

Development of a Mars Curiosity Rover Simulator

A working model intended for modern space science education
and outreach



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Terms of Reference

Title

Development of a Mars Curiosity Rover Simulator for the Cape Town Science Centre

Description

Our knowledge of the planet Mars has been greatly expanded by several rovers that have landed on the planet over the past twenty years. The most capable of these is the Curiosity Rover, which is currently exploring the surface of Mars. The Cape Town Science Centre has requested the UCT SpaceLab to design and build a model of a Mars exploration rover that will be the centrepiece of a future Mars exhibit at the Centre.

Deliverables

Skills and Requirements

Mechanical Design, Software and Electronics Interfacing and Programming.

Area

Science and Technology

Declaration

1. I know that plagiarism is wrong. Plagiarism is to use another's work and pretend that it is one's own.
2. I have used the IEEE convention for citation and referencing. Each contribution to, and quotation in, this report from the work(s) of other people has been attributed, and has been cited and referenced.
3. This report is my own work.
4. I have not allowed, and will not allow, anyone to copy my work with the intention of passing it off as their own work or part thereof.

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Sean Wood

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Acknowledgments

Abstract

- Open the **Project Report Template.tex** file and carefully follow the comments (starting with %).
- Process the file with **pdflatex**, using other processors may need you to change some features such as graphics types.
- Note the files included in the **Project Report Template.tex** (with the .tex extension excluded). You can open these files separately and modify their contents or create new ones.
- Contact the latex manual for more features in your document such as equations, subfigures, footnotes, subscripts & superscripts, special characters etc.
- I recommend using the **kile** latex IDE or *TeXstudio*, as they are simple to use.

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Glossary

Abbreviations listed here are used throughout the document.

- MSL - Mars Science Laboratory
- RSVP - Rover Sequencing and Visualization Program
- RCE - Rover Compute Element
- MEP - Mars Exploration Program
- TMI - Trans-Mars Injection
- CPU - Central Processing Unit
- MIPS - Million Instructions per Second

Chapter 1

Introduction

1.1 Background to the study

A very brief background to your area of research. Start off with a general introduction to the area and then narrow it down to your focus area. Used to set the scene [?]. The section should highlight challenges in the study area to put your work in context [2].

1.2 Objectives of this study

1.2.1 Problems to be investigated

Description of the main problem(s) to be solved and/or hypothesis of your work. Questions to be answered in order to confirm the hypothesis or solve the problems are also articulated here.

1.2.2 Purpose of the study

Give the significance of investigating these problems. It must be obvious why you are doing this study and why it is relevant. Contributions of your work should also be given here.

1.3 Scope and Limitations

Scope indicates to the reader what has been and not been included in the study. Limitations tell the reader what factors influenced the study such as sample size, time etc. It is not a section for excuses as to why your project may or may not have worked.

1.4 Plan of development

This section summarizes the methods, tools, techniques and the order of doing things followed in order to accomplish your work. It also includes such planning tools as project Gantt chart, Critical path analysis and mind mapping.

1.5 Report Outline

Here you tell the reader how your report has been organised and what is included in each chapter. You should give a synopsis for each of your chapters here.

I recommend that you write this section last. You can then tailor it to your report.

Chapter 2

Literature Review

2.1 Space Exploration and NASA’s Journey to Mars

2.1.1 A Brief History

The human race possesses a trait that proposedly sets us apart from the majority of life forms around us; the powerful will to explore what is unknown. It is the curiosity and the thrill to push past the boundaries of what is thought to be possible, perhaps felt stronger by some, that forms the basis of many scientific endeavours relating to facts of life and existence around and outside of the immediate environment in which we live.

A prime example of such a drive to explore is in the research and exploration of outer space, which, from a technological perspective, transitioned from astronomer’s dream to scientist’s and engineer’s reality during the Cold War. Although space exploration as we know it today is motivated by human curiosity, it was during this period of political tension that significant breakthroughs in spacecraft and rocket propulsion technology were brought about. This period is referred to as the “Space Race” and stemmed from research and development of nuclear weaponry during World War II [3, p. 147]. The race began with the attempted launches of artificially made satellites [4, pp. 3-5] and within the 40 years following the success of the USSR’s *Sputnik I* in 1957, the first object to be put into orbit by man, space technology progressed from early manned flights beginning in 1961¹ through the *Apollo 11* lunar flight to having flown by of the majority of the planets in our solar system.

By 1981, the launch of *Columbia* [5], a space shuttle designed to be used for more than one flight, marked the beginning of reusable space technologies answering to the problem of cost and with the forethought of future increase in space flight frequency and demand. Today, the efforts to lower the cost of space travel and the attempt to bring space exploration into the private sectors to make these opportunities more realisable by the public are evident in Elon Musk’s SpaceX development of the Falcon 9, a reusable rocket that returns and lands safely back on the surface of Earth [6].

¹First human in space, Soviet launched

The National Aeronautics and Space Administration (NASA) of the United States has been and still is responsible for a large chunk of mankind's search among the stars and, with respect to research and exploration, has made great efforts to better understand the planet that we live on in conjunction with the immediate spacial environment around Earth, the solar system and the planets within, and that which lies in deep space. After the Apollo lunar missions, efforts by NASA to explore involved one of the first space stations, the *Skylab*, which suffered technical difficulties originating from launch but proved the ability to conduct research in space as well as allow astronauts to perform repairs and maintenance to artificial bodies in that environment [7]. *Skylab* was followed by the International Space Station (ISS), intended to be a more sustainable microgravity environment in which to conduct research that might require such conditions. Research of this type include a very broad range of investigations from the effects of near-weightlessness on plants and animals through to growth of human-like tissues and protein crystallisation [8]. An area of research that specifically relates to this project is in the development of technology to allow for longer, cheaper and faster flights in space, both in spacecraft materials and systems and in astronaut health and performance. This is closely coupled with the search by entities around the world for other forms of life outside of Earth's atmosphere fuelled by the prospect of finding environmental architectures similar to ours. One of NASA's goals outlined in [9] is to send humans to Mars and this has lead to enormous amounts of research, promising engineering and technological successes that will ultimately allow humankind to extend civilisation across more than one planet.

2.1.2 Mars

NASA has identified that Mars is a planet with greater similarity in formation and conditions in its history and as a result has been a target of exploration for more than 40 years. This has involved multiple flybys and orbits starting from 1962 through to the first lander, the *Viking 1*, to touch down on the surface of the planet in 1975 [10]. NASA's Jet Propulsion Laboratory (JPL) landed the spacecraft, named *Pathfinder*, that contained the first successful rover vehicle, the *Sojourner*, in 1997 [11]. The purpose of this mission was to prove the possibility of cheaper spacecraft development and the transport of scientific equipment to the planet as well as taking photographs of the red surface, from the surface.

2.2 The Mars Science Laboratory and Curiosity

2.2.1 Overview

The Mars Science Laboratory (MSL) is a mission that was launched by NASA to further explore the surface of Mars, one of many orbiter, lander and rover type missions as part of the Jet Propulsion Laboratory's (JPL²) Mars Exploration Program (MEP). The program is structured to work towards a set of goals to ultimately understand and determine the potential for life on Mars [12] by observation of the current climate and geology. The MSL is the latest mission in operation as part of MEP and was intended to span roughly

²Jet Propulsion Laboratory of California Institute of Technology

2.2. THE MARS SCIENCE LABORATORY AND CURIOSITY

one Martian year after touchdown on Mars. However, it has continued to operate for more than double that amount of time.

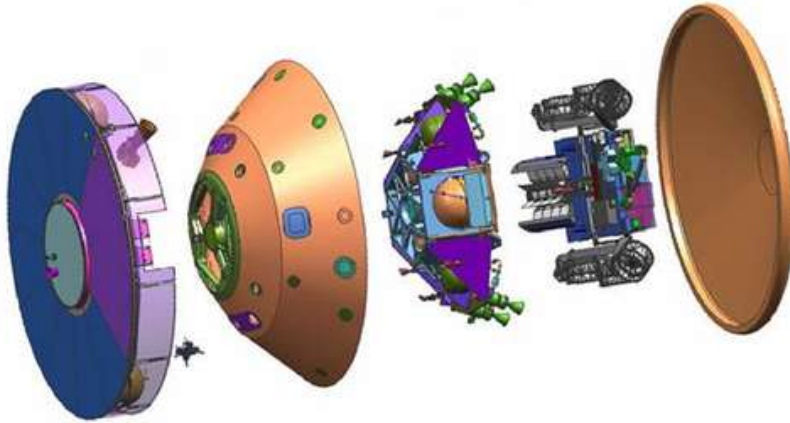


Figure 2.1: An exploded 3D model of the Mars Science Laboratory spacecraft including the cruise stage (far left) and heat shield (far right) [1]

MSL was launched from Cape Canaveral Space Station, Launch Complex 41, atop an Atlas V vehicle, a two stage rocket [13]. The mission required the launch vehicle to insert the five-piece MSL spacecraft into a transfer orbit in a process known as a Trans-Mars Injection (TMI) allowing the spacecraft to arrive at Mars after a 566 million kilometre trip that lasted 256 days. Figure 2.2.1 shows a 3D render of the components of the spacecraft that made the trip. Four trajectory correction manoeuvres were made during the flight to result in a landing near “Mount Sharp” in Gale Crater, deemed the most accurate landing on Mars of any other spacecraft [14].

2.2.2 Primary Mission Goals and Objectives

Touching down on the surface of Mars, the MSL had primary objectives tailored to contribute to the four goals as outlined in the MEP. The objectives were carried out by the MSL’s flagship component, the Curiosity rover, and consisted of a wide range of biological and geological observations such as to determine the chemical building blocks that exist on the surface including organic carbon compounds, prospective historical biological activity, atmospheric processes of evolution, surface radiation and state and distribution of water [15].

Apart from the primary objectives, the MSL mission pushes further the boundaries of space exploration in that it proved the ability to land heavier vehicles at incredibly precise landing accuracy as well as the achievement of wider surface coverage to collect and observe more diverse samples of the surface of Mars.

2.2.3 Curiosity Technical Breakdown

23% of the MSL spacecraft’s total mass of 3.893 metric tonnes was thanks to the missions vehicle, *Curiosity*. The six wheeled, instrument-bearing rover features much improved

hardware over previous vehicles along with a multiple systems of new instruments to enable the carrying out of the mission objectives.

The mechanical and technological specifications are broken down in the sections that follow.

Mechanical Structure

Structurally, *Curiosity* comprises of mechanical features and principles borrowed from the previous three rovers, *Sojourner*, *Spirit* and *Opportunity*, however, was made much larger (almost double the size). The reason behind the increase in size was the need for extra volume in which to fit the significantly larger set of scientific instruments, 100 times larger than the suite on *Sojourner* [16].

![Body structure image]

The body of the rover, a shallow, rectangular box, dominates its structural layout and serves as the central feature onto which all others subsystems are mounted. The chassis is also host to some of the rover's scientific instruments as well as the avionics box. The electronics that make up the avionics operate in a warm environment [17], thus requiring the chassis to provide thermal insulation from the external conditions of Mars. The regulation of internal temperature, aided by the use of electrical heaters, is taken care of by a heat rejection system involving a pumped-fluid loop with the source of heat being the power generator, discussed in a section to follow. Thermal regulation also widened the range of potential landing sites with respect to their distance from the equator.

Overall, *Curiosity* was designed to exceed normal standards of mechanical robustness given the fact that hand-on maintenance is not a possibility when operating so far away from Earth. All subsystems on the rover minimised the opportunity for accidental collisions that might result in unfixable damage to the subsystems and thus jeopardy of the entire mission. In addition to the stringent design procedures, complex simulations of the rover's mechanical operation were done in virtual environments which allowed engineers to ensure, as far as possible, the success of the design in the differing environment that is on the surface of Mars.

Manoeuvrability

One of the main similarities between *Curiosity* and its predecessors is the mechanical subsystem that provides the rover's ability to move around the surface of the planet. The six wheels, each half a meter in diameter, are constructed from aluminium with titanium spokes specially designed to allow for an amount of flexibility required for shock absorption and support. Protruding from the skin of the wheels are cleats in the shape of chevrons. This is an improvement over previous rovers where the cleats were horizontal, a flawed design in that sideways slippage was possible. The angled nature of the chevron cleats on the wheels of the *Curiosity* aimed to prevent this motion. The thin, tubeless design allowed the wheels to be as light as possible which is important not only for

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driving on soft parts of the Martian landscape (termed “floating”), but also for the unique landing sequence the rover had to carry out. The significant increase in the total weight of *Curiosity* meant that conventional means of landing, such as the use of air-cushion support, was not possible. The MSL leveraged the mechanical suspension subsystem on its rover for touchdown instead of providing a separate lander itself. Here, the springy wheel design helped minimise the damage brought about by the impact. As far as weight minimisation of the wheels was concerned, during the moments before the rover was released to land on the surface, the wheels were deployed in a dynamically stressful fashion from their folded position kept during flight. The deployment was sudden and extra weight would have increased the already significant forces imparted on the suspension subsystem during this manoeuvre [18].

However, the feature that is definitive of current and previous Mars mobility systems is the structural arrangement of the wheels in the mechanical suspension subsystem. Each wheel is mounted to an end of the mechanical linkage designed based on the “rocker-bogie” principle. On each side of the rover, the linkage consists of two pivoting beams, one mounted to the side of the rover body, named the “rocker” and the other mounted to the middle-facing end of the rocker, called the “bogie”. The front-facing end of the rocker and both ends of the bogie each host a wheel structure which consists of a pivot and strut for the front and rear wheels and a strut for the middle wheel. Both mount points allow for rotation of the beams such that, to a certain extent, the linkage as a unit remains level despite uneven terrain. This means that any of the three wheels on a side of the rover may lift due to an obstacle, up to the size of the wheel itself, without any of the other wheels lifting off the ground. This results in the obvious benefit of a maximisation of stability, minimisation of angular displacement of the rover body and maximisation of wheel contact with the surface of Mars. Figure ![] shows one of the sides of the mobility system.

![RockerBogie image]

In addition to the freedom of movement of each wheel, the rocker beams from both sides of the rover are connected via a differential bar mounted atop the rover body. The bar, which pivots about a central point on the deck of the body, limits the relative movement of the rocker beams such that one rocker will rotate absolutely in the opposite direction of the other. This significantly reduces the amount of tilt and pitch the body experiences when wheels on one corner of the rover are lifted above the other corners as well as maintains even load across all wheels. In addition, the differential provides the second axis of stability needed to keep the body from toppling forward or backwards about the rocker pivot points.

All six wheels have drive motors that may act independently with each motor mounted to a strut. The four corner wheels’ struts are connected to a pivot, actuated by a highly geared motor to allow independent rotation for steering. The configuration allows for *Curiosity* to turn conventional arcs as well as turn on the spot, an advantage for its mobility. Priority was not placed on speed for the drive motors but rather they were designed to provide high torque for robustness and for travelling on Martian terrain. The maximum speed of *Curiosity* is approximately 4 centimetres a second [19].

The mechanical mobility systems are coupled with the advanced navigational system aboard the rover, a pairing between an arrangement of navigational cameras and software. Four pairs of black and white “Engineering Hazard Avoidance Cameras” (Hazcams) with a field of view of approximately 120 degrees are positioned at the lower front and rear of the rover body, providing the rover with awareness of obstacles. The pairs of cameras create 3-dimensional maps of the terrain in front of and behind the rover. Together with the aid of this environmental mapping, two additional pairs of cameras with a much narrower field of view, namely the “Engineering Navigation Cameras” (Navcams), are mounted to the mast of the rover to provide a complementary perspective of the terrain.

Rover Compute Element

At the heart of *Curiosity* is the computational entity responsible for control of all systems on-board the rover as well as to facilitate communications with the team on Earth. This set of pairwise redundant computers is called the “Rover Compute Element” (RCE) which contain more memory than previous rovers and are hardened against the effects of radiation from the outside environment. The RCE makes use of a *RAD750* CPU designed by IBM and manufactured by BAE Systems Electronics, the radiation-hardened version of the *PowerPC 750*. The *RAD750* has a clock frequency of 110-200 MHz providing more than 266 MIPS of processing power. The pair redundancy of the RCE is such that one of the “sides” of the RCE is operating at a time, but the other side kept in “cold backup”. A software feature named “second chance” was built into the system whereby the alternate side of the RCE could take over basic control during the critical moments of the MSL’s entry, descent and landing [17]. During the flight to Mars, multiple versions of the entry, descent and landing software was sent to the spacecraft to improve the complicated procedure. After the landing, the original software was replaced by one which included control of the rover specifically on and around the surface of Mars. The RCE did not have enough memory to accommodate both flavours of the governing software and as such, each was installed at different points during the mission [20].

Instrumentation

Communication

Power

2.3 Space Education and Outreach

2.4 Web Technologies for Modern Outreach

2.5 Additive Prototyping and Manufacturing Techniques

2.6 Existing Curiosity Rover Models

2.7 Problem Definition

2.7.1 Hardware Requirements

2.7.2 Software Requirements

2.8 Conceptual Design and Development

2.8.1 Concept Proposals

2.8.2 Comparative Analysis

2.8.3 Final Design Choice

2.9 Vehicle Design and Development

2.9.1 Mechanical Design

2.9.2 Electrical Design

2.10 Vehicle Build and Manufacture

2.10.1 Manufacturing Plan

2.10.2 Bill of Materials

2.11 Software Design

2.12 Software Development

2.12.1 Overview of Requirements in Context

2.12.2 Technology Choices

2.12.3 Plan of Structure

Architectural Layout

Build Process

2.12.4 Rover Sequencing and Visualisation Program Server

High Level Architecture

Development

2.12.5 Rover Sequencing and Visualisation Program Client

High Level Architecture

Developement

2.12.6 Rover Compute Element

High Level Architecture

Developement

Chapter 3

Electro-mechanical Integration

Chapter 4

Testing and Results

Chapter 5

Discussion

Here is what the results mean and how they tie to existing literature...

Discuss the relevance of your results and how they fit into the theoretical work you described in your literature review.

Chapter 6

Conclusions

These are the conclusions from the investigation and how the investigation changes things in this field or contributes to current knowledge...

Draw suitable and intelligent conclusions from your results and subsequent discussion.

Chapter 7

Recommendations

Make sensible recommendations for further work.

Bibliography

- [1] JPL, “Cruise configuration.” [Online]. Available: <http://mars.nasa.gov/msl/mission/spacecraft/cruiseconfig/> [Accessed: 2016-07-25]
- [2] E. Kamen and B. Heck, *Fundamentals of Signals and Systems Using the Web and MATLAB*. Prentice Hall, 2000.
- [3] J. Cornwell, *Hitler’s scientists : science, war, and the devil’s pact*. New York: Viking, 2003.
- [4] J. Schefter, *The race : the uncensored story of how America beat Russia to the moon*. New York: Doubleday, 1999.
- [5] W. Harwood, “Sts-129/iss-ulf3 quick-look data,” Oct 2009. [Online]. Available: <http://www.cbsnews.com/network/news/space/129/129quicklook2.pdf> [Accessed: 2016-07-23]
- [6] R. Simberg, “Elon musk on spacex’s reusable rocket plans,” February 2012. [Online]. Available: <http://www.popularmechanics.com/space/rockets/a7446/elon-musk-on-spacexs-reusable-rocket-plans-6653023/> [Accessed: 2016-07-23]
- [7] W. Compton and C. Benson, *Living and working in space: a history of Skylab*, ser. NASA SP. Scientific and Technical Information Branch, National Aeronautics and Space Administration, 1983. [Online]. Available: <https://books.google.co.za/books?id=Qpax6JcVyG8C> [Accessed: 2016-07-23]
- [8] NASA, “Fields of research,” March 2008. [Online]. Available: <https://web.archive.org/web/20080123150641/http://pdlprod3.hosc.msfc.nasa.gov/A-fieldsresearch/index.html> [Accessed: 2016-07-23]
- [9] N. Aeronautics and S. Administration, *Authorization Act of 2010*, 2010.
- [10] S. Robbins, “Journey through the galaxy: Mars program,” 2008. [Online]. Available: http://jtgnew.sjrdesign.net/exploration_space_planetary_mars.html [Accessed: 2016-07-23]
- [11] J. Nelson, “Mars pathfinder / sojourner rover,” 2000. [Online]. Available: <http://www.jpl.nasa.gov/missions/details.php?id=5913> [Accessed: 2016-07-23]
- [12] JPL, “Nasa’s mars exploration program’s science theme.” [Online]. Available: <http://mars.jpl.nasa.gov/programmissions/science/> [Accessed: 2016-07-25]

- [13] W. Harwood, “Mars science laboratory begins cruise to red planet,” November 2011. [Online]. Available: <http://spaceflightnow.com/atlas/av028/> [Accessed: 2016-07-25]
- [14] T. J. Martin-Mur, G. L. Kruizinga, P. D. Burkhart, M. C. Wong, and F. Abilleira, “Mars science laboratory navigation results,” Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA, Tech. Rep., 2012. [Online]. Available: http://issfd.org/ISSFD_2012/ISSFD23.IN1.1.pdf [Accessed: 2016-07-25]
- [15] JPL, “Mars science laboratory: Mission objectives.” [Online]. Available: <http://mars.jpl.nasa.gov/msl/mission/science/objectives/> [Accessed: 2016-07-25]
- [16] E. Lakdawalla, “Curiosity in context: Not exactly ”Viking on wheels,” but close,” November 2011. [Online]. Available: <http://www.planetary.org/blogs/emily-lakdawalla/2011/3271.html> [Accessed: 2016-07-30]
- [17] N. Aeronautics and S. Administration, *Mars Science Laboratory Landing*, 2012. [Online]. Available: http://www.jpl.nasa.gov/news/press_kits/MSLLanding.pdf [Accessed: 2016-07-31]
- [18] E. Lakdawalla, “Curiosity wheel damage: The problem and solutions,” August 2014. [Online]. Available: <http://www.planetary.org/blogs/emily-lakdawalla/2014/08190630-curiosity-wheel-damage.html> [Accessed: 2016-08-03]
- [19] JPL, “Mars Science Laboratory: Curiosity wheels and legs.” [Online]. Available: <http://mars.jpl.nasa.gov/msl/mission/rover/wheelslegs/> [Accessed: 2016-08-14]
- [20] J. Hanna, “’impressive’ Curiosity landing only 1.5 miles off, NASA says,” August 2012. [Online]. Available: <http://edition.cnn.com/2012/08/10/us/mars-curiosity/index.html?eref=mrss.igoogle.cnn> [Accessed: 2016-08-14]

Appendix A

Additional Files and Schematics

Add any information here that you would like to have in your project but is not necessary in the main text. Remember to refer to it in the main text. Separate your appendices based on what they are for example. Equation derivations in Appendix A and code in Appendix B etc.

Appendix B

Addenda

B.1 Ethics Forms