diameter of around 75 cm. Figure 17 depicts the workspace volume of the Perseverance.

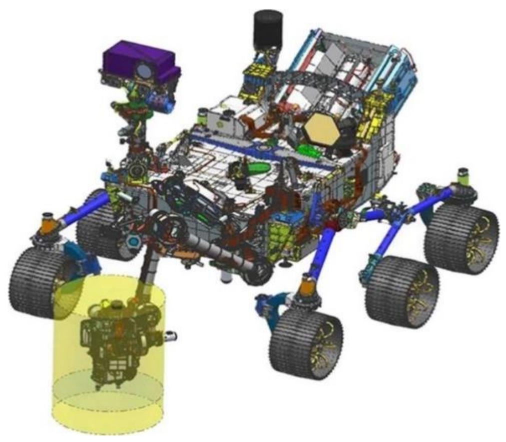

Figure 17. Mars 2020 rover (Perseverance) with the primary workspace volume highlighted (Moeller *et al*., 2021).

The maximum length of the Robotic Arm (RA) when straight in front of the rover body is 2.2m, and as stated in the responsibilities of the RA earlier, it must be capable of lifting and operating the tools turret assembly with a total turret mass of 40.1kg as well.

The tools turret on the Perseverance contains the following tools & instruments (Jens *et al*., 2018; Moeller *et al*., 2021):

1. The drill or the "Corer"
- Drill bit-swappable drill system.
2. Facility Contact Sensor (FCS)
- Precise ground-contact positioning sensor for the tools which require extra placement precision.
3. Gas Dust Removal Tool (gDRT)
- A cold gas-based dust removal system for imaging / sensing tools. gDRT utilizes compressed nitrogen. (Jens *et al*. 2018)
4. SHERLOC and PIXL instruments
a. SHERLOC: Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals
- Biosignature-detecting sensor
b. PIXL : Planetary Instrument for X-ray Lithochemistry
- X-ray fluorescence (XRF) spectrometer with self-supplied X-ray source.

The Robotic Arm (RA) can achieve the positioning requirement through its 5 rotary actuators along the RA & turret assembly, giving the RA a 5 degrees of freedom of movement. The joints utilized on the RA are as follows: turret joint, shoulder elevation joint, elbow joint, wrist joint, and the shoulder azimuth joint. For most of the tools & instruments on the turret (SHERLOC, PIXL, gDRT, and the FCS), only the precise positioning of the turret at the target position is required, as they are simply proximity-based equipment. However, the same cannot be said about the drill/corer. For the drill, when drilling/coring into the Mars regolith or rocks, there will be a reaction force which will require the RA to exert its force to maintain the position of the corner. Otherwise, the drill would "creep" away from the desired position or not be able to penetrate into the material (Moeller *et al*., 2021). Thus, the Robotic Arm design must consider the required drilling force as well. The Robotic Arm (RA) can exert a minimum of 300 Newtons of force at the tip of the RA while operating in the primary workspace (Moeller *et al*., 2021).

Also, as per the third responsibility of the RA of docking the turret with the ACA to transfer drill bits and Mars samples, the RA must also be able to supply enough force to unload and exchange the drill bits with the ACA. The RA can supply a minimum of 600N of preloading force for drill bit exchanges. (cite entire section) This responsibility is important, due to the fact that the drill bit exchange occurs very often (as a part of the SCS sample caching), instead of only occurring when the drill bits are worn like in the MSL mission with the Curiosity. Since the RA can exert forces, there must also be a force sensor equipment on board the RA as well, and that is exactly what the FTS is for. The FTS system (Force-Torque-Sensor) is a force sensor located on the RA, between the turret itself and the turret joint. The readings from the sensor are used to determine the required amount of preload forces during drilling / ACA docking operations and also for the potential unexpected collision between the turret and its surroundings (the ground or the rover itself) (Moeller *et al*., 2021; Schaler *et al*., 2021). Other than the task/responsibilities - specific design requirements and considerations, structural considerations such as material strengths, weights, and thermal requirements must also be considered as well, which more details will be discussed in the following section: structural analysis.

Structural Analysis of RA & Turret Assembly

The extremely specific details/designs of the Robotic Arm (RA) of the Perseverance are not available to the public, but due to the fact that the RA on the Perseverance is extremely similar to the one of the Curiosity (of the MSL mission) barring the turret weight requirements, we can make an assumption that their design processes are the same, and thus the RA structural analysis is likely to be the same as that of the Curiosity (NASA, 2019; Moeller *et al*., 2021).

Just like any other parts on the Perseverance rover, and any other space-related payloads, the RA & turret assembly needs to be as light as possible while not sacrificing any strength and other important mechanical properties required by their respective missions, in order to ensure that the weight of the payload on each rocket launch are minimum, and thus cutting down on launch costs and ensuring that the 'minimized mass' can be used in some other critical parts/equipment instead (Patnaik *et al*., 1994.). Most of the main "limbs" of the Robotic Arm (RA) of the Perseverance are made from Titanium (Moeller *et al*., 2021; Bailey *et al*. 2022).

In the MSL rover (Curiosity), the Titanium used was the Ti-6Al-4V (Grade 5 Titanium alloy) (Billing and Fleischner, 2011), and we can assume that the same type of Titanium alloy is used in the RA of the Perseverance as well. Titanium alloy possesses an incredible strength-to-weight ratio when compared to other materials. A comparison of the common aerospace materials is presented in Table 4.

Table 4. Common space materials' mechanical properties comparison (ASM International Handbook Committee, 1990a, 1990b; Boyer *et al*., 1994).

Material/ properties	Tensile Yield Strength	Density	Strength / Density ratio
Unalloyed Ti (Gr.1)	310 MPa	4.51 g/cc	68.74
Alloyed Ti (Ti-6Al-4V)	880 MPa	4.43 g/cc	198.65
Stainless Steel (Type 304)	215 MPa	8.00 g/cc	26.88
Aluminium Alloy (7075-T6)	503 MPa	2.81 g/cc	179.00

It can be seen that the Titanium alloy possesses incredible strength while maintaining minimal density. Not only does Titanium alloy possess an incredible strength-to-weight ratio, but it also has outstanding corrosion resistance and thermal properties as well. The latter will be discussed in the next section.

Not only do the main RA limbs have to be able to sustain the load requirements/force preload requirements of the mission, but so do the joints, as they make up the RA & turret assembly. In the MSL rover (Curiosity), the RA assembly goes through a static test to ensure that the arm assembly is strong enough to operate within the designated force & torque ranges without failing. One of the many static test setups is shown below in Figure 18.

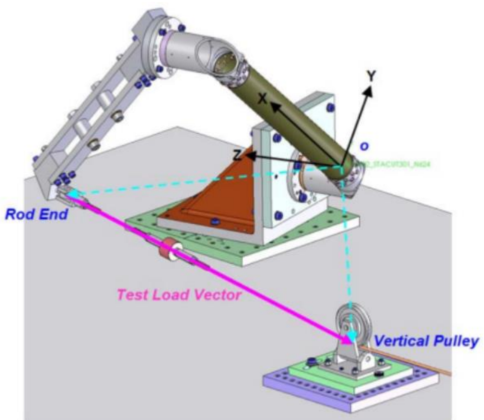

Figure 18. Typical static load testing of the MSL robotic arm (Billing and Fleischner, 2011)

When discussing the structural analysis of the RA & turret assembly, there are also subsystems within the RA & turret assembly that are important to the operation of the assembly as well: the RA caging system and Cabling system (Billing and Fleischner, 2011).

System Design

The robotic arm & tools turret assembly has two main subsystems: the cabling subsystem and the caging subsystem. (Billing and Fleischner, 2011)

The caging system refers to the Robotic Arm (RA) mount, which the RA is mounted onto during the launch from Earth, descent on Mars, and roving operations on Mars. Figure 19 depicts the caging system of the Curiosity. The design of the caging system must consider the extreme temperatures of Mars (considering the expansion of the caging material when meshed onto the RA & turret) and the g forces during launch and landing exerted onto it (to ensure that the RA does not break during launch and landing.) The caging system is designed and planned through dynamic analysis, in which the results help determine which material to use and which actuator (and subsequently the degree of freedom) is to be locked in order to ensure the safety of the Robotic Arm (RA.)

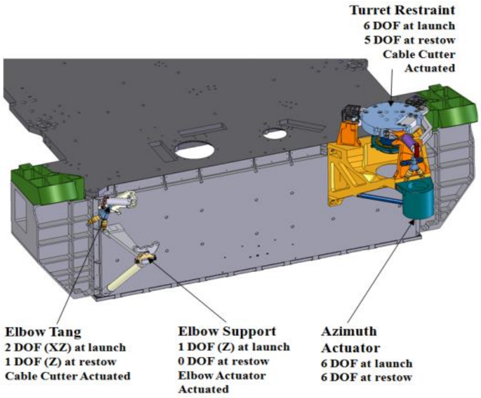

Figure 19. Caging mechanism of the MSL rover (Curiosity) (Billing and Fleischner, 2011)

The Cabling Subsystem (Billing and Fleischner, 2011)

The cabling subsystem refers to the internal cabling systems of the robotic arm, tools turret, and the rover itself. The cables inside of the structure are used to transmit power and transfer data signals of the components. The type of cables used inside of the RA & turret assembly is the 'Flex cables', thin, laterally connected sets of "flat" cables, combining to make a sheet of cables as shown in Figure 20 below. The cables are configured in such a way that makes the operations of the components not interfere with each other, i.e., intricate data signal cables from the tools are separated from the 'noisy' power transmitting cables. The design priority of the cabling system is the longevity of the cables themselves, as the cables inside the RA will be extended and contracted constantly during the rover's operations. Thus, the cables must be contained from potential Mars dust that could act as an abrasive and further shortening the lifespan of the cables. Phenolic seals are used to prevent intrusion of the particles. The cables are stored in a spool when the arms are in a contracted position, and dry lubricant of MoS_2 (Moly Disulphide) is used on the cabling spools, allowing it to operate in the extreme cold without requiring an external heater.

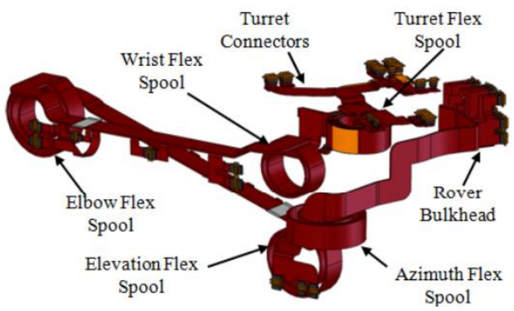

Figure 20. Flex cabling system of the MSL rover (Curiosity) (Billing and Fleischner, 2011)

Thermal Analysis of RA & Turret Assembly (Kempenaar *et al.*, 2018)

In addition to meeting the specified strength and weight requirements of the Mission, the RA & turret assembly must also meet the thermal requirements as well. When discussing the thermal requirements, two criteria are present: material survivability in the Martian temperatures, and CTE (Coefficient of Thermal Expansion) requirements within the arm assembly, i.e., ensuring that when the entire arm assembly is built, the chosen material will not fail under the extreme Martian temperatures and not expand beyond the expected margins and interfere with other parts in the arm assembly. To design the RA & turret assembly, the "extremes" temperature of the potential mission landing site must be considered as the baseline operating temperature of the assembly. Initially, the temperature requirement specified in the ERD, Environmental Requirements Documents, was to be the most extreme temperatures within the latitude range of 30N and 30S. However, the selection of the thermal baseline was changed to match the potential landing site of the Perseverance rover, and out of 8 landing sites, the Holden crater was chosen to be the base design environment. It possesses the most extreme temperature ranges. Later on in the design process, the landing site was further selected to be the Columbia Hills site. However, the difference in the temperature extremes of the Holden crater and the Columbia hills were not too far off the Holden crater extremes, and thus, the 'baseline' extreme temperatures remain to be that of the Holden crater. In the Figures 21 and 22, the 'hot' and 'cold' related temperatures & Solar flux of the ERD, Holden crater, and the Columbia hills are shown.

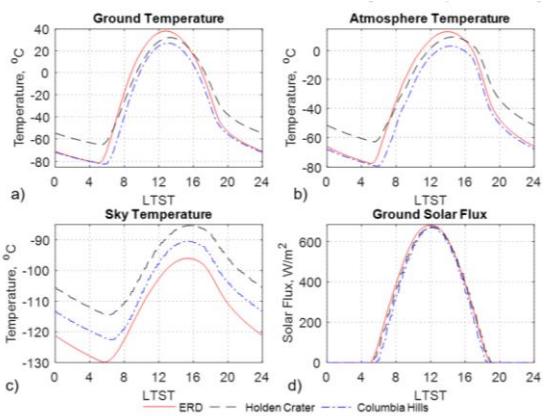

Figure 21. Shows Related 'hot' temperatures & solar flux of the ERD, Holden crater, and Columbia Hills: (a) Ground Temperature, (b) Atmosphere Temperature, (c) Sky Temperature and (d) Ground Solar Flux (Kempenaar *et al.*, 2018)

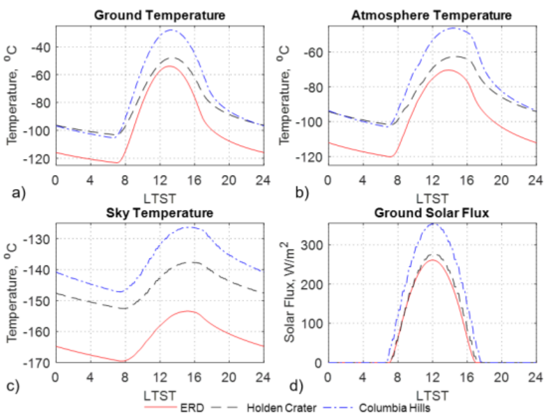

Figure 22. Related 'hot' temperatures & solar flux of the ERD, Holden crater, and Columbia Hills: (a) Ground Temperature, (b) Atmosphere Temperature, (c) Sky Temperature and (d) Ground Solar Flux(Kempenaar *et al.*, 2018)

When discussing the thermals detail of the RA & tools turret assembly, it is important to point out that the operational temperature for each component of the rover is different due to their different working nature, e.g., The sensors & electric-powered equipment on the turret requires an external heating device to operate during cold periods, while the 'static' pieces such as the RA frames & Flex cabling do not need to be actively warmed. In the Figure 23, the different thermal zones on the rover are shown. Note: AFT refers to 'Allowable Flight Temperature, e.g., the "survivable temperature' of each zone

Color	Zone Type	Typical AFT Range (Non Op)
	Uncontrolled HW	-128°C to +50°C
	HRS Controlled HW	-40°C to +50°C
	Zones w/ Survival Heaters	RBAU -20°C to +30°C RPFA -40°C to +50°C $PIXL_{HVMM}$ -20°C to +35°C $SHERLOC_{LPS}$ -85°C to +50°C $SHERLOC_{SDE}$ -40°C to +50°C SCMU -40°C to +50°C
	HP/CP HX	-90°C to +100°C
	MMRTG	+65°C to 200°C

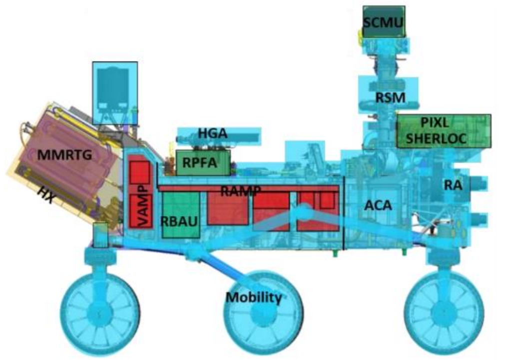

Figure 23. Thermal zones of the Perseverance rover, RA, and turret components are outlined in red (Kempenaar *et al*., 2018)

The Robotic Arm (RA) is in the uncontrolled HW zone, with the AFT range of -128°C and 50°C, and thus its materials alone must be able to withstand the extreme temperatures range of Mars during its operations. Referring to the common space materials, a comparison of the thermal properties of the materials is shown in Table 5.

Once again, the obvious choice of alloyed steel has the best properties out of the 4. The alloy has a high heat expansion resistance, able to maintain shape and form under extreme temperatures (due to low CTE, Coefficient of Thermal Expansion) while having a respectable thermal resistivity, i.e., being able to protect the inner components from extreme temperatures.

Table 5. Common space materials' thermal properties comparison (ASM International Handbook Committee, 1990a, 1990b; Boyer *et al*., 1994).

Material/ properties	CTE @ 500°C	Thermal Conductivity
Unalloyed Ti (Gr.1)	9.7 μm/m-°C	16 W/m-K
Alloyed Ti (Ti-6Al-4V)	9.7 μm/m-°C	6.7 W/m-K
Stainless Steel (Type 304)	18.7 μm/m-°C	16.2 W/m-K
Aluminium Alloy (7075-T6)	25.2 μm/m-°C ** @ 250°C	130 W/m-K

Discussion

Rover Structure Design Factor

Based on the information available for various models of Mars Rovers, including the Curiosity, several design factors, and requirements could be drawn. These design factors could be categorized and divided into three main categories: environmental, mechanical, and operational. Environmental factors refer to the environmental conditions of Mars. The Mars rovers must be able to withstand the imposed conditions. The mechanical factors refer to mechanical aspects of the rover's structure, such as the safety factor. Lastly, the operational factor is the operational lifespan. Table 6 shows the summary of the design factors considered.

Table 6. Design Factor Conclusion

Group of Design	Important Factor
1. Environmental Factor	Resistant to rough ground Corrosion resistant Magnetic dust resistant Radiation Resistant
2. Mechanical Factor	Minimum safety of factor Able to handle the total load Weight optimization
3. Operational Factor	Minimum lifespan

One of the challenges of Mars exploration is its environmental conditions. With these unique conditions, the rover's material that makes up the structure must be able to handle them. The first challenge is the ground's surface of Mars. Mars's surface is rocky, uneven and consists of craters (NASA, 2022). Therefore, conventional inflated tires would not be practical, as they would be more prone to malfunction, such as puncture, and difficult to repair or replace. Modern Mars Rover utilizes a rigid wheel with impressed patterns on its surface, which helps with grip and friction and can resist the rough surface of Mars. Since Mars has a different atmosphere, this could cause oxidation of the structure to occur. And since the atmosphere is thinner, radiation could also affect the corrosion of the material. Lastly, there is also a potential issue of magnetic dust, which will require the material not to be ferromagnetic (Sharma *et al*., 2021). The environmental conditions of Mars purely dictate the material properties and technology that the rover must possess in order to operate and function. Which means that the more information about the environment we acquire, the better the design decisions can be made with future generations of the rover.

The mechanical aspect of the structure is important for the Rover. According to NASA, all spacecraft, both manned and unmanned, must have a minimum Ultimate Safety factor of 1.4, which is to be used in conjunction with a yield factor of safety at 1.0. However, for untested structures, at least 2.0 Ultimate Safety factor is used, along with 1.25 yield factor of safety (Modlin and Zipay, 2014). From the safety factor, the design of the structure is derived. To be able to determine the values, the actual load of the Rover needs to be known. In the case of Perseverance, including all the instruments on board, it is weight at 1025 kg. However, despite being about the same size as a sedan, the Rover weighs roughly 20% less. This is because of the weight optimization, which helps when getting the Rover from Earth to Mars(NASA, 2009). All of the mechanical aspects allow the rover to function without structural problems in space. Even though there was a 14% increase in weight between the Curiosity and Perseverance, the newer rover has received upgrades to the majority of its system, and fitted with additional tools. The further improvements in weight optimization could increase the amount of tools the rover could carry, and improve the logistical aspect of future rover missions.

The last factor is the operational factor or the operational requirements for a Mars Rover. According to NASA, the Perseverance Rover's mission has an expected duration of 1 Martian year or approximately 2 Earth years (NASA, 2013). This means that the rover would last at least 2 years and most likely even longer than that. As we had seen from previous NASA Mars Rovers, these rovers lasted longer than their intended mission duration. The Sojourner, or the Pathfinder, had a battery rated for 1 month of use. However, it continued to transmit data two months after it landed (NASA, 2019). The Curiosity Rover's primary mission duration was 233 months. However, ten years later and it is still operational today. From this trend, it seems that Mars rovers are significantly more resilient than their intended duration.

Future Aspect

The future aspects of planetary rovers lie in many factors. Most of them revolved around the progress of technology, namely new wheel designs using shape-memory-alloy (SMA) (Welch, 2020), applying new methods of detecting planetary surface objects (Xie and Yang 2023), high-quality solar cells with greater photovoltaic energy harvesting efficiency (Girish *et al*., 2023), or even introducing modern communication technology, which allows for more reliable connections and much shorter latency.

Between Mars and Earth (Bonafini, 2022; Matthies *et al*., 2022). All these features have the potential for future planetary rovers' designs. SMA, or shape-memory alloy, is an alloy that can return to its original shape after deformation using thermal treatment (Tadaki *et al*., 2003). Replacing the traditional rigid wheel with SMA wheels will change how the wheel surface interacts with Mar's terrain. Instead of a rigid surface going on top of sharp rocks, which are prone to punctures, SMA wheels enable the materials to bend in the shape of the terrain and later slowly return to their original form. Integration of such materials into the rover's wheel designs decreases the need for wheel maintenance, resulting in a larger exploration range and improving fuel efficiency. The spring-like structure of the alloy also provides better suspension support for the instruments within the rover's body(Welch, 2020).

Raman spectroscopy is a label-free, non-destructive, and non-invasive method that provides information about the molecular composition and structure of a sample. The technology is widely used in biomedical analytics and clinical diagnostics, such as the detection and staging of cancer (Cordero *et al*., 2018). However, recent research indicates the prospect of such technology in Mars exploration. Specifically, with Raman spectroscopy, planetary scientists can approximate when the volcanic activities on Mars began, which leads to a better understanding of the planetary structure (Torre-Fdez *et al*., 2023).

Solar energy is a common energy source for aerospace applications. Due to the growth of the current solar industry, newer and better technologies are being introduced to the market more and more. A greater photovoltaic light harvesting efficiency means better power production, resulting in more power to utilize. With new technologies currently being developed and presented, the study of appropriate solar cell modules and their fabricated materials is still taking place (McMillon-Brown and Peshek, 2023).

Since Mars rovers are partly controlled remotely from operating facilities on Earth, the traveling time of the signal can cause delays and stalls in data transmission during their exploration missions(Bonafini, 2022). Hence, the future goal of deep space communication between Earth and Mars is based on performance factors such as systems capable of providing high data rates, low latency, energy-efficient, reliable, and mobility-resistant communication infrastructures in the Martian environment (Koktas and Basar, 2022). Research for the next generation of Martian communications is still taking place.

According to many recent scientific publications and research papers, the future of the Mars rover is far from over. With the success of NASA's space exploration programs (four previous successful American rovers) and the advancement of current technologies, the future development of Mars rovers is filled with endless possibilities.

Conclusions

From the content above, a mechanical assessment of Perseverance and Curiosity was taken. Three parts of the rover were applicable for a structural or mechanical assessment, which were the body, wheel, and arm. For the three parts, the assessment could be categorized into three main points, the part's purpose, its design principle, and the structural analysis, which included the material that was used.

The body of the rover is designed to house several systems of the rover. Perseverance was designed with collecting samples as a priority. Therefore, the equipment that it was fitted with reflected that decision. Part of the body is the chassis, which provides structural support for the body. Due to the extreme conditions of Mars, the most suitable materials for the chassis are metal alloys. In terms of thermal analysis, the material and design are able to maintain an acceptable operating range. The wheels of the Perseverance are rigid, consisting of metal alloys. Since Mars' surface terrain is rough and inconsistent, the wheels' design must be able to withstand it while also handling the weight of the rover. Lastly, the arm of the rover allows the rover to interact with its surroundings. While also being able to handle the ranges of temperature on Mars. With this reason in mind, the arm is equipped with sample collection tools such as drills, cameras, and sensors. All of these design choices can potentially categorize into three main factors, which are environmental, mechanical and operational. With the environmental factor influencing the material choice, the mechanical factor influencing the possible number of tools being installed, and the operational factor, which dictates the operational lifespan of the rover.

In the future, the possibility for improvement is high. Possible replacement and improvement of several components would possibly result in improved data collection, better transverse systems and increased operational lifespan for the next installments of the rover.

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