



# RESEARCH OF SHAPE MEMORY ALLOY WHEELS FOR MARS ROVERS

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## **ABSTRACT**

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The degradation of Curiosity's wheels has stated that new technologies need to be used for solving the problem of wheel wear on Mars exploration. One of these technologies is invented by NASA and consists in the usage of Shape Memory Alloys (SMA) to build a flexible deformable wheel that show no permanent damage after deformation.

This thesis is the investigation of how Shape Memory Alloys work to understand its usage in exploration rover wheels, in particular for Mars rovers.

The thesis starts with an investigation to understand how wheels of rovers were made in the past, how they are done nowadays and how are they going to be in the next years. Leading to a deep research on Shape Memory Alloys, going through the material itself and its properties, explaining how it works and how the structure of the wheel developed by NASA works.

The research provides a background on rover wheels, that lead to the understanding of Shape Memory Alloys and their usage on wheels for Mars exploration rovers.

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Key words: shape memory alloy, rover

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It's human nature to stretch, to go, to see, to understand.  
Exploration is not a choice, really; it's an imperative.

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*Michael Collins | Astronaut | Gemini 10 | Apollo 11*

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## Preface

Before starting with the thesis itself I would like to share my thoughts on how this work started and how it led to the present thesis. I have always been amazed by space technologies, even though my bachelor's degree is not oriented in space, everyone can focus his own work on what he thinks is more interesting, for me, my focus has always been on space. Following the end of my 3<sup>rd</sup> year on the university, I started thinking about what I was going to do on my bachelor's thesis as it was the first project that I could decide what I could do and almost completely do it by my own, so I had to pick a subject of interest. On that time, I saw a documentary of the Curiosity and started thinking about Curiosity's wheels damage and how the wheels work nowadays, that led me to investigate on why are the wheels rigid and this small research led me to know the existence of a new technology that NASA has been developing for the last years, as I wanted to know more I decided to do it as my bachelor's thesis. Even though I am not a material science student, I think the work done in this paper was useful for me as it let me to know more about this new technology and can help others to get inspired, and possibly follow my work to make an implementation of the wheel.

It also made me to improve as a human being as I did this thesis while doing an international mobility program in Tampere, being out of home, getting to know people from different part of the world that share the same passion than me made me realize how important is to work together regardless of where are people from, and working as a group is essential on achieving great challenges and goals.

## List of Symbols

$M_g$	Weight
S	seconds
P	Pressure
A	Area
D	Diameter
$f_s$	Frictional force
$(\mu_s)$	Constant of friction
$b$	Base
$l$	Length
$\delta$	Deflection factor
$c$	Rate of deformation
$M_s$	Martensite start temperature
$M_f$	Martensite finish temperature
$A_s$	Austenite start temperature
$A_f$	Austenite finish temperature
$M_d$	Martensite deformation temperature

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I would like to thank my university, the *Univeristat Politècnica de Catalunya* for teaching me the values of work, and the basics of engineering, so I can become an exceptional engineer in the future.

I would also like to thank my thesis supervisor Antti Perttula for guiding me through my thesis.

And last but not least I would like to thank my family for supporting me my whole life and my friends for being there always that I needed it.

# **Part I**

## **INTRODUCTION**

# 1. Introduction

Space technology is evolving every day and new challenges appear as we advance on our aim to discover new worlds. Mars has been since many years our focus on space exploration, right now we do not have yet the technology to send humans to Mars, even though we will soon, we are now in a phase where we send different spacecrafts to explore the planet for us, between these there are the rovers, and rovers play an important role on this exploration phase as they are able to move through Mars surface while making science missions.

Many generations of rovers have been sent to Mars, and as we persevere in our technology, we try to go further and achieve bigger goals. This thesis is the investigation and research of one of the new technologies Mars rovers could use in the future, not only on Mars but also on the Moon and even on Earth, although the thesis is mainly focused on Mars applications.

Since NASA's Curiosity rover started having problems with the wheels, the wheels have been in the spotlight of engineers to try to avoid damage and find solutions to it. NASA has developed a new concept of wheel; it uses shape memory alloys to build a flexible wheel that can adapt to the surface recovering its original shape, without permanent damage.

The purpose of this thesis is to do a proper research of exploration rovers, to understand how this new technology works, to question its viability on Mars environment, to find problems of this innovation and to lead this research to new ideas that could improve this technology.

## 1.2 Objectives

The main objectives and goals of this thesis are described below:

- To understand the functionality of the wheel for planetary exploration applications, in specific for Mars.
- To document the technology.
- To discover new technologies.
- To try to find possible implementations.

# **Part II**

## **BACKGROUND**

Mars is not quite like Earth, in fact, is a very threatening place for humans, it is cold, windy, dusty, and even has a toxic atmosphere for us.

Mars is the nearest and most habitable planet in our solar system, even with all the extreme conditions that it has, life could possibly be sustained, that is why it is so interesting for us.

Since the 1960s, Mars has been in the spotlight of space companies and in the 1965, the Mariner 4 successfully reached Mars being the first mission to reach the red planet, it sent 21 photos, the first photos of another planet from space.

Since then, we have aimed to go there and study more the Red Planet.

## 2.1 About Mars

Mars is smaller than Earth, its radius is half of Earth's radius, and its mass is less than one tenth of the mass of Earth. So, gravity on Mars is quite weak compared to our planet, due to the less amount of mass, the average gravity acceleration is  $3.72076 \text{ m/s}^2$ , about 38% of that on Earth, that means that everything that we carry to Mars will have less gravitational force than on Earth. This is an important point because the rover will weigh less than normally would do here. Let's put a simplification example:

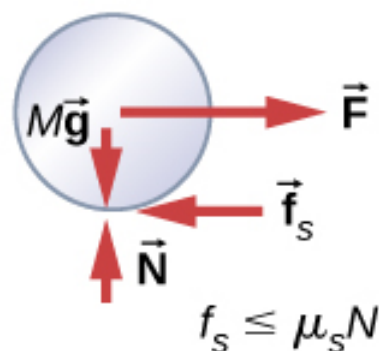


Figure 1. Force diagram of a wheel

We see here a simplified diagram of the forces that a wheel must suffer,  $M_g$  is the gravitational force that pulls the mass of the wheel to the ground, on Mars, the value of  $M_g$  is way lower than on Earth. That directly affects the frictional force that is necessary for the wheel to spin, see that  $f_s$  is equal or lower than the constant of friction ( $\mu_s$ ) multiplied for the N force (same value than  $M_g$ ) so if  $M_g$

is lower, so it is  $f_s$ . Meaning that it will be harder to provide traction as the rover will weigh less. This also affects the testing of the Rover's wheels on Earth, gravity it is not something we can change obviously, so a clever way to test prototypes is to make a similar model that would weigh the same on Mars (reducing its mass).

Mars atmosphere is about 100 times thinner than Earth, that means it has way less pressure; about 6 millibars (Earth's atmospheric pressure at sea level is approximately 1013 millibars).

Its composition is made of:

- Carbon dioxide ( $CO_2$ ): 95.32%
- Nitrogen ( $N_2$ ): 2.7%
- Argon ( $Ar$ ): 1.6%
- Oxygen ( $O_2$ ): 0.13%
- Carbon monoxide ( $CO$ ): 0.08%
- Also in minor amount (ppm) there is: Water ( $H_2O$ ) - 210; Nitrogen Oxide ( $NO$ ) - 100; Neon ( $Ne$ ) - 2.5; Hydrogen-Deuterium-Oxygen ( $HDO$ ) - 0.85; Krypton ( $Kr$ ) - 0.3; Xenon ( $Xe$ ) - 0.08

Corrosion is also an important aspect to consider on Mars, in fact, corrosion resistance is one of the most important properties in selecting materials for surface operations spacecrafts. Currently the materials are selected assuming that the corrosion on Mars is the same as that on Earth. But the discovery of liquid brines on the surface of Mars led to several investigations to know if corrosion was a cause on the Curiosity rover wheels as the components of the Martian environment that could cause corrosion on metals include: the atmosphere, soil composition and chemistry, the radiation and the liquid brines [1]. More studies are needed to understand the interaction between materials and the Martian environment, so it is still not clear if corrosion can be a problem for metallic compound on Mars.

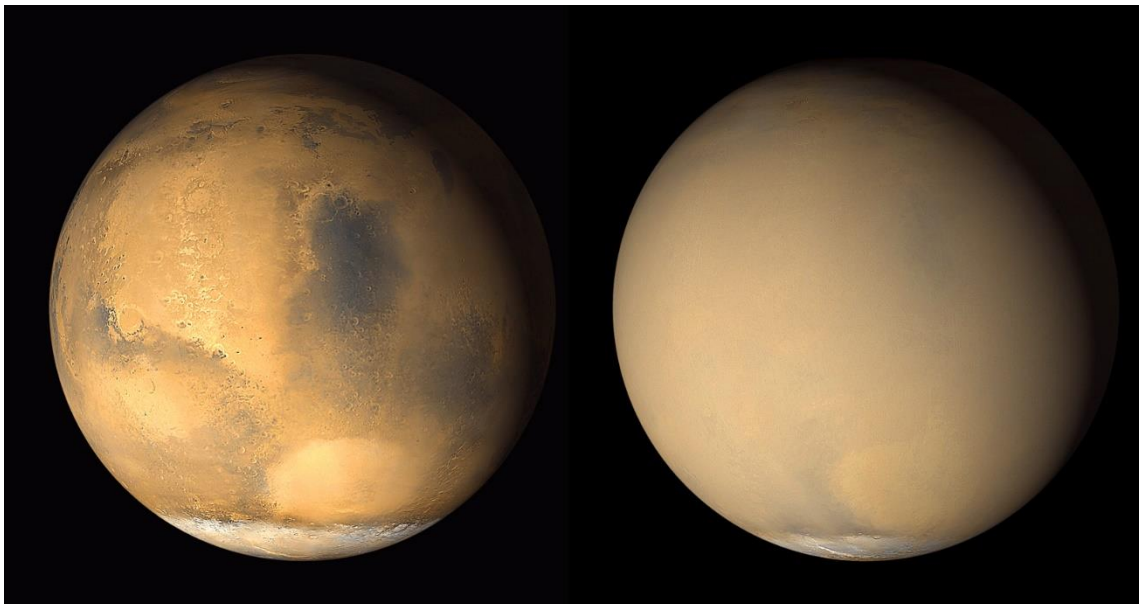
Mars also has an interesting surface.

Its surface it is made primarily of magmatic rocks, also from sedimentary and metamorphic rocks. These rocks consist predominantly of minerals that crystallize from magma. But we can find a lot of different terrains on mars; rocky

sites, sand dunes, craters, volcanic locations, etc. and they all can be shrouded by a single sandstorm, covering it all with windblown dust.

Wind on Mars redistributes surface material, these winds are not usually very fast (only some kilometers per hour), but Mars is capable of windstorms that can strip the surface of some dust and uncover rocks. Rovers found that the atmosphere gets turbulent on each sunny afternoon as heat rises from the surface. This turbulence generated the famous “dust devils” and they play an important role in lifting the fine dust into the atmosphere, exposing what was hidden beneath the dust.

In Figure 2 we can see how Mars can change because of a dust storm.



*Figure 2. Mars before a dust storm in June (on the left) and after a global dust storm in July (on the right). Picture taken by Mars Global Surveyor*

A Mars rover needs to be able to climb any type of terrain that can be found on the designated mission site. From sand dunes to solid rocky hills.

To show how different surfaces and landscapes can be on Mars, below it can be seen different real images of different locations in Mars.

From Figure 3 where it is observed the Ineson Hill on Mount Sharp, a dark mound, that rises about 16 feet above the surface. To Figure 6, where it can be seen sand dunes and a dust environment.

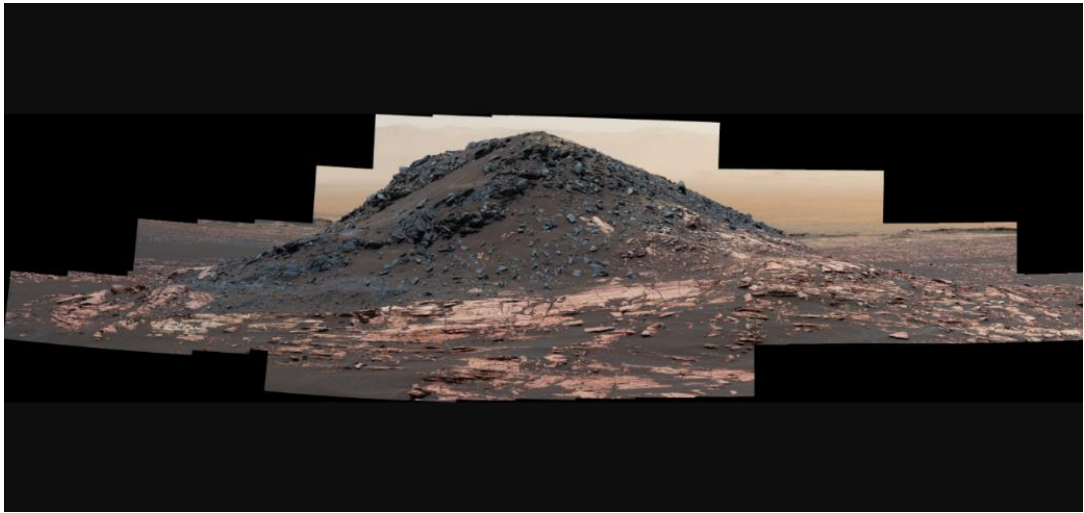


Figure 3. 'Ireson Hill' on Mount Sharp, Mars. Picture taken by Curiosity Mars rover's Mastcam



Figure 4. Photograph taken by NASA's Mars Curiosity rover in 2017. It shows the 'Vera Rubin Ridge'. Credit: NASA/JPL-Caltech/MSSS

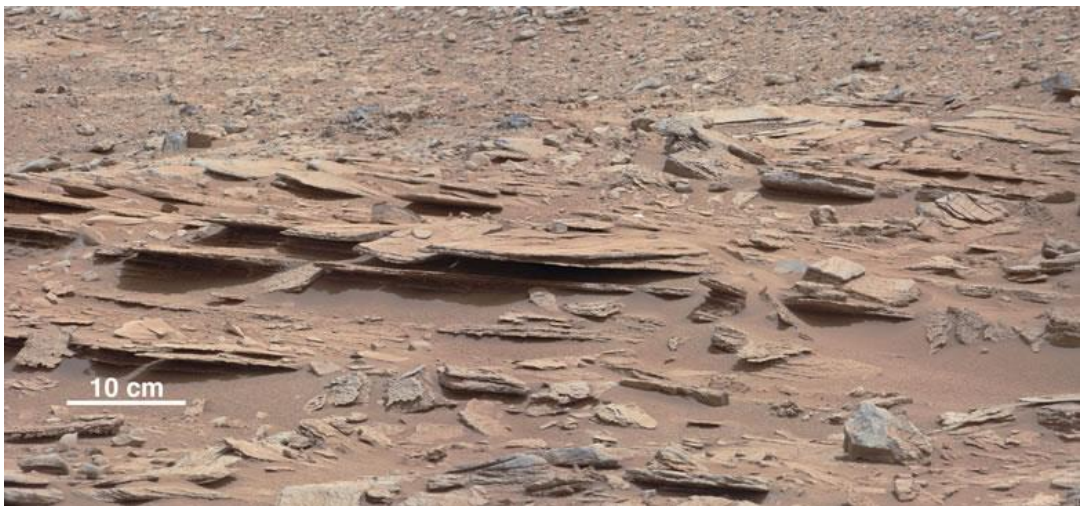


Figure 5. Photograph taken by NASA's Mars Curiosity rover in 2012. It shows a portion of a rock outcrop inside the Gale Crater. Credit: NASA



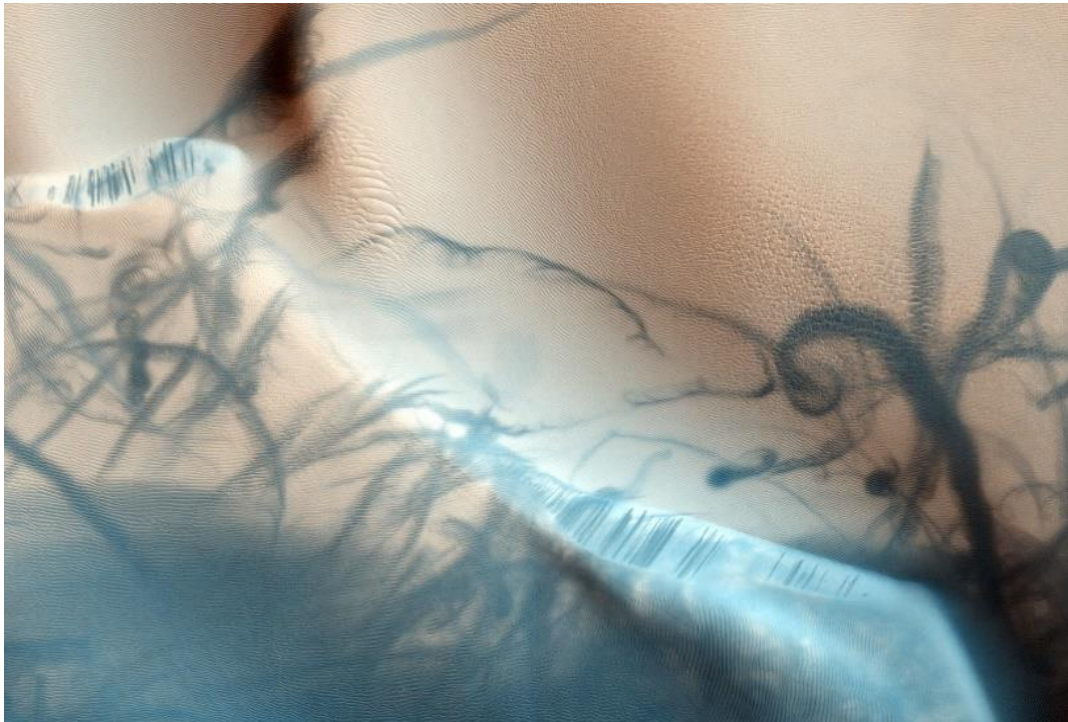


Figure 6. Dust devil tracks on Mars. Credit: NASA/JPL/University of Arizona

## 2.2 The wheels of a Rover

Wheels take an important part on the traction of the rover as they are the only part in contact with the surface. A rover is a vehicle designed to climb many different surfaces as steep slopes, sand dunes and more, for that reason, the wheels need to be also specially designed for those tasks. On Earth, the wheels that regular cars use are normally pneumatic tires, made from synthetic or natural rubber, that materials are not suitable for space applications. On Mars, temperatures can get to  $-150\text{ }^{\circ}\text{C}$ , at that temperature the rubber would convert into a rigid-solid material as rubber's glass transition temperature is  $-70^{\circ}\text{C}$  approximately. Rubber would become fragile, and in addition, rubber is heavy.

To understand why rovers use wheels there is next a quick overview to the main locomotion principles and locomotion systems that currently exist.

Here are stated 4 locomotion principles for robots to move:

- Walking
- Rolling
- Hopping
- Hybrid

### Walking:

Robot walking try to simulate human walking, this type of locomotion is very efficient in climbing uneven surfaces and has good capability of obstacle crossing.

### Rolling:

Are the most efficient system in terms of energy efficiency on flat surfaces. In ideal rolling a wheel does not lose energy, compared to walking that each time the leg impacts the ground is losing energy.

### Hopping:

It has been proved that a robot with just one leg and a small foot can stay upright by simply hopping.

### Hybrid:

It is called Hybrid locomotion to a robot that performs locomotion in multiple ways.

Also, there are different locomotion systems to perform the job; here are stated the wheeled, legged, tracked and hybrid.

See table 1.

locomotion → feature ↓	Wheeled	Tracked	Legged	LW hybrid	LT hybrid	WT hybrid	LWT hybrid
maximum speed	high	medium/ high	low (static walking) to medium (dynamic walking)	medium/ high	medium	medium/ high	medium/ high
obstacle crossing capability	low	medium/ high	high	medium/ high	high	medium	high
step/stair climbing capability	low	medium	high	high	high	medium	high
slope climbing capability	low/ medium	high	medium/ high	medium/ high	high	medium/ high	high
walking capability on soft terrains	low	high	low/ medium	low/ medium	medium/ high	high	medium/ high
walking capability on uneven terrains	low	medium/ high	high	high	high	medium/ high	high
energy efficiency	high	medium	low (static walking) to medium (dynamic walking)	medium/ high	medium	medium/ high	medium/ high
mechanical complexity	low	low	high	medium/ high	medium/ high	low/ medium	high
control complexity	low	low	high	medium/ high	medium/ high	medium	high
technology readiness	full	full	full for static walking; in progress for dynamic walking	full (usu- ally static walking)	full (usually static walking)	full	full (usually static walk- ing)

Table 1. Synthetic comparison of locomotion system features. Article: Locomotion systems for ground mobile robots in unstructured environments

According to the table the wheeled system is the most energy efficient, less mechanically complex and the less control complex, also as energy efficiency is hugely important on Mars because energy in rovers is limited, the wheeled system is the most reliable. For these reasons, the wheeled system is the most used in rover space missions.

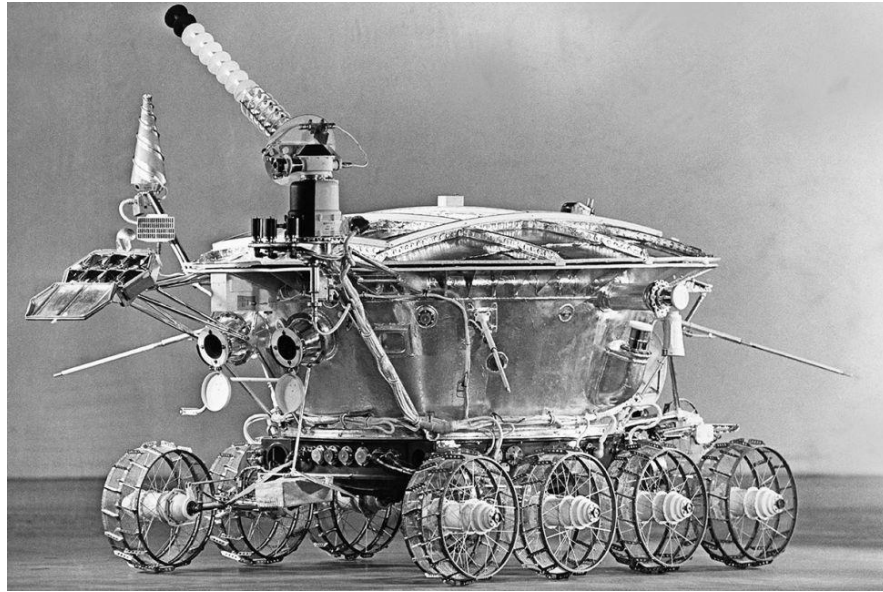
## 2.2.1 The Lunokhod 1

On November 17<sup>th</sup>, 1970, the automatic space station “Luna 17” made by the Soviet Union descended and landed on the surface of the Moon. It deployed a

remote-controlled lunar rover named Lunokhod 1, being the first mobile vehicle on the surface of the Moon.

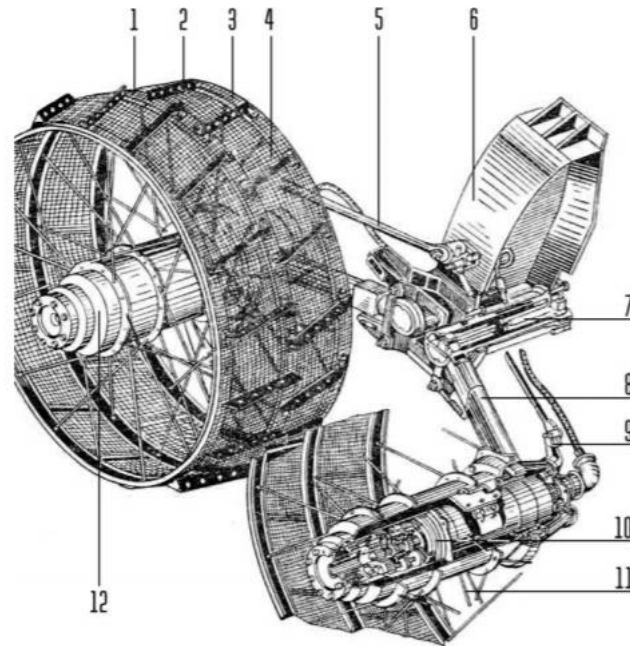
Its goal was to travel to various locations and conduct lunar soil tests under the control of the operation center on Earth.

The Lunokhod 1 weighed 756 kilograms and had dimensions of 1.35m (height) x 2.15m (length).



*Figure 7. Picture from the Lunokhod 1*

The Lunokhod 1 implemented an automatic “self-propelled” chassis where the motors of rover to propel itself were located inside the wheel. In Figure 8 it can be seen an illustration of the motor in-wheel module of the Lunokhod 1.



*Figure 8. Motor inside the wheel of the Lunokhod-1 self-propelled chassis (drawing made by V.V.Grinev)*

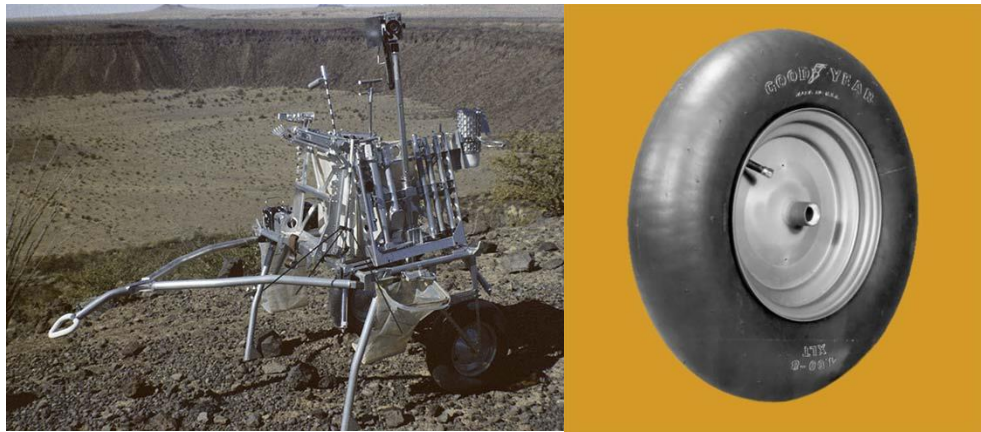
With the self-propelled chassis, an eight-wheeled model was contemplated as the main propulsion system. It suited the dimensions of the landing module and it also suited the requirements of high cross-country capability and stability. Each of its 8 wheels were rigid rim wired meshed with bicycle-type spokes and metal cleats for incrementing traction; their dimensions were 510 mm in diameter and 200 mm in width, they could be controlled independently for different speeds. It also allowed the rover to make an almost 0 degree turn radius, this rotation is achieved by controlling the speed of the wheels on the opposite sides. In fact, the wheels had to be rigid due to the significant axial deformation of an elastic wheel.

### 2.2.2 MET-ROVER

The MET (Modularized Equipment Transporter) was a two-wheeled vehicle used by the Apollo 14 mission, it worked as a portable workbench carrying the lunar hand tool carrier, the geology tools, the closeup stereo camera, two 70 mm Hasselblad cameras, a 16 mm data acquisition camera, film magazines, a dispenser for sample bags, a trenching tool, worktable, sample weigh bags and the Lunar Portable Magnetometer [2].

The wheels were 400 mm in diameter and 100 mm wide, and were filled with nitrogen gas, being the first tires on the Moon. The tires were designed by Goodyear Tire and Rubber Company, and it faced one big challenge; NASA required Goodyear to make a tire where the inflation pressure had to be 1.5 psi

on the surface of the Moon. It was a difficult challenge because a tire with 1.5 psi on Earth, has 16.2 psi on the surface of the Moon (that is because on Earth the atmospheric pressure is 14.7 psi and on the Moon is non-existent). The problem was solved pre-inflating partially the tire so that it reached the 1.5 psi pressure on the surface of the Moon.



*Figure 9. Left: MET prototype used by the Apollo 14 astronauts for their surface simulation training. Right: Picture of the Goodyear's MET Wheel*

### 2.2.3 Lunar Roving Vehicle

The Lunar Roving Vehicle or LRV was an electric vehicle made to be driven in the low gravity conditions of the Moon, and to travel through the lunar terrain so the astronauts could get further than the past missions, extending the mission capabilities. The first LRV sent on the Moon was on the Apollo 15 mission and it was driven for 27.8 km in 3 hours and 2 minutes of driving time.

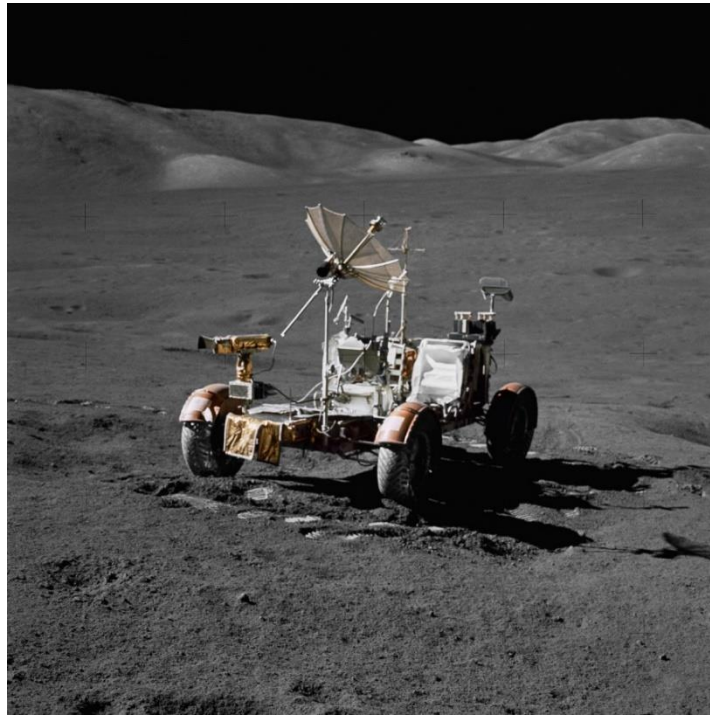


Figure 10. Picture of the Lunar Roving Vehicle taken during the Apollo 17 mission. (Credit: NASA)

The LRV had a total mass of 210 kg but was designed so it could carry an additional payload of 490 kg on the lunar surface. Its dimensions were 3.1 meters long with a wheelbase of 2.3 meters and a height of 1.14 meters. The wheels of the LRV were composed by an aluminum hub and a rigid rim where a steel wire mesh was attached to it. The steel mesh was an 818 mm in diameter and 230 mm wide zinc coated mesh with 0.83 mm diameter steel strands attached to the rim. titanium chevrons covered 50% of the contact area of the wheel to provide more tractions.

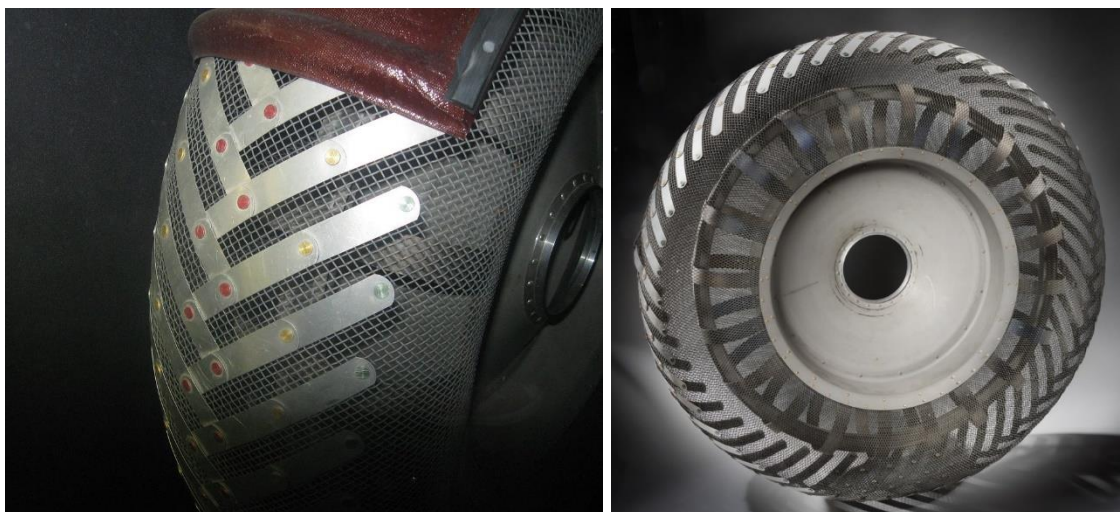


Figure 11. Left: Close-up photograph showing the chevrons shape treads of the Lunar Roving Vehicle Wheel. Picture taken in the 'Apollo to the Moon' exhibition at the National Air and Space Museum in Washington, D.C. Right: Photo of the Lunar Roving Vehicle Wheel

## 2.2.4 Sojourner

Following the successful landing on the Moon of the Apollo Program, NASA aimed to another challenge, Mars Exploration. The Mars Pathfinder landed on Mars on July 4<sup>th</sup> of 1997, carrying a rover named Sojourner. The goal of the Pathfinder was to land successfully and deploy what will become the first wheeled vehicle to operate on another planet.



Figure 12. Picture of the Sojourner Rover near "The dice" (left). Picture of the Sojourner Rover Wheels (right). (Credit: NASA/JPL)

The Sojourner, also known as the Microrover Flight Experiment (MFEX), is a 6 wheeled vehicle that weights 11.5 kg, has a normal height of 280 mm, being 630 mm long and 480 mm wide. The 6 wheeled chassis of the rover was chosen over a 4-wheel design because it provided greater stability and obstacle crossing capability, also 6-wheeled rovers can overcome obstacles 3 times bigger than 4-wheeled rovers. Also, the 4 corner wheels are independently steerable to be able to turn in place. This 6-wheeled chassis has a rocker bogie suspension mechanism designed by the JPL (Jet Propulsion Laboratory) to allow the rover to traverse obstacles 1.5 his wheel diameter in size and providing added stability to the vehicle, without using springs.

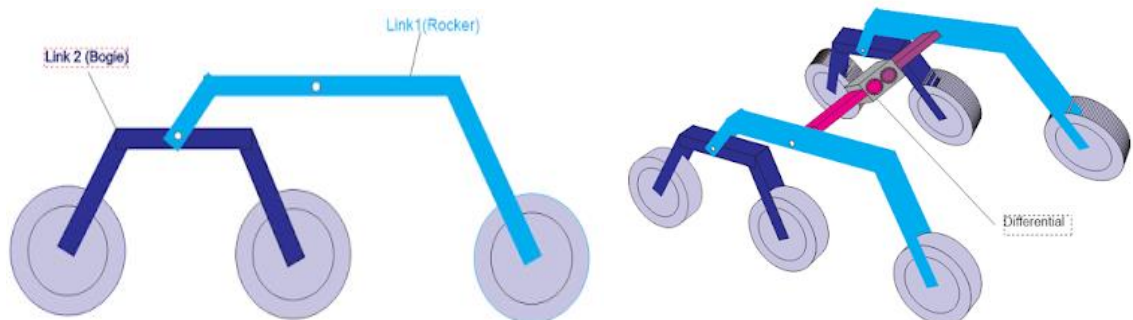


Figure 13. Diagram of the Rocker-Bogie mechanism



The wheel itself has a diameter of 130 mm, 80 mm of width, and they are made of aluminum, with stainless steel treads and cleats on the wheel to provide better grip on rocky surfaces and improved traction on soft sand [3].

## 2.2.5 Mars Exploration Rovers

After the Pathfinder, the next mission to Mars was the Mars Exploration Rovers, the Spirit (MER-A) and the Opportunity (MER-B), this mission is part of the Mars Exploration Program. They were launched on 2003 and landed in January 2004. The mission had 4 main goals [4]:

1. Determine whether life ever arose on Mars.
2. Characterize the climate of Mars.
3. Characterize the geology of Mars.
4. Prepare for human exploration.

The Rovers dimensions are 1500 mm high, 2300 mm wide and 1600 mm long, with a total mass of 180 kg. As the Sojourner, a rocker-bogie mechanism has also been used in their 6-wheeled rover, which allow the rovers to go over rocks or through holes that are bigger than a wheel in diameter. The MER apported an improvement to the mobility of the vehicle; the Sojourner's rocker bogie mechanism was modified for the Mars Exploration Rover Mission, also, the mobility system of the MER rovers is in the back of the vehicle because the difference in weight and center of gravity from the Sojourner. The wheels are approximately 260 mm in diameter, almost twice larger than the Sojourner's, and incorporates a new design; a spiral shape that connects the outer part of the wheel with the hub to provide safety and stability by absorbing shocks during movement.

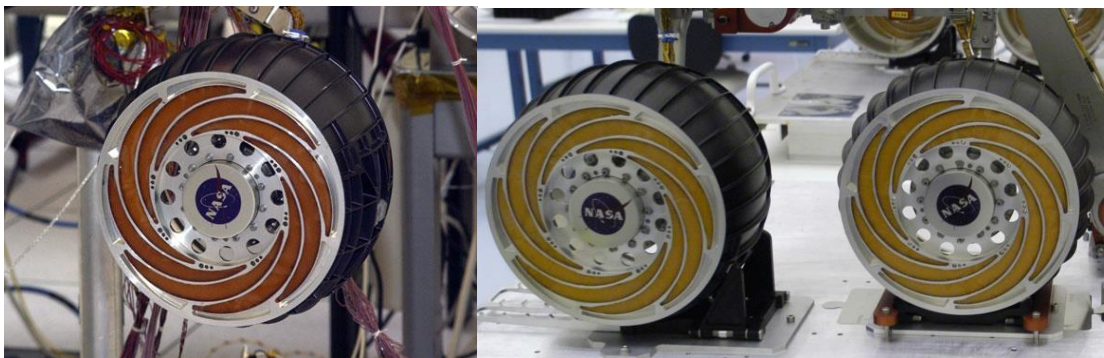


Figure 14. Pictures of the MER Rovers Wheels. See the spiral pattern of the wheel. (Source: NASA)

The wheels also have cleats, to improve traction on soft soil and climbing conditions, and the orange filling of the wheel is an open-cell foam called solimide, a composite with good flexibility in low temperatures (ideal for Mars), it was bonded to the wheel, filling the empty spaces between the spiral shape in order to prevent rocks, dust and other stuff, to get inside the wheel, possibly interfering the mobility of the rovers.

But the Opportunity and Spirit become stuck on soft soil. The rovers lost traction while driving through loose sand conditions. The Opportunity's wheels were buried in sand and after several simulations and tests, NASA's Jet Propulsion Laboratory in Pasadena, California, (JPL), achieved to move the rover and free him. But with the Spirit, NASA tried several attempts and could not release him, as the wheels were not able to generate traction at all, it then became a stationary science platform.

## 2.2.6 Curiosity

The Curiosity was the Rover of the Mars Science Laboratory Mission, its mission was to explore the Gale Crater in order to know if Mars ever had the right environmental conditions to support small life forms. The Curiosity was the most complex machine ever sent to another planet, with two different brains to process information, six-wheels, seventeen cameras, a robotic arm, nuclear powered, and even a laser to analyze rocks from distance.

Compared to the last rovers, Curiosity was huge; weighing almost 1 ton (899 kg), 3000 mm long, 2700 mm wide and 2200 mm tall (like the size of a small SUV).



*Figure 15. A picture of the three JPL Mars Rovers. Front and center is the flight spare of the Sojourner, Marie Curie. On the left is the Surface System Test Bed (SSTB) of the Mars Exploration Rover. At right is the Vehicle System Test Bed (VSTB) nearly identical to the Curiosity Rover [5]. (Credit: NASA/JPL-Caltech PIA15279)*

The Mars Science Laboratory introduced a new challenge, to land something considerably large. Chief engineer Rob Manning wrote in a 2014 mission memoir: “We came to realize that we did not know how to land anything on Mars reliably, let alone something large”. NASA’s Jet Propulsion Laboratory (JPL) formed a team to identify and design the technology it was needed to be able to precisely land a large rover on Mars. The engineers analyzed two different strategies for the final stage of the landing, previously successful landings: the Viking landing, and the Pathfinder’s landing. The Viking lander employed retrorockets to slow the descent to a near-standstill and then dropped the spacecraft to the ground. In other way, the Pathfinder used a different approach, the spacecraft was folded into a tetrahedron fitted with airbags, that hung from a rope below a rocket pack connected to a parachute. At the last moment (100 meters above the surface) the airbags inflated, and the rope cut [5].

Neither options fitted the Mars Science Laboratory mission, it was too heavy for both landings; if the Viking strategy was used, the landing would be too unprecise, but the Pathfinder strategy couldn’t be used as well, as the airbags had a maximum payload of 200 kg. A combined landing strategy was the correct strategy.

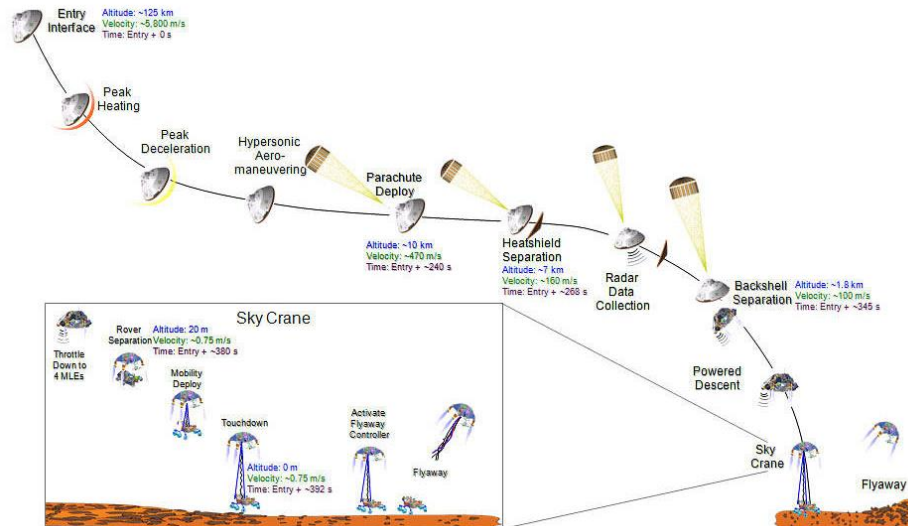


Figure 16. This image shows the Entry, Descent and Landing sequence. (Credit: NASA)

Using this Entry, Descent and Landing sequence, the Curiosity's wheels had to resist the impact of the landing, absorbing the mechanical shock of the touchdown so the rover itself could not get harmed. Also, they needed to be as lightweight as possible, and they had to provide traction in all the possible landing scenarios. The wheels have a crowned profile being 500 mm in diameter at their centers and 465 mm in diameter at their edges. They have 400 mm of width. The wheels consist of an aluminum tire machined from a block of aluminum, and a titanium hub and spokes. The spokes have a complicated shape that allow them to deform in every direction. The wheels are very thin, only 0.75 mm, in order to reduce the mass of the wheels, but thick enough so it wouldn't puncture if all the rover's weight rested on a single point over a pointy rock. For traction, the wheels incorporated treads or "grousers" on the surface of the wheels and chevron pattern features to avoid slipping downhill. All this together, make the wheels to deform and return to the original shape [5].



Figure 17. Diagram of the Curiosity's wheel. (Credit: NASA/JPL-Caltech/Emily Lakdawalla)

The Curiosity carried a rocker-bogie mechanism for travelling more stable through Mars terrain. The “rocker” arm is attached to the front wheels and is the longer one. The middle and rear wheels are attached together to form a “bogie”, that is connected to the rocker part with a pivot that allows 45° tilting. The rocker is also attached to the chassis with a pivot that can tilt as much as 20°. Each side of the rover has a rocker and a bogie, and they are connected in the chassis via a mechanical differential pivot, so the movement on each side of the rover doesn't affect the other side. The chassis maintains stable, it keeps an average of the pitch angle of both rockers. This mechanism is extremely useful on climbing tilted surfaces because it allows the rover to have the six wheels in contact with the surface all the time, maintaining traction on the wheels while the rover is climbing.

### 2.2.7 Wheel degradation on Curiosity's wheels

Curiosity's wheels showed wear at Sol 411 during a routine examination of the wheels. NASA noticed a puncture on the front left wheel of the rover, although the puncture was not very significant, it got worse and grew over time. The team reinspected the wheels on Sol 463 noticing the growth of the puncture and scheduled numerous detailed wheel inspections. This was not the only damage on the wheels, more tears appeared on all the wheel but not on the rear wheels. The punctures were caused by two main factors: metal fatigue of the stress during rotations, and forces caused by the rocker-bogie mechanism. The motors of the wheels act at fixed rotation rates, so when a wheel finds an obstacle to climb, the wheel must travel more distance (and more vertical) than the other wheels while

moving at the same speed, this causes the wheel to suffer a considerable force [5].



*Figure 18. Curiosity's wheels punctures. (Credit: NASA)*

Having a damaged wheel on Mars was not something that could be fixed so the team had to be extremely careful on where to locate the rover so it would not get more harmed, or even get the rover stuck.

## 2.2.8 Perseverance

The Perseverance is the rover of the Mars 2020 mission, a rover mission that forms part of the NASA's Mars Exploration Programme. This rover landed on the February 18<sup>th</sup> of 2021. The Perseverance rover was similar to the Curiosity but introduced a redesign of the Curiosity's wheels in order to avoid punctures and more damages.



Figure 19. The aluminum wheels of NASA's Curiosity (left) and Perseverance rovers. (Credit: NASA/JPL-Caltech)

The wheel changed in size, reducing width, being more narrow but larger in diameter (526 mm) and made of a thicker aluminum, so overall the wheel weights more and is more robust. Also, the tread profile has been redesigned to avoid punctures and tears over sharp, pointy rocks.

### 2.2.9 ExoMars 2022

The ExoMars is an astrobiology program by the European Space Agency that will search for signs of past life on Mars, overall. The mission will land the first European rover on the surface of Mars, and it is planned to land in 2022. The rover, named Rosalind Franklin will combine the capability to travel through Mars and to study the planet at depth. The rover changed the tendency of NASA of building a rocker bogie mechanism on their rovers and ESA studied the different suspension mechanism that the rover could use. Two main mechanisms were on the spotlight: the 3-bogie mechanism and the JPL rocker bogie mechanism.

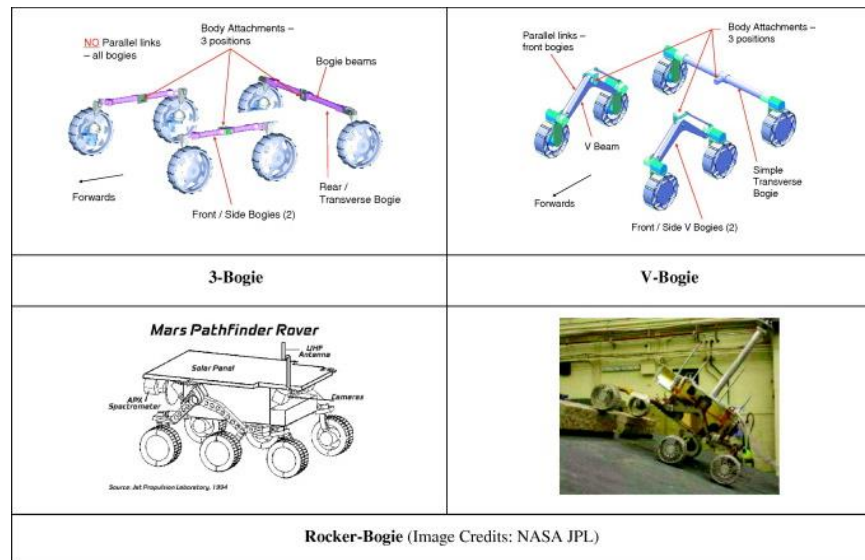


Figure 20. In the picture is showed some of the different possible mechanisms concepts that the Rosalind Franklin rover could carry

In Figure 20 it can be seen the 3-bogie mechanism and the rocker bogie mechanism. The 3-bogie consists in two independent longitudinal side bogies and one transverse bogie. Both concepts were compared and the 3-bogie was the one selected for the rover as “it was found to be the lightest, least complex, provided sufficient stability with a footprint that could be stowed within the lander volume envelope, and offered step obstacle climbing performance that was better or comparable with the other short-listed concepts.”(Patel et al., 2010).

The peculiar feature of the mobility system of the rover is the 6 flexible metal wheels that can deform without damage. The wheels are 250 mm in diameter and a width of 100 mm, with a rigid aluminum hub connected to 3 flexible steel bands as spokes, allowing possible deformation to the flexible rim. Two ‘bump stop discs’ protect the spokes from over deflecting when subjected to high loads. The European Space Agency investigated the advantages of flexible wheels in front of rigid wheels, and to explore the capabilities of them.





Figure 21. The ExoMars rover Rosalind Franklin's wheels. (Credit: ESA)

## 2.3 Flexible wheels and their interaction with different soil conditions

A flexible wheel is a wheel that its contact surface (tire) deforms in normal operating conditions, without excess loads. This means that the wheel can have a larger footprint than a rigid wheel with the same nominal diameter. The wheel deforms under the rover's mass and depending on the different soil conditions. Mars rovers wheels are usually made of metal, due to the threatening conditions they have to go through; high radiation, thermal stress and high vacuum conditions. Normal rigid wheels have an average of deformation of 10%, flexible wheels can deflect more than 10% without breaking.

In Figure 22 there is illustrated the possible different ways that a wheel can interact with the surface. In the first scenario is represented a rigid wheel driving on deformable terrain, the wheel does not show deformation because rigid wheels have an average deflection of less than 10% of the diameter. In the second illustration is shown a flexible tire going over the same surface than in the first one, in this case the wheel deflects about more than 10% the diameter of the wheel. The wheel maintains most of its original shape, but it gets flat on the contact area with the ground. In the third image it is illustrated a flexible metal wheel driving on deformable terrain. This flexible metal wheels can deform more than 10% of the wheel's diameter and are made of thin metal layer to provide elastic properties. The wheel behaves adapting an ellipse shape while in contact with the surface, having more surface in contact, thus providing more traction [6].

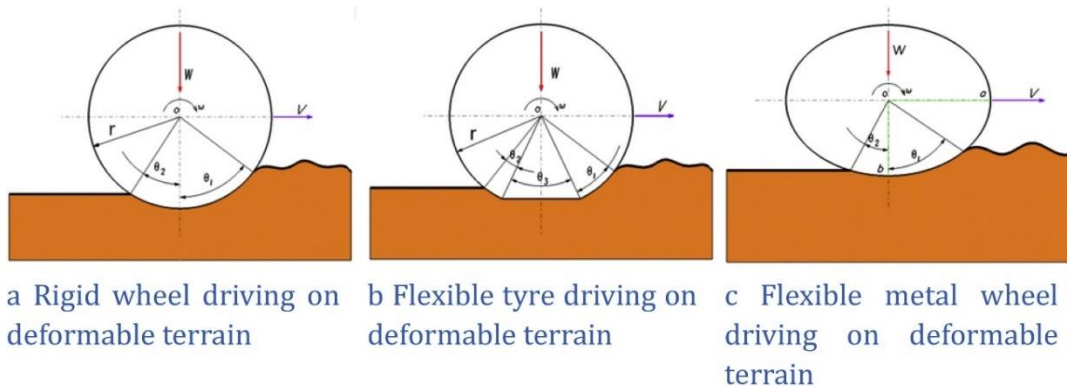


Figure 22. Possible wheel interactions with the surface [6].

By incrementing the amount of surface in contact means that less pressure will be applied to the ground. To explain this fact a bit more some equations have been used to show the relation between surface contact and pressure.

Being  $P$  the pressure of the wheel applied to the ground,  $M_g$  the weight of the wheel and  $A$  the surface of contact or area:

$$P = \frac{M_g}{A} \quad (2.1)$$

The area of contact with the ground is also the width of the contact patch ( $b$ ) multiplied by the length of the contact patch ( $l$ ):

$$A = b \times l \quad (2.2)$$

The side length is also:

$$l = 2\sqrt{\delta(D - \delta)} \quad (2.3)$$

Where  $\delta$  is the deflection resulting from the weight of the wheel  $M_g$ , and  $D$  the diameter of the wheel. Hooke's law of elastic deformation gives the rate of deformation of a body  $c$ , by dividing  $M_g$  by  $\delta$ :

$$c = \frac{M_g}{\delta} \quad (2.4)$$

Putting together these equations, ground pressure is obtained more detailed:

$$P = \frac{M_g}{b \times 2\sqrt{\frac{M_g}{c} \left(D - \frac{M_g}{c}\right)}} \quad (2.5)$$

So, by increasing the surface of contact of the wheel with the ground, the pressure that the wheel applies to the ground is directly lowered, meaning that a

bigger surface of contact contributes in a less sinkage of the wheel, providing better performance.

Energy efficiency is hugely important on rover missions as it is directly impacting rover's energy consumption. Energy of rovers can be limited, and its consumption directly affects on how much the rover can operate without recharging, the weight and dimensions of the battery pack and can even affect on the ability of the rover to climb surfaces, as a much more energy efficient system will allow the rover to climb much more difficult surfaces with less effort. Even though a flexible wheel is a bit less energy efficient than a rigid wheel, the benefits of flexible wheels overcome the loss of energy efficiency, and if an adaptive wheel could be used; a wheel that can adapt to different type of surfaces, it might lead to a more energy efficient system.

## 2.4 Summary

The fact that rigid wheels have caused some problems in the past even though they have been used for almost all rovers raises questions about the design and the concept of these. In fact, many studies have proved the advantages of flexible wheels in front of rigid wheels, lowering the ground pressure so it performs better, improves the durability, and provides better traction. It has also been proved through several studies that the performance of the Spirit, in the conditions that got him stuck, would have improved if instead of the rigid MER wheels, flexible wheels would have been used.

Seeing the struggle that the Curiosity had with his wheels has made the scientific and technological community focus on the design of new wheels. In fact, the next section, provides an investigation of a new concept of flexible wheels that is expected to be used in future lunar and Martian missions.

## **Part III**

# **SHAPE MEMORY ALLOY WHEEL**

### 3.1 Concept

Mars rover wheels have been in constant development since the first mission, going through classic spoke wheels, rigid and finally to flexible wheels. Even if in the Moon, a flexible wheel was used, the concept of a flexible wheel for Mars it has not been used at the moment. The ExoMars will be the first mission to introduce the concept of a flexible wheel in its rover and it will be a huge step forward for the next generation of, not only rovers, but any type of vehicles used in Mars in the future. Also, humans landing to Mars is the next aim for space agencies, so all kind of development is currently going on.

While NASA was developing the next Mars exploration rovers, they wanted to take a look back to the Moon and reinvented the lunar wheel, developing new designs with newer materials, technologies, and a better functionality. Indeed, the wheel is a redesign or evolution of the 'spring tire' invented by NASA Glenn and their industry partner Goodyear, inspired by the Lunar Roving Vehicle wheels. The spring tire is a concept of flexible wheel designed during the mid-2000s by NASA and Goodyear. This spring tire is a wheel that consist in several hundred coiled steel wires woven into a flexible mesh, allowing the tire to support high loads while deforming so it can adapt to the surface. But for Mars it needed a better design, even though the spring tire performed good in traction and durability, for Mars NASA Glenn engineers thought it was needed to improve traction in soft sand, durability and reduce overall weight [7]. So, several prototypes were developed to improve those features.

Comparison of Mars Spring Tire (MST) Prototypes			
Tire	MST0	MST1	MST2
Dimensions	23" X 8"	21" X 8"	21" X 8"
Tire mass <sup>1</sup> (not including rims)	~5.78 kg	3.59 kg	5.41 kg
Tire material	Spring Steel	Spring Steel	Spring Steel
Design focus	Early lunar spring tire prototype from 2010	Low mass, meet M2020 volumetric requirements	Added bump stop for durability, extra springs for improved floatation in sand
Testing results	Very high tractive performance / low durability	Poor tractive performance (mesh was too porous) / no durability test	Slight improvement in traction (tire was too stiff) / slight improvement in durability

<sup>1</sup>The M2020 tire mass requirement was 5.4kg




Figure 23. Comparison of Mars Spring Tire (MST) Prototypes. (Credit: NASA)

The prototypes were tested in NASA's Jet Propulsion Laboratory (JPL) and even though they performed well they noticed plastic deformation of the steel wires when rolling over very punishing terrain simulating Mars surface. The project got stuck until engineer Colin Creager and Materials Scientist Santo Padula had a conversation about a new material that could work in the tires instead of spring steel, this changed the overall direction of the project [7].

The new concept of wheel for Mars exploration rovers that NASA has been developing consists in a shape memory alloy mesh that can withstand excessive deformation without permanent damage and recovering its original shape after the stress is removed.

In this part it is going to be explained in detail the material and the design of the wheel, testing its functionality and its viability.



*Figure 24. Picture of a Shape Memory Alloy wheel tire developed by NASA. (Credit: NASA)*



## 3.2 Material

The material used for the wheels is a Shape Memory Alloy (SMA) called Nitinol. Nitinol is a metal alloy normally composed by roughly 50% nickel and 50% titanium, that has Shape Memory Effect behavior as well as superelasticity. It was discovered in 1959 during a Naval research project. This material has plenty of applications on biomedicine due to his specific properties, like biocompatibility and good magnetic resonance imaging opacity (to be seen by X-ray, for example), but it has applications in plenty of other areas, like structural engineering, thermal and electrical actuators, and more. But the most interesting property for the purpose of a wheel is the superelasticity, that allows the alloy to act as a super spring.

### 3.2.1 Properties

Nitinol has two main properties that characterizes him, the shape memory alloy effect and the superelasticity. The Shape Memory Alloy effect is the capability of the alloy to “memorize” its shape before stressed is made upon the alloy, in a way that the metal can recover its own shape. Nitinol doesn't behave as conventional materials. When conventional materials are deformed under stress, the atomic bonds are getting stretched to deform. This type of materials have a unique characteristic, that allow him to make an atomic rearrangement when stress is induced and deformation occurs. That allows the material to deform about 30 times more than a conventional material without plastic deformation (permanent deformation). Conventional materials like steel, aluminum, brass, and similar elastic-plastic materials show plastic deformation after a strain of  $\sim 0.3-0.5\%$ , so his elastic range (range where deformation is recoverable) is only bellow that strain. This amount of deformation limits many applications and uses. In the other hand, Nitinol and other shape memory alloys can achieve a strain of  $\sim 8-12\%$  before showing significant plastic deformation. But Nitinol is not the only material suitable for a tire, there is a list of materials that show shape memory effect or superelasticity that could also be used to produce a tire, for example; silver cadmium (Ag-Cd), copper-based alloys (Cu-Al-Ni, Cu-Sn, etc.), iron-based alloys (Fe-Ni-Co-Ti, Fe-Mn-Si, etc.), nickel-based alloys and many others, but the most used and effective materials are Ni-Ti, Cu-Zn-Al, and Cu-Al-Ni.

It takes profit of the temperature effect making the structure of the metal to change between different phases, this phase transformation is called martensitic transformation. When the metal is at high temperatures, Nitinol adapts a simple cubic structure known as austenite, and remembers the shape in this high temperature state. At low temperature it converts into a more complicated monoclinic crystal structure known as martensite. The change between these two structures is the main factor causing the shape memory effect. In the next figure it can be seen the general hysteresis loop of a Shape Memory Alloy.

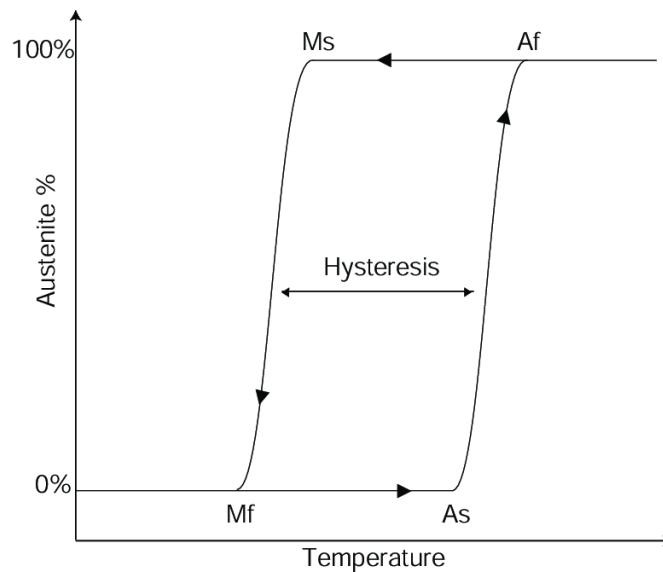


Figure 25. Thermal hysteresis loop of a Shape Memory Alloy [8].

The hysteresis loop shows the change of the alloy composition through different changes in temperature. When the alloy is cooled, the structure starts to transform to martensite, and at high temperatures the alloy adapts an austenite form. From full austenite, martensite starts to form as the alloy is cooled to the  $M_s$ , martensite start temperature. It keeps forming martensite until all the structure is only martensite, the temperature where the transformation is completed is known as  $M_f$ , or martensite finish temperature. Similar happens when its heated. Starting from full martensite, the alloy is heated, and it starts to form Austenite at  $A_s$ , or austenite start temperature, and the transformation finishes at the  $A_f$ , or austenite finish temperature, where all the alloy is full austenite.

While being in stable martensite structure (bellow  $M_f$ ), if the metal is deformed, it causes non-plastic deformation maintaining the martensite crystal structure, this deformation is known as de-twinning, and it consists in the rearrangement of the atomic structure without breaking atomic bounds, so the atoms are connected the

same way all the time. When the load is removed, the martensite elastically recovers a small amount of deformation. Heating above the  $A_f$  temperature, when the structure is full austenite, makes the material return to its original shape [3], as the austenite phase memorizes its macroscopic shape.

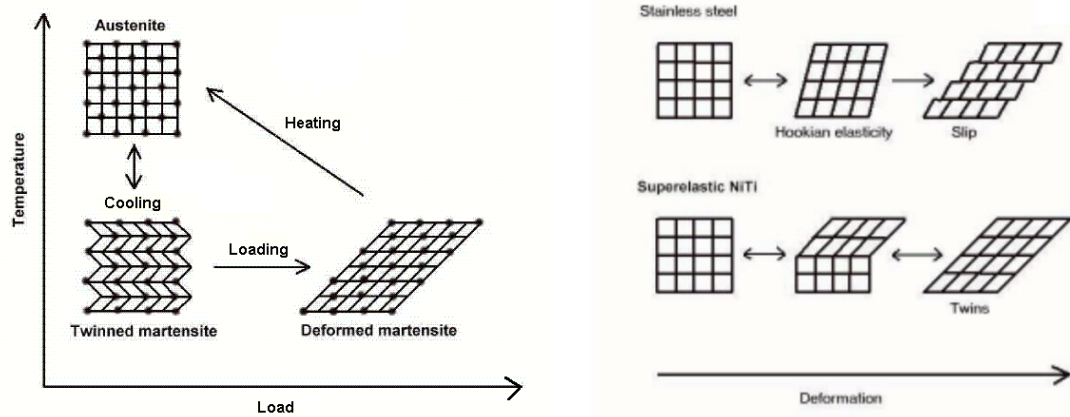


Figure 26. Left: Load-Temperature diagram of a SMA material. Right: Schematic that shows the behavior of the crystal structure of two different type of materials when they undergo deformation; above, a conventional metal and below a superelastic material.

In Figure 26 it can be seen how the cycle of temperature-load of a material like Nitinol. If austenite is cooled martensite starts to form creating a twinned structure (the alloy form groups that are imaging themselves over a plane, each group being reflections from each other), after loading that same structure a process known as detwinning starts on the martensite, and if heating is applied to the deformed martensite it starts forming austenite, recovering the shape that it had before (when “original” austenite). On the right of Figure 26 its pictured how two different materials behave while undergoing deformation. The material from the upper part of the picture it’s a conventional material like stainless steel that when undergoes deformation, the crystal blocks slips, that means that exists a permanent displacement of one part of the crystal structure relative to another one, so it suffers permanent deformation, i.e., plastic deformation.

The material at the bottom of the image is Nitinol on its martensitic phase (already twinned structure), that when it undergoes deformation instead of causing slip, the crystal structure starts detwinning, that means that an atomic rearrangement is done so it can deform without permanent deformation; meaning that the atoms keep the same bonding than before. Therefore, when austenite is achieved after the deformation in martensitic state, the original austenitic structure is recovered regardless of the deformation in martensitic state. Also, Nitinol is an intermetallic

compound, that means that in difference from ordinary alloys, the atoms (nickel and titanium) have a very specific position in the structure, facilitating the shape memory effect. The ability of Nitinol to switch between these two crystalline structures is what gives the alloy its shape memory properties.

But the most interesting property of the Nitinol it is the superelasticity. A main fact that causes this effect is that it is possible to form martensite only with stress applied, without involving cooling factors. Therefore, in a certain range of temperature, if stress is applied on austenite it starts to form martensite at the same time that deformation occurs. In this case, when the load is removed, the martensite becomes unstable, and it causes the martensite to recover its austenitic phase and original shape. This is extremely important for the applications of Nitinol in the Mars rover or in any space application. Having a compound that is able to deform and fully recover its shape without giving any type of energy has plenty of ways to be useful.

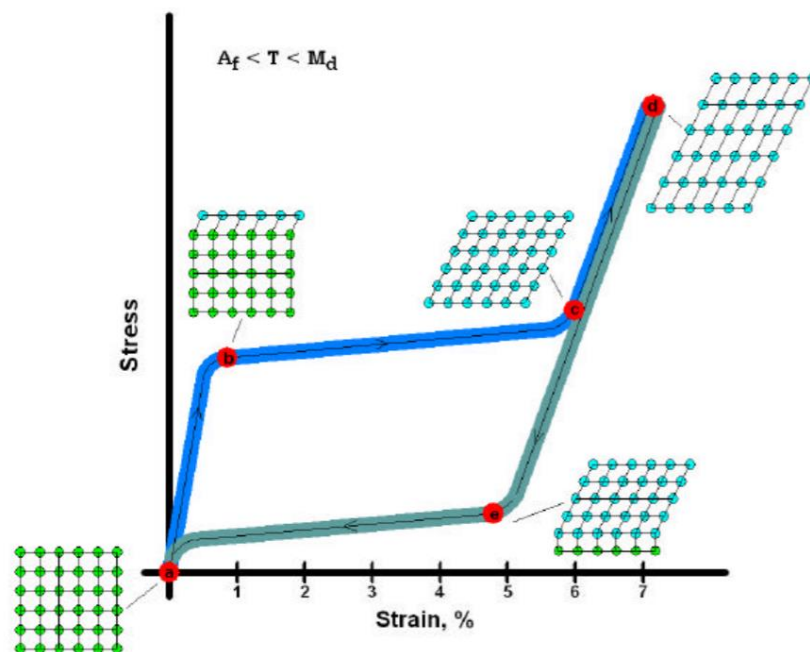


Figure 27. Schematic of the superelastic behavior of Nitinol, when found above the austenite finish temperature,  $A_f$ , and below the martensite deformation temperature,  $M_d$ . Starting at a) on full austenite structure. Stress is applied on the austenite structure forming a twinned structure shown on b), and at the same time forming martensite. The structure is keeping loaded until c) when it transforms the material into full martensite. Continuing loading the martensite until d) causes elastic deformation on the structure. If stress is removed from d) it elastically recovers until c) and if unloading is continued it forces the transformation of austenite on e) until it fully transforms to austenite on a) when unloading is complete and no stress is applied anymore [9].

Nitinol needs to be in full austenite to has superelastic properties, so depending in which temperature the  $A_f$  is found is extremely important in having a spring tire. Anyway, Nitinol superelastic properties are found in a small range of

temperatures above  $A_f$ , approximately 40 degrees above  $A_f$ . This limit of temperature is known as  $M_d$ , the limit of temperature where superelasticity can be found; below this temperature is possible to form martensite under load due to twinning, above this temperature, since martensite cannot be formed under load, it deforms plastically. But it is possible to change the temperature of  $A_f$  to vary the range of temperatures that the superelastic properties are found, in order to adapt to the desired conditions. This is done by changing the composition of nickel and titanium of the alloy.

Nitinol is most likely composed of 50-51% nickel by atomic percentage, and 55-56% by weight percentage. If the composition of nickel/titanium is changed, the transformation temperature (temperature when Nitinol start to behave as a superelastic material) also changes. Therefore, the range of superelasticity can be controlled by changing the ratio of nickel to titanium in the alloy.

Figure 28 shows how the Nitinol's composition affects the point of martensitic transformation ( $M_s$ ). As nickel increases in Nitinol's composition, the  $M_s$  temperature decreases, it can decrease that much that it is possible to have superelastic properties on Nitinol at room temperature ( $\sim 20^\circ\text{C}$ ). This is extremely important on Mars applications.

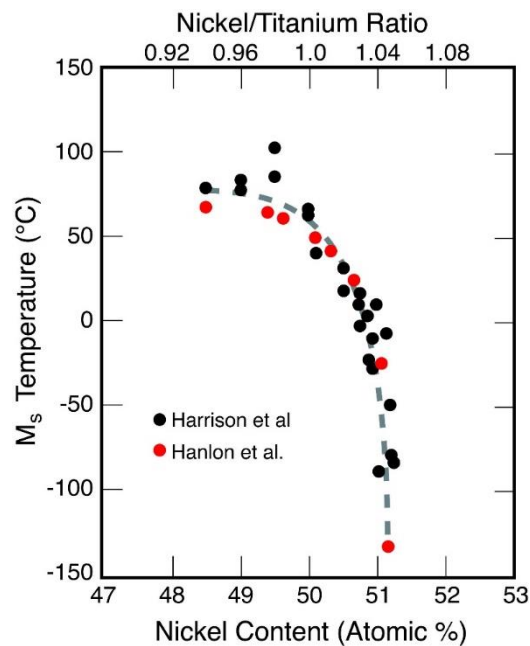


Figure 28. The variation of the martensitic transformation temperature by the change on Nitinol's composition

Mars temperatures can vary a lot. According to the measures the Curiosity rover made on the Gale Crater, the maximum temperature recorded by the rover was 20°C and the minimum was -127°C. Even though these were the maximum and minimum in a whole year, average temperatures in Mars go from -5°C to -80°C. So, for sending superelastic Nitinol to Mars, it needs to behave in this huge range of temperatures. It is a big challenge to set Nitinol to behave superelastically in such changing temperatures, just because the superelastic window is only 40 degrees approximately above  $A_f$ .

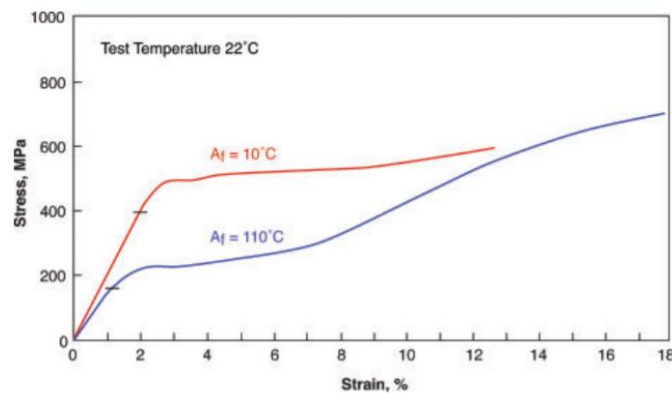


Figure 29. Stress-strain curves at room temperature of two compositions of Nitinol; a superelastic Nitinol ( $A_f = +10^\circ\text{C}$ ) and thermal martensite Nitinol ( $A_f = +110^\circ\text{C}$ ) [10].

To understand more how superelastic materials differ from conventional SMA materials, in Figure 29 is represented a stress strain diagram to show how the two types of Nitinol behave on different loads at room temperature, and how much they deform with the same stress applied. The two types of Nitinol pictured in the figure are the  $Ni_{49-9}Ti_{50-1}$  ( $A_f = +10^\circ\text{C}$ ) superelastic austenite at room temperature (20°C) and the  $Ni_{49-7}Ti_{50-3}$  ( $A_f = +110^\circ\text{C}$ ) thermal martensite at room temperature. As it can be seen in the diagram the superelastic Nitinol has a higher stress plateau; when stress induced martensite starts to form than the thermal martensite structure; when twinning and deformed martensite happens, meaning that superelastic Nitinol can allow more stress until it starts to deform significantly [10].

### 3.3 Structure

The design of the Lunar Roving Vehicle tire was not optimal for Mars, Mars gravity is higher than on the Moon and the LRV only had 450 kg of mass compared to

the almost 1000 kg of the Curiosity, so it had to support much heavier loads, travel faster, improve traction and improve durability, all of that made the tire unsuitable. To change the wire diameter was not an option as its application was limited by two main factors:

1. Contour terrain capability was lost.
2. Loss in durability caused by the increment of wire stress.

Using the original wire mesh from the LRV to accomplish the requirements was too limited. Using helical spring geometries on tires have been proved to have many advantages over normal wire mesh tires like additional flexibility, higher carrying capability and better performance like traction, especially in soft soil conditions, also spring geometries are a way to store energy so there is little energy loss when deformation occurs. But the use of conventional materials like steel, aluminum and alike have problems of plastic deformation. These materials show elastic properties until an amount of deformation of 0.3% after this they enter the range of plasticity, where permanent deformation occurs. Due to this amount of deformation, helical spring geometries can be useful in these materials as they limit the amount of strain that is applied on the material while deformation occurs, so more deformation can be achieved before entering in the range of plasticity. Increasing the diameter of the wire for avoiding permanent deformation is not an option as well, as it carries a huge increment of the material mass, cost and in some cases, an increase of 500% in metal volume, also reducing the performance of the material [11].

In the wake of the problems with plasticity (permanent deformation), SMA introduced a solution to this deformation issues. The innovative wheel keeps the helical spring geometries but replaces conventional materials for shape memory alloys, in order to achieve a much significative strain without permanent deformation. As it has already been explained, SMA can improve the amount of strain before irreversible deformation. In conventional materials the strain before plasticity occurs is about ~0.3-0.5%, and in SMA materials it can get up to ~8-12%, that means that SMA can deform almost 40 times more than conventional materials before plastic deformation. That increases the utility of the material and of the spring wheel itself. Having a material that can deform more without losing

its capability of recovering the shape its fundamental as the main utility of the wheel is to be flexible, and by being more flexible it can adapt more into different geometries, so it can achieve a better performance.

There are many advantages of using SMA on the springs. Despite conventional materials, SMA wire size (of the springs) can be increased without losing much utility. They provide a longer life cycle as SMA do not suffer as much as conventional materials, also, SMA can reduce the overall weight of the wheel, in fact Nitinol has 2/3 of steel's density, that means that it reduces its mass by ~33% compared to steel with the same geometry and the interlaced spring sheet is lighter than other spring designs with a similar amount of deformation.

The tire is a combination of helical springs made from SMA, in specific Nitinol. The tire forms a toroidal shape in order to be able to adapt to different geometries providing good traction and stability. But not all springs are oriented the same way, some springs may be oriented differently to distribute load. Also, an external covering for the SMA springs may be added to protect the structure from impact damage, to avoid sinkage or to generate traction.

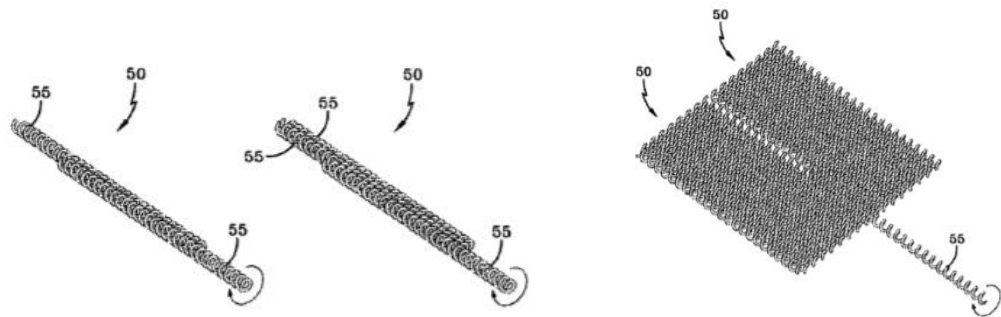


Figure 30. Left: It can be seen how to SMA spring are combined with each other. Right: The springs can be combined to create a rectangular sheet [11].

There are four main steps to build the tire (Padula et al., 2019) :

- i) Interlacing SMA springs together to form a rectangular sheet with a length corresponding to the desired tire circumference.
- ii) Interlacing the borders of the sheet to form a cylinder.
- iii) Attaching those ends of the cylindrical mesh to a “bead” (a cable or wire that holds the springs at the diameter of the rim).
- iv) Bringing closer the two beads (one each side) causing the central part of the sheet to expand radially (creating pressure on the edge of the shape) so the toroidal shape its formed.



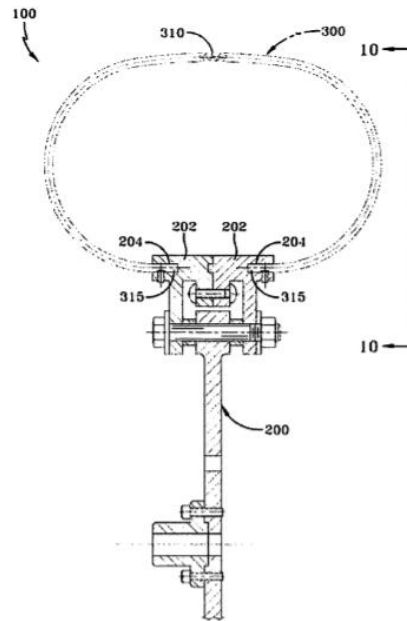


Figure 31. Bending the rectangular sheet and attaching to the edges creates a toroidal shape as it can be seen on the image [11].

An extra rim is located between the two external rims, this is done to distribute the point of gravity and the forces that the rover creates into the wheel, to have the weight of the suspension and the rover vertically and on the center of gravity, that way a lot of momentum is avoided. If the wheels were attached to the suspension by a side and not in the center of gravity, it would be harmful for them.

To clarify this concept, a basic schematic of a wheel with an inner rim is shown below in Figure 32.

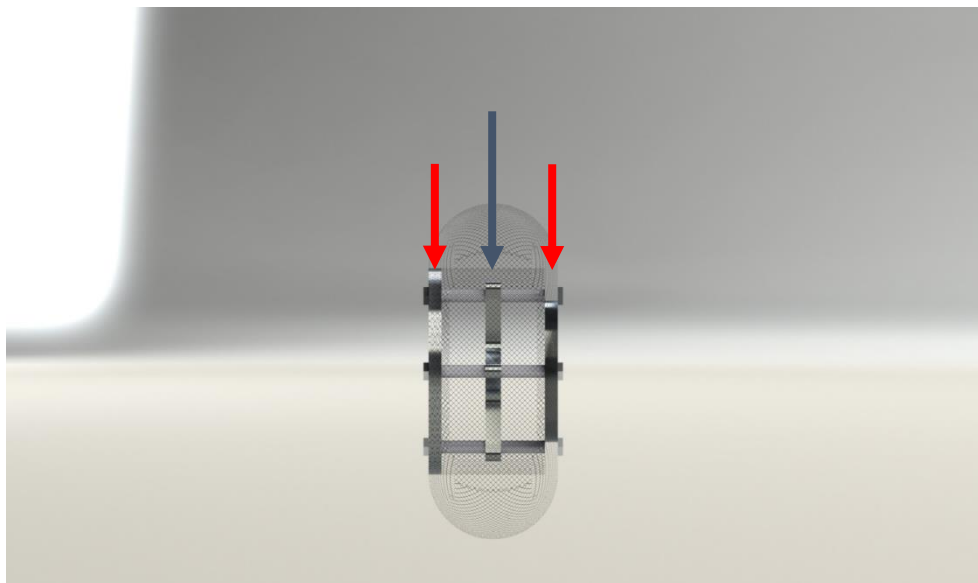
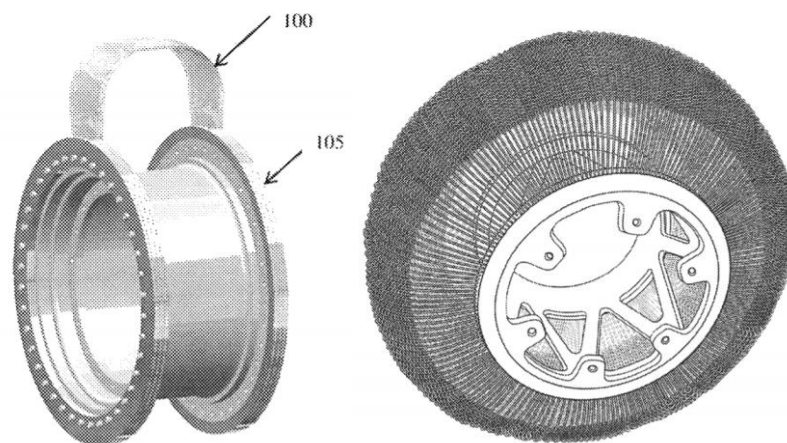


Figure 32. Schematic of where the forces should be located to not modify the wheel rotation or harm the wheel. Red arrows show the incorrect location of the connection with the suspension. In blue the correct position.

The tire provides increased deformation capability, so it can contour different surfaces adapting to the possible different geometries that are possible to find on Mars, it also provides stability and durability to the rover; as the shocks of climbing rocks or different surfaces are absorbed by the SMA tire and not totally by the suspension mechanism or the rigid wheel, meaning that the rover and its components will travel more safely by mitigating shocks and vibrations. The rover would travel faster as the wheel would be less damaged than a rigid wheel.

But using springs is not the only way to achieve the requirements of the wheel, NASA has designed another structure to overcome the limitations of the spring tire, improving flexibility and load-carrying capabilities of the tires. This innovation is a continuation of the spring tire design and consists in a radially stiffened SMA tire that allows the tire to undergo huge deformation without permanent damage and allows rovers to increase speed without damaging shocks and impacts.

It utilizes SMAs (like Nitinol) as radial arched elements instead of springs, that large number of shape memory alloy radial stiffening elements increase the load carrying capability of the tire without compromising the flexibility and deformation that can undergo without permanent damage. So, by replacing springs with radial elements made of the same material (Nitinol) an improvement on carrying capability is achieved.



*Figure 33. Left: Schematic of the radially stiffened SMA wheel according to an embodiment of the innovation. Right: A representation of an assembly of wheel and tire using radially stiffened shape memory alloy element [12].*

The way they are connected to the rim is similar to the spring tire, both ends of the elements are attached to each side of the rim forming arches in the middle

section, this pattern is used for the whole circumference. The tire can be accommodated to different requirements, like changing the radial element diameter to achieve different load carrying capacity, the same thing can be achieved by changing the arch of the radial element, all this depending on the embodiment of the application.

# **Part IV**

## **CONCLUSIONS**

## 4.1 Conclusion

For many year rovers have been using rigid wheels for exploration and several problems have been found with that. Rigid wheels also limit the rovers performance and limit their speed as going fast could damage the wheels because of the shock the wheels would suffer. The Spirit rover from the Mars Exploration Rovers got stuck in loose soil and the Curiosity rover wheels showed important damage after only 10 miles, that makes the scientific community to investigate new ways to move on Mars and the good performance of the Lunar Roving Vehicle put flexible wheels on the center of attention.

It has been proved by many studies that flexible wheels show many advantages over rigid wheels. In fact, some studies have proved that the Spirit rover would have had better performance over the same terrain that got him stuck. And having a flexible alloy that can deform without permanent damage and recovering the shape it had before undergoing deformations, puts in the spotlight the Shape Memory Alloys for their incredible properties.

In fact, the Shape Memory Alloy wheels can provide better traction over deformable terrain, improve performance on rigid terrain as it contours the surface, better shock absorption leading to a longer life cycle, better stability and it can provide more speed as well, increasing the range that the rover can drive on the planet.

The work presented provides a deep research on Shape Memory Alloys and its functionality on Mars rover wheels. Its usage can provide better performance and increment the mission possibilities, even though several testing and more investigation need to be done before using it on rovers.

### 4.1.2 Future steps

The work of this thesis can lead to an investigation on how SMA wheels can be improved to achieve an adaptive wheel type, that can change its shape when it is needed to change its performance.

As on Earth, there are some situations where we might need a lower or higher pressure on our car tires, the same can happen on Mars. A tire that can increment the area of contact with the surface might lead to a better performance on loose soil, as incrementing the area of contact supposes a less sinkage and more traction. Same can happen with lowering the area of contact, the wheel could higher the pressure on the edge of the wheel to have better resistance and rise higher the rover when going over rocky surfaces, that could lead to a much safer travel.

This could be possible changing the distance between the two side rims of the SMA wheel, even though it makes sense, several studies are needed to prove it is possible and suitable, and it could be a continuation of this thesis.

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