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.
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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 namual 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.

Contents

List of Figures

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Glossary

Abbreviations listed here are used throughout the document.

- MSL - Mars Science Laboratory
- RSVP - Rover/Robot 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
- WEB - Warm Electronics Box
- RTOS - real-time operating system
- DSN - Deep Space Network
- DFE - direct from earth
- DTE - direct to earth
- HGA - high-gain antenna
- RLGA - Rover low-gain antenna
- bps - bits per second
- FFL - fixed-focal length
- Mastcam - Mast Camera
- APXS - Alpha Partical X-ray Spectrometer
- MAHLI - Mars Hand Lens Imager
- CheMin - Chemistry and Mineralogy

- SAM - Sample Analysis at Mars
- RAD - Radiation Assessment Detector
- DAN - Dynamic Albedo of Neutrons
- REMS - Rover Environmental Monitoring Station
- MARDI - Mars Descent Imager
- NAC - Narrow Angle Camera
- MAC - Medium Angle Camera
- XRD - X-ray Diffraction
- XRF - X-ray Fluorescence
- SA/SPaH - Sample Acquisition, Sample Processing and Handling
- QMS - Quadrupole Mass Spectrometer
- GC - Gas Chromatograph
- TLS - Tunable Laser Spectrometer
- SMS - sample manipulation system
- CSPL - Chemical Separation and Processing Laboratory
- UVS - Ultraviolet Sensor
- ICU - Instrument Control Unit
- COTS - commercial off-the-shelf
- MMRTG - Multi-Mission Radioisotope Thermoelectric Generator
- CNC - Computer Numerical Controller
- SoC - System on a Chip
- CSI - Camera Serial Interface
- eMMC - embedded Multi-Media Controller
- STL - Standard Tessellation Language

Chapter 1

Introduction

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 [1].

Objectives of this study

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.

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.

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.

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.

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

Space Exploration and NASA's Journey to Mars

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 [2, p. 147]. The race began with the attempted launches of artificially made satellites [3, 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 1961[1] 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* [4], 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 booster stage that returns and lands safely back on the surface of Earth [5].

[1]First 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 [6]. *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 [7]. 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 [8] 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.

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 [9]. NASA's Jet Propulsion Laboratory (JPL) landed the spacecraft, named *Pathfinder*, that contained the first successful rover vehicle, the *Sojourner*, in 1997 [10]. 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.

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A short paragraph on current goals by NASA relating to modern Mars exploration
and the need for rovers, to introduce the next section
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The Mars Science Laboratory and Curiosity

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 (JPL[2]) 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 [11] 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 one Martian year after touchdown on Mars. However, it has continued to operate for more than double that amount of time.

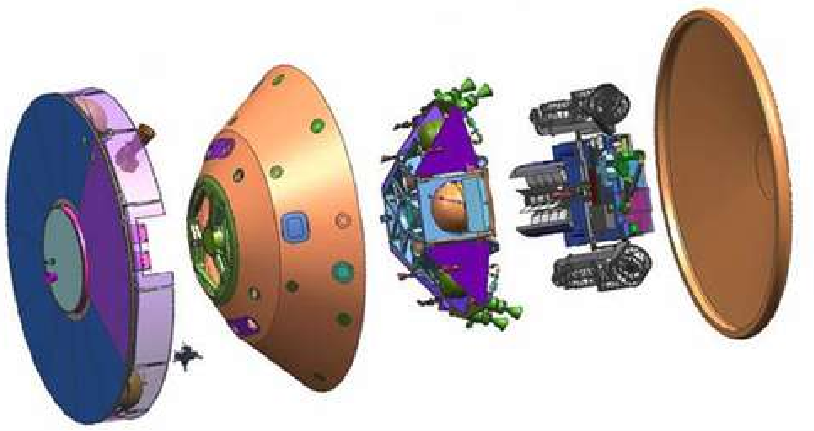

Figure 2.1: An exploded 3D model of the Mars Science Laboratory spacecraft including the cruise stage (far left) and heat shield (far right) [12]

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 **??** 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].

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A piece on the choice of a landing site for Curiosity
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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

[2]Jet Propulsion Laboratory of California Institute of Technology

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.

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 body to provide thermal insulation from the external conditions of Mars, giving it the name the Warm Electronics Box (WEB). 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 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 design 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 facilitation of communications with the team on Earth. This set of pairwise redundant computers is called the "Rover Compute Element" (RCE) which contains more memory than previous rovers and is 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 while 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 should the primary side fail [17]. During the flight to Mars, multiple versions of the entry, descent and landing software was sent to the spacecraft as improvements to 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].

The RCE software involves the use of a real-time operating system (RTOS) approach to core scheduling and operation. JPL opted for a COTS solution for the RCE software and used an RTOS product from Wind River Systems called VxWorks. The operating system was first released in 1987 and has been used in multiple industries from space and defence to consumer electronic and automotive applications [21], not to mention having been a part of 20 previous JPL's missions. Over the years, VxWorks has been improved in areas of modularity and upgradeability and offers a wide variety of application layers aimed at the Internet of Things. The choice by JPL, yet again, to use VxWorks on the RCE was motivated by the operating system's reliability and maturity, an extensive set of supporting tools and low-level scheduling hooks for critical real-time operations [22].

Additional Internal Systems

Stemming from the central control principle of the RCE are other computing and sensory subsystems that monitor and maintain healthy operation of the rover. One of these systems is the Inertial Measurement Unit (IMU) which gives *Curiosity* a rotational awareness about three axes: roll, pitch and yaw. It is used with the acquired 3D map of the rover's immediate surroundings to estimate the angular position of the rover during navigation and thus ensure that the rover is stable and safe.

Curiosity also has an internal control subsystem that monitors various measurements including temperature, power consumption, power storage and communication systems. The control loop will ensure that the rover remains operational and can produce warnings should any of the measurements be abnormal.

Communication

Communication with the rover from the ground station on Earth is arguably the most critical component of the mission besides the rover itself. It allows the upload of series of commands generated by the team together with the software here on Earth as well as the download of scientific data, rover telemetry and images to aid the team in keeping the rover geographically aware. The communication systems were designed to be redundant and to ensure good quality links despite challenges involving the Earth's and Mar's rotation about their own axes and obstructions as a result. Figure 2.2 shows a depiction of the telecommunication system structure.

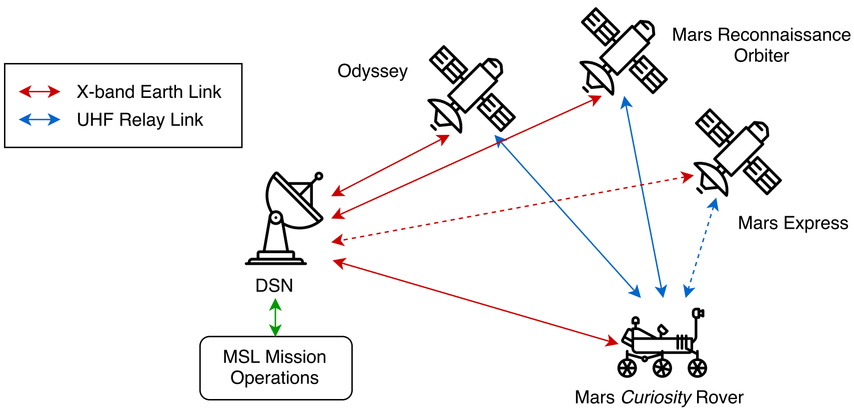


Figure 2.2: Diagram showing the structure of the MSL telecommunications system. Adapted from [23].

The Earth based component of this communication link originates from a collection of large antennas placed strategically around the Earth that alongside performing astronomical observation, provides communications for spacecraft that are travelling at an interplanetary scale. The system, a part of JPL, is called the NASA Deep Space Network (DSN) which consists of three facilities positioned in California, Spain and Australia [24]. The positioning of the antennas in this way allows effective communication irrespective of the angular position of the Earth, meaning longer contact time between the team on Earth and *Curiosity*. For JPL, the DSN is close to home and thus mainly hosts the central data hub for communications with the rover.

On the Martian side of the link, the rover has aboard three antennas, two of which support the X-band[3] communication frequency and a third for Ultra-High Frequency (UHF) software radio communication. The X-band telecommunication system gives the rover a direct communication connection between Mars and the DSN on Earth and consists of a high-gain antenna (HGA) and the Rover low-gain antenna (RLGA) [25]. The HGA is movable with two degrees of freedom allowing *Curiosity* to point it accurately back at Earth. This antenna facilitates direct to Earth (DTE) command transmission and direct from Earth (DFE) telemetry at between 160 bps and 800 bps depending on the DSN station size. The RLGA is used mainly for contingency DFE commands and is kept as more of a redundant communication feature. Downlink communication via the RLGA is also possible but again used in case of primary communication failure.

The main method of communication with the rover when on the surface of Mars, however, is via the UHF system which uses the currently operational Mars orbiter spacecraft, the Mars Reconnaissance Orbiter (MRO) and Odyssey, as relays to the DSN. Relaying communication via multiple spacecraft which are orbiting the planet means that less power for signal amplification is required from the rover itself and the time of coverage from the perspective of the DSN stations is increased because objects orbiting the planet are obstructed by the planet body for shorter periods of time. MRO is the primary relay and Odyssey remains the redundant relay for when MRO is unavailable, provided the significantly lower data transfer speed allowed data transfer within DSN time and UHF energy constraints.

Instrumentation

Scientific observation and investigation of the surface of Mars by the *Curiosity* rover forms the crux of the MSL mission and the instruments aboard the rover are the tools with which JPL and NASA are doing such. The ten instruments, primarily scientific, hosted by the rover body, are each designed to perform specific tasks on different aspects of the rover's surroundings and samples from which it may acquire. The typical flow of investigation would be initiated by inspection of high resolution images from the rover's array of cameras. Features of interest are then located, navigated to and further inspected by the instruments mounted on the rover's robot arm and hand. Features may be inspected using those tools, or brought into the rover's body for further analysis, should that be required. Additionally, atmospheric features may be observed using the instruments design for these types of investigations.

[3]X-band - a radio frequency band within the microwave region (specifically between 8.0 and 12.0 GHz) used for engineering communication and radar

The range of instruments, as highlighted by the flow of investigation above, are split into four categories based on their method of contact with their subject. The list below shows the classification as mentioned and provides a short summary of each of the instruments.

- **Remote Sensing Instruments**
  - *Mastcam (Mast Camera)*: a suite of two fixed-focal length (FFL) cameras, one the Narrow Angle Camera (NAC) with a 5.1° FOV and 100 mm focal length, and the other the Medium Angle Camera (MAC) with a 15° FOV and a 34 mm focal length [26]. Each camera contains 8 Gb of buffer memory able to store over 5 500 raw frames, as well have the ability to pass the images through a collection of filters. Both cameras, although different in their FOV, focal length and color filter specifications, were designed to work together to provide stereoscopic views of landscapes, rocks and structures and the atmosphere.
  - *ChemCam (Chemistry and Camera)*: a suite of two remote sensing devices, the Laser-Induced Breakdown Spectrometer (LIBS) and the Remote Micro-Imager (RMI) [27]. The LIBS is the first ever laser sensing device in the field of planetary science and has the ability to investigate the elemental breakdown of rocks and other material under its sub-millimetre beam, an advantage over other breakdown spectrometers in that it can target very specific points on the surface. The RMI, which images through the same telescope as the LIBS, provides context and a highly targeted visual on the point at which the LIBS is operating. The RMI has a very small FOV of 19 milliradians and can distinguish the LIBS target point at any range within that of the LIBS laser beam. ChemCam provides further advantage over other contact-based analysis devices in that the team can use it to take samples more often without the need of the already tricky terrain traversal of the rover.
- **Contact Science Instruments**
  - *APXS (Alpha Partical X-ray Spectrometer)*: a compound instrument consisting of an electronics system situated in the body of the rover and a sensor module on the hand of the rover's robot arm. Spectral measurements are made by placing the sensor in direct contact with the material of interest, or up to 2 cm away from it, and observing X-ray emissions for a time between 15 min and 3 hours [28]. The sensor will then transmit the resultant data to the rover which contains up to 13 spectra and additional engineering information. The APXS on this rover is a significant improvement over that on *MER* with between three and six times the sensitivity for low and high atomic number elements respectively.
  - *MAHLI (Mars Hand Lens Imager)*: a focusable, high-resolution, colour camera positioned on the end of the robotic arm used to take close-up images of subjects on the surface in places to which the rest of the rover's cameras do not have access. The camera has a range of features which give it flexibility in the nature of subjects that it might capture, including night illumination, auto focus, focus stacking and video [29]. Other use cases include searching for UV material, sky imaging, sample observation, stereo-pair imaging and rover self-portraits (fault diagnosis and for education and outreach).

- **Analytical Laboratory Instruments**
  - *CheMin (Chemistry and Mineralogy)*: an in-body chemical and mineral analyses instrument which operates using the principles of powder X-ray Diffraction (XRD) as well as X-ray Fluorescence (XRF) on a nominal (but not maximum) amount of 74 samples as delivered by the Sample Acquisition, Sample Processing and Handling system SA/SPaH [30]. Drill or scoop samples from this system reach the CheMin's funnel system on the deck of the rover, piezoelectrically vibrated to ensure transfer of the sample. Sample material is filtered numerous times, initially in the CHIMRA sorting chamber and then through filters in the sample cell. Sample analysis can there-onwards take up to 10 hours. The primary goal of the analytical observations performed by the CheMin is to identify and assess the historic or even current presence of water in the samples in an attempt to better understand the state of Mars with respect to the possibility of life on the surface. Raw CCD frames of the diffraction patterns and histograms are processed on the rover and then sent via downlink transmissions with the possibility of indication of indicators of previous inhabitance by life forms.
  - *SAM (Sample Analysis at Mars)*: a collection of three instruments: the Quadrupole Mass Spectrometer (QMS), a Gas Chromatograph (GC) and a Tunable Laser Spectrometer (TLS) [31]. The instruments can work together and separately for much the same reason as the CheMin in terms of the search for evidence of life forms, but with focus in the area of organic chemistry in general as opposed to just water. The analyses form part of five science and measurement goals outlined for SAM are tightly coupled to the core MSL mission goals, and involve a multitude of investigations into the state and history of formation and destruction of compounds to reveal indicators of previous life. The sample manipulation system (SMS) and Chemical Separation and Processing Laboratory (CSPL) provide a means for the samples to be in the correct state and to reach the three instruments. The two support devices ensure correct environments are maintained within SAM for the analysis of the samples.
- **Environmental Instruments**
  - *RAD (Radiation Assessment Detector)*: a charged particle telescope, mounted to the deck of the rover, which analyses particles with the aim of obtaining and characterising the spectrum of particle radiation on Mars. This is done to estimate the amount of radiation a human would encounter if they were to be on the surface on Mars and further understand what this radiation may have meant for life on Mars above and below the surface [32].
  - *DAN (Dynamic Albedo of Neutrons)*: an active/passive neutron spectrometer provided by the Russian Federal Space Agency with the aim of estimating hydrogen content in the subsurface layers when the rover is traversing the planet. Most of the measurements take place during short stops that the rover may make during these journeys, the longer the measurement time resulting in more accurate measurements [33].
  - *REMS (Rover Environmental Monitoring Station)*: a pair of horizontally outward facing booms attached to the Remote Sensing Mast, below the Chemcam, as

well as an additional sensor on the deck of the rover. The Instrument Control Unit (ICU) for the REMS is positioned inside the rover body. The booms, sitting approximately 1.5 m above the surface of Mars, record wind speed and direction, pressure, relative humidity, air temperature and ground temperature while the deck-bound Ultraviolet Sensor (UVS) ultraviolet radiation. The position of the booms relative to each other and to the rover and its RMS was carefully engineered such that the wind perturbation would be as minimal as possible, an attempt to keep the wind measurements as accurate as possible. The measurements that the REMS takes are systematic and 5 minutes of observation takes place every hour of every sol[4] regardless of what operational state the rover is in, with the sensors operating at a data frequency of 1 Hz. Energy constraints allow total use of the REMS for three hours a day, which means that the REMS may autonomously increase the length of any of the 5 minute measurement operations if an atmospheric event has been detected.

- *MARDI (Mars Descent Imager)*: a FFL colour camera fixed to the body of the rover, pointing directly downwards, which is capable of taking 1600 x 1200 images used during the landing of the MSL spacecraft. The camera consists of a 90 degree circular FOV lens behind which sits a rectangular FOV sensor. The camera started taking images on command at the time of heat shield separation and continued to do so at 5 images per second until approximately 2 minutes after touchdown. Each image stored realtime into flash memory (for later transmission) can be compressed, also in realtime. The burst of images was used to provide geographical indication of the exact landing point of the rover and a framework within which engineers could base early operations. Downlink transfer of these images would have been in the form of thumbnails first and then a subset of full resolution images afterwards.

Power

Unlike conventional spacecraft and planetary space vehicles, *Curiosity* is not powered using solar means but rather energy is in the form of heat given off by the decay of a radioactive isotope, plutonium-238 dioxide. 4.8 kg of the decaying material is hosted inside of the generator named a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) produced by Rocketdyne and Teledyne Energy Systems, assembled and tested by Idaho National Laboratory [34]. The heat produced by this decay process is then converted into electrical energy through the use of thermocouple devices and excess heat is transferred to the rest of the rover body for heating, as mentioned in a previous section. The thermocouple has the advantage of being able to leverage the cold outer-space environment for the "cold junction", making RTGs well suited to interplanetary travel. Radioisotope Thermoelectric Generators (RTG) are not new to the space industry and provide missions the longevity and more consistent and reliable sources of power that one might require.

![Image of rear end of the rover, the position of the MMRTG]

The design concept behind the MMRTG is a generator that is more flexible in its field

[4]sol - the duration of a solar day on Mars

of applications as well as one which includes a high degree of safety, a desirable design feature in any space technology. Another goal of the MMRTG design is to optimise the power level over a lifetime of 14 years whilst minimising its weight [35].

Robot Sequencing and Visualisation Software

While many portions of the *Curiosity's* operation and movement are autonomous and require little direct input from the control team on Earth, the ground station has ultimate control over the functioning of the rover, the set of tasks it carries out and the timing with which to do so. The team also requires the ability to assess the state of the rover, its geographical position and its configuration along with, at the very least, depictions of its immediate surroundings. JPL engineers and scientist achieve such control and awareness with a specially created software suite which has been progressively developed and further improved alongside and for multiple recent Mars rover missions. The Rover Control Workstation (RCW) was developed initially to control the earlier Mars rover vehicle, *Sojourner* [36], and was later used as a basis upon which the *MER* control suite was written, the Rover Sequencing and Visualisation Program (RSVP).

The principle behind the RSVP involved the goal to maximise the use of each sol on Mars whilst relieving the requirement for operators on Earth to have to endure the asynchronous timing of sols and Earth days which was viewed as an operational constraint. Another issue was the fact that traversal of a rover on Mars resulted in the lack of knowledge of the vehicle's final position, requiring the downlink transfer of telemetry and analysis of that data upon which to plan further activities. This process introduced time lag and a suboptimal use of time for rover operation. The RSVP, along with the RCW, introduced a set of tools which make the daily command cycle a more optimal procedure, starting with the ability to rapidly interpret data received from the instruments on the rover and reconstruct the state of the rover in the most accurate way possible, presenting this depiction of state to the operator. This includes spatial positioning of the rover and the environmental context within which it is situated. Further, the RSVP provides rapid composition and simulation of commands to send to the rover, which will autonomously carry out the commands therefore freeing the operator from the time-frame of another planet.

Thus, RSVP was designed around the concept of the downlink-uplink cycle and contained two parts, Data Analysis and Sequence Generation. The Data Analysis facilitated functions of state awareness and immersion broken down into the following features:

- **State Analysis**: Analysis of the data obtained by sensors on the rover body pertaining to the state of subsystems of the rover to result in an understanding of the overall state of the rover.
- **Image Browsing**: Review and processing of images taken by the rover's cameras allowing the user to construct mosaics of panoramic sequences.
- **Terrain Modelling**: Construction of a 3D model of the immediate terrain as acquired from the rover's stereoscopic imaging systems which can later be used to

plan traversals and ensure safe paths on the surface of Mars.

- **Terrain Visualistion, Immersion and Telepresence**: The use of the constructed 3D model of the terrain to immerse the operator into the environment giving the operator a better understanding of the surface and the positional state of the rover.

The RSVP's second part involves the notion of intelligent Sequence Generation and a convenient and efficient process flow in the construction of sequences of commands to send to the rover [37]. The range of commands that an operator can send to the rover is wide and these commands have varying target levels of operation and an associated variation in the level of autonomy as a result. An example of a very low-level, non-autonomous command might be to turn on a heater while a heavily autonomous, complex command might involve setting a target traversal destination and allowing the rover to construct a route based on sensor data and algorithms. Sequence generation follows a fairly comprehensive process initiated by a meeting of the group of operators whereby they will discuss the state of the rover and the aim of the particular day's events. Scenarios are analysed and weighed against the constraints of the situation. Further meetings are held to plan the detail of the activities agreed upon and to receive approval of the plans. The RSVP aids this process by allowing the team to input a draft of the set of sequences and outputting a simulation of the execution of such sequences. Distribution of the set of commands to all the teams involved allows understanding of the objectives and events by all parties and after the final sequence has been approved and the RSVP has completed validation of the sequence, the commands are built to be sent via uplink.

The variant of the RSVP used for *Curiosity* was confusingly renamed to the *Robot* Sequencing and Visualisation Program and contains much the same principle of operation and software features as the RSVP used for MER. The RSVP, in both MER and MSL cases, is clearly separated into two program user-interface components. The sequence generation is carried out in the Robot Sequence Editor (RoSE) [38] which is aware of the wide set of commands and how they will affect the rover as well as the compilation of commands for uplink. A view of the RoSE is shown in Figure 2.3. Visualisation is taken care of by the program component called HyperDrive host to a high-fidelity set of 3D and stereo Martian surface displays [39], and example of which is shown in Figure 2.4.

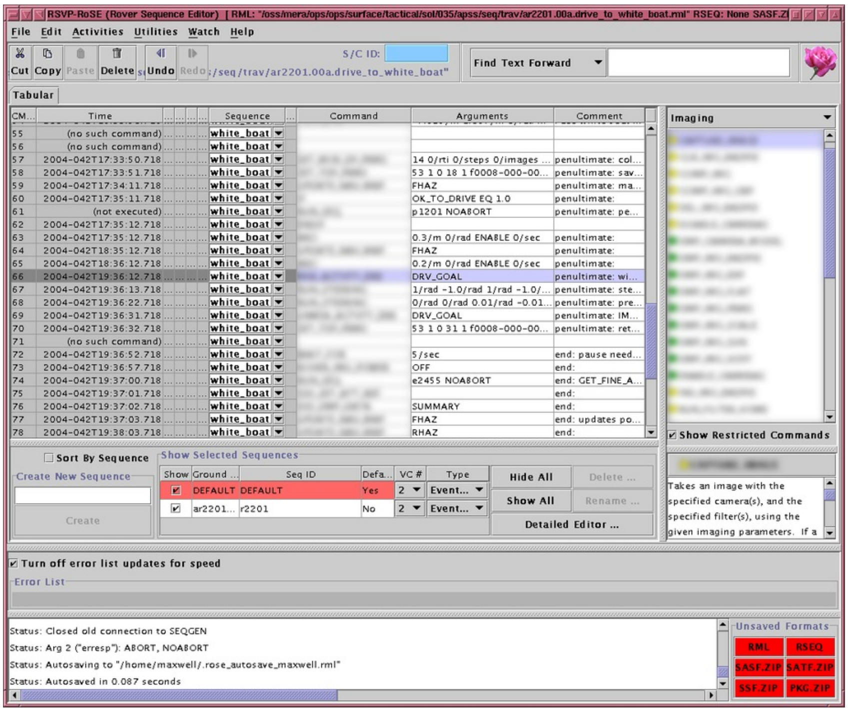


Figure 2.3: A screenshot of the RoSE as implemented in the RSVP used for MER [40]

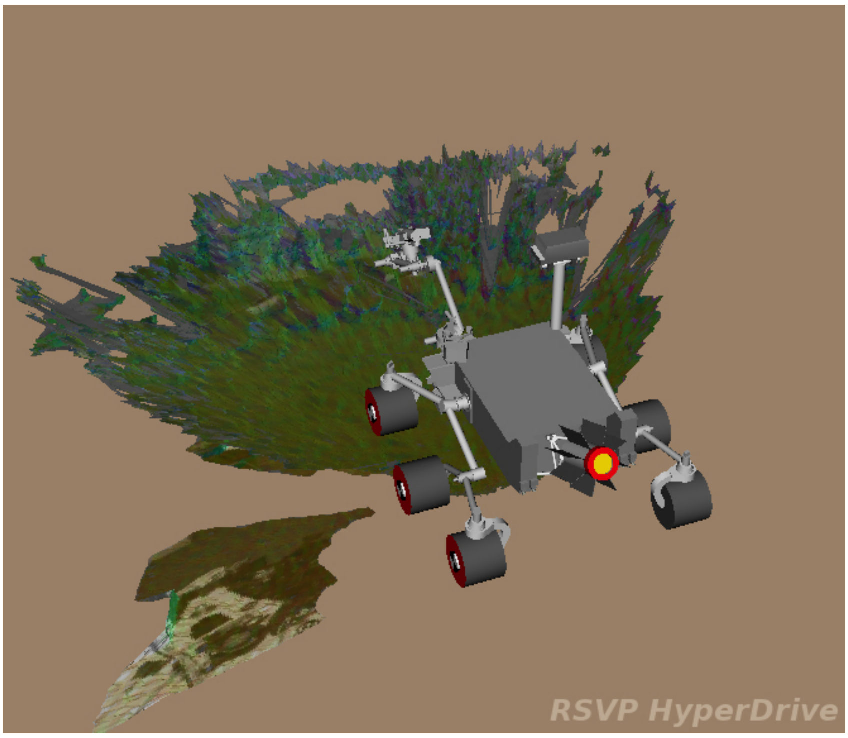


Figure 2.4: A view of the 3D model output by the RSVP HyperDrive program component for visualisation and immersion [41]

Space Education and Outreach

Web Technologies for Modern Outreach

Until recently, the world of computers and their interconnectedness has been primarily a means of personal communication and collaborative, distributed computation with minimal focus on openly sharing information and educating. It has been with the exponential increase in performance and availability of communication and network technologies that the notion of mass sharing and consumption of information in a real-time sense has made a prominent standing in the way that the world makes use of the computational devices that they might possess.

In recent years, online education has gained significant popularity due to the flexibility that it provides to the learner and the convenience to the educator. In 2001, MIT launched the OpenCourseWare initiative [42] where learners may view educational content from MIT at no additional cost other than the cost of an internet connection by any means. UC Berkeley followed suit in 2006 along with Yale, Stanford and Harvard in later years and online education, beginning simply as a prospective endeavour, turned rapidly into the educationally rich internet that exists today. Multiple other organisations joined the fast growing culture, such as Kahn Academy, offering free education to those who have access to the internet.

It is this ease-of-access that has driven the appeal of the web as a distributive platform for educational material. Institutions and organisations realised that education need not be hindered by the logistical constraints imposed on educators and that the web allowed them to educate learners in developing countries and other remote locations right from where they might be situated. They also realised that the material could be shared to a significantly larger audience compared to that in a classroom or lecture theatre. Today, advancements in web technologies and the progressive nature of current web standards means that the level of interactivity possible through a browser is only increasing.

The web has, more recently, developed itself around a core culture of open source. It is the concept where development of a product or project can be accessed, used and contributed to, at no additional cost [43]. Open source culture operates with a notion of constructive debate in collaboration in order to promote development and quality of the project and it inherently provides a highly educational environment in which people can tackle steep learning challenges with a positive and constructive outcome. Additionally, the availability of use of open source projects and culture make it possible for anyone to create and share a service or product on the internet with very little initial resources or funding required and it is this opportunity that many of the sources of online education have taken to their advantage. In a short amount of time, one can share large and complex forms of data securely and remotely for the benefit of others around the world.

Existing Curiosity Rover Models

Chapter 3

Rover Model Development Methodology

Development Objectives

Problem Definition

The project aimed to propagate the theme of science education and outreach, leveraging the modern technologies of today, through the development of a working, scaled down version of the *Curiosity* rover. The project brief indicated that the typical use case as desired by the client was to have the rover simulate chosen, significant features of the rover on Mars to shed some light on the level of capability of space technologies that are currently in operation. The model will be set either in a simulated Martian environment or in a small display area and be required to be remotely controllable, providing video and telemetry to viewers and viewer's devices the same way the RSVP would to the flight team at JPL.

As an initiation of the project, the requirements were explored and collated below into a list of those pertaining to the vehicle itself in a sense of the hardware as well as the software that encompassed the operation of the vehicle as an educational piece. The requirements made sure to maintain as little reference to technologies available as possible as this detail was to be further developed after analysis of the requirements on a functional level.

Project Requirements

1. Develop and build a model of the Mars *Curiosity* rover. The rover model should:

   (a) be a scaled down representation of JPL's rover currently operational on Mars with a level of resemblance adequate for use in a realistic exhibit. In other words, it should have been realistic enough such that someone who might have seen a picture of *Curiosity* beforehand could identify the rover,

   (b) have traversal capabilities that reflect those on *Curiosity*,
   (c) be able to make use of these traversal capabilities on uneven terrain such as one which would be a simulated surface as part of the exhibit without resulting in an unrecoverable state,
   (d) offer video streaming to connected clients
   (e) have reasonable awareness of obstacles to prevent resulting in an unrecoverable state as well as to provide an indication of the navigational and environmental awareness systems on *Curiosity*,
   (f) have data communication facilities available to best represent the communication systems and subjects of those that are a part of MSL, and
   (g) be completely wireless, again reflecting the nature of operation of *Curiosity*.

2. Develop a software system to accompany the above rover in its functioning. The software system should:
   (a) be able to receive data in the form of video and telemetry from the model,
   (b) be able to present the data received to users or operators in an interactive manner on a platform that is available and accessible,
   (c) allow input of commands or control by the users in a manner which is both friendly to a wide range of audiences and age groups and as closely representative of the manner in which JPL's flight team would do so,
   (d) transmit these commands to the model to be executed, and
   (e) facilitate the reception and transmission of the above data wirelessly.

Analysis of Constraints

As with any engineering design project, the rover development was faced with multiple constraints that affected the resulting design. Below is a brief list of the constraints known at the beginning of the project.

- Typical exhibition space limited to a dimension of 3m x 3m
-

![Fill out]

Functional Analysis

The client requirements as highlighted in the previous sub-section were analysed to result in a functional outline in lieu of developing a list of specifications. This analysis served as the starting point for the componentization of the project, allowing for the conceptual development to follow the breakdown. This is discussed further in the next section. Here, each of the requirements, and combinations of them, were used to result in a breakdown of functions and aspects. A significant effort was made from the start of the project to develop the rover in a modular fashion. This is not to be confused with the outcome being modular (although this was still a desirable feature) but is instead the way in which ideas were formed and developed. The functions outlined in this analysis were treated as modules, where possible, and developed so that each module had as little dependence in operation as possible on another. Following this mindset allowed for the simplification of the design process and the robustness of what was developed against constraints and unforeseen obstacles during development.

The current requirements distinguished clearly the two aspects of the project which inevitably became the two major points of development. Both aspects, the mechanical vehicle and the software system, and their differing natural design approaches made it suitable to discuss them separately, where appropriate. The specifications indicated the possibility of a subset of *Curiosity's* primary functions be included in the model. The requirement of a video feed as well as simulated terrain traversal implied there be at least the mast subsystem, which included the moving head components, and a functioning wheel and suspension system that could be controlled. The ability to drive the rover as well as point the camera via motion of the head component was deemed a combination of functions that would contribute well towards providing an engaging experience for the users. These two systems were driving of the inclusion of the accompanying systems and components, a breakdown of which can be seen in Figure 3.1.

![Fill out] ![Need to include something about outreach]

Rover Equivalence and Terminology

Following the educational theme of the project, much of the terminology used on *Curiosity* was borrowed for use in subsystems and components on the model, in both mechanical and software aspects.

![Fill out]

Technical Specifications

The technical specifications were derived from the client requirements and the functional analysis, with knowledge of the systems and subsystems on *Curiosity* (taken from review of literature as covered in Chapter 2). The specifications further compartmentalised the vehicle and software systems as evident in the structure of them in the lists that follow. These technical specifications served as the baseline requirements for the final design. Section 3.1.6 adds to the these specifications a list of secondary objectives which were considered during the design process, but were not mandatory.

Vehicle Specifications

- Mechanical

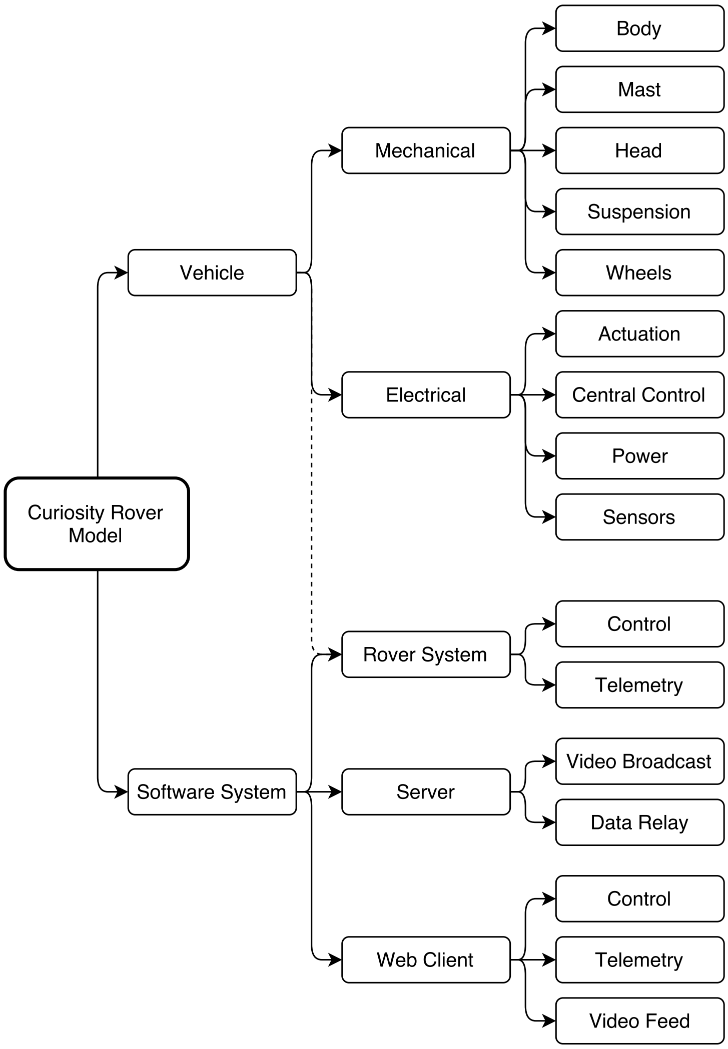


Figure 3.1: Diagram showing the simplified breakdown of functional entities of the project

- General Specifications:
  - Must be as proportional as possible to the Curiosity rover on Mars
- Body:
  - Box shaped
  - Allow mounting of the mast and differential on the top surface
  - Allow mounting of the suspension system on either side
  - Allow mounting of additional sensors
  - Allow mounting of additional detail such as side panels and other mockup objects
  - Allow mounting of electrical internals
  - Provide protection/coverage of electrical internals from the external environment
- Mast:
  - Provide mount point for the head module
  - Facilitate full rotation about the z axis (camera panning/yaw axis)
  - Facilitate at least 120° degrees rotation about the y axis (camera pitching axis)

    - Be structurally secure providing robustness against lateral forces on mounted head module

  - Head:
    - Be mounted onto the mast module
    - Provide mount point for a sensor
    - Allow mounting of a camera module

  - Suspension:
    - Ensure body stability
    - Maintain stability despite uneven terrain. This includes terrain which might require asymmetrical articulation of the system (a rock underneath one side of the rover and flat terrain underneath the other)

  - Wheels and Hubs/Pivots:
    - Match the shape and proportion of the wheels on Curiosity
    - Provide traction required for the proposed terrain
    - Have steering capabilities which would amount to arc pattern traversal as well as rotation of the rover around a central fixed point

- Electrical

  - Actuation:
    - Provide continuous rotational actuation for driving. The actuation speed should be controllable and must be of high enough torque to satisfy traversal specifications
    - Provide sufficient magnitude rotational actuation for turning of the wheels for steering. The rotational position should be controllable and must be of high enough torque to facilitate turning of the wheels in-place
    - Provide required magnitude rotational actuation for panning and pitching of the head/mast module. Both axes must allow positional control

  - Central Control:
    - Host onboard software system for control of hardware
    - Facilitate wireless communications with the server
    - Interface with actuation and sensory input hardware
    - Have performance capabilities sufficient for processing and streaming of video data from the head module

  - Power:
    - Provide power for the central control hardware as well as actuation and sensor hardware components
    - Fit inside or on the body module
    - Have the ability to be turned switched off or on
    - Allow convenient removal of source
    - Allow easy access to charging ports
    - Provide a means of indication of voltage for telemetry and low-battery warnings

- Sensors:
  - Provide immediate environment data required to implement elementary obstacle detection and avoidance
  - Be mounted in locations similar to those on *Curiosity*
  - Be compatible with the central control module in terms of data interface
- Camera:
  - Facilitate a monoscopic video feed
  - Be mountable to the inside of the head module
  - Be compatible with the central control module in terms of data interface

Software System Specifications

- Rover Embedded Software
  - General Specifications:
    - Allow connection of a remote client for telemetry and control as well as another for video streaming
    - Be robust against hardware errors and intermittent communication so as to maintain operation in these circumstances
  - Control:
    - Provide a programmatic means to peripheral hardware access
    - Translate control input commands into hardware output signals for control of peripheral hardware components
    - Declare/define and execute programmatic sequences facilitating procedures such as system booting, communication initialisations, hardware initializations, self diagnosis ![probably need to make a list of the required sequences]
  - Telemetry:
    - Emit system telemetry to the connected client consisting of system, process and hardware state as well as sequence execution notifications
  - Video Stream:
    - Provide a stream of the video data to the connected client
    - Provide video resolution on or above VGA (640x480) resolution
- Server
  - General Requirements:
    - Manage communication with the rover system
    - Manage communication with the connected web clients
    - Serve web application to the connected web clients
    - Manage roles of the connected web clients with respect to their level of access and ability to control the rover
  - Video Broadcast:

    - Connect to and accept video data from the rover video stream
    - Broadcast video stream to a scalable number of connected user clients
    - Be robust against communication intermittency in terms of connection with the rover system
  - Data Relay:
    - Relay control input commands from a controlling web client to the rover
    - Provide a means of simulating long-distance communication
    - Relay telemetry data from the rover system to the connected web clients
    - Relay state information of the rover system and server system to the connected web clients

- Web Client
  - General Requirements:
    - ![Fill out]
  - Control:
    - Provide two means of control of the rover, if access is granted:
      1. RoSE-style command sequence input, allowing composition of a sequence of commands and playback of such commands
      2. Interactive joystick/button interface
  - Telemetry:
    - Accept and display telemetry received from the rover via the server and from the server itself
  - Video Feed:
    - Accept and display video feed received from the broadcast

![Need to include something about the outreach specifications]

Secondary Objectives

Conceptual Design and Development

It was clear from the composed list of specifications that both electrical and mechanical aspects of the project required development of a large number of parts. In a typical conceptual design process, one could propose a number of complete concepts (i.e. incorporating all aspects of the project) and then make a judgement based on analysis of these concepts. For this project, it was decided that each of the subcomponents outlined in the specifications be conceptually envisioned separately with consideration of neighbouring or related subcomponents and the compatibility between each. Analysis was then undertaken for each of the subcomponents and a final design was composed in a convergent manner, taking the best concept from each of the analyses.

The fact that the design of *Curiosity* off which this model was based helped to maintain structure during a highly parallel, componentised conceptual development. However, the majority of the software components and some hardware components relied on the design of other components therefore the design process was not *entirely* parallel. In fact, in the case of the vehicle development, it was due to it being largely a process of replication that most of the conceptual development involved material and manufacture design choices as opposed to brand new conceptual ideas that required analysis of design feasibility.

Rover Concept Proposals

Body

All of the proposed ideas for the body component of the model revolved around the idea of a hollow box structure. The box was required to host electronics but at the same time, provide structural stability for all other components that were to be mounted to it. Therefore, the choice here was between the materials from which it would be built.

Concepts

1. **Carbon Fibre:** The first idea envisioned the use of carbon fibre to form a box structure that could be very thin and light but still offer the required strength. The carbon fibre would be cured around a mould made from another rigid, easy to use material. When rigid, holes would be drilled for mounting components and electronics. This concept includes the use of fibre glass which is commonly interchanged with carbon fibre. Both materials offer similar tensile strength, however, carbon fibre is far more robust in flexure [44].
2. **Perspex/Acrylic Sheet Assembly:** The next idea involved creating the box by designing and cutting panels from acrylic sheet of acceptable thickness, and later fusing the panels to form the structure. Cut-outs could have been included in the design together with holes for shafts and mounting points, which may also have been drilled after the fact. Internal support structures could have been included if the strength of the bonds or of the structure in general was in question due to the fact that acrylic sheet offers high flexibility. Figure ![] shows an example of how the panels might be assembled.

![Perspex concept render]

3. **3D Printing:** One of the aims of the project was to develop the model with high realism in an attempt to make the use of the simulator an engaging and appealing experience. The idea of 3D printing the box structure was considered and it would have allowed for a large degree of detail to be included at little additional effort or cost. Most features such as mounting points (those beyond just holes) and aesthetic detail could have been designed on top of base and internal structural support. A material could have been chosen which might offer the required rigidity, however, due to the nature of the manufacturing process, specifically the reliance on heat for the deforming of the plastic filament in the printing process, 3D printed components would not provide the same strength and robustness as compared to that of the other concepts. A 3D model of the rover created and published by NASA was found which was intended for 3D printing. Of specific interest was the body component which shows the detail that is achievable with this method a render of which is in Figure ![].

   ![Figure of 3D nasa body model]

4. **Milled Aluminium:** Aluminium was another concept that was considered due to its easier manipulative qualities (compared to those of steel) as well as significant reductions in weight. The box structure could have been milled from a block to form the hollow structure that is required, using CNC technology. Holes for mounting and a fair degree of aesthetic detail, which may not have lived up to that achievable by 3D printing means, may have been possible as well. Having the box structure made from aluminium would have meant that threaded holes for mounting would have been possible, eliminating the need for full-stack fasteners.

Discussion

All of the above concepts were achievable, however, each drew on very different material requirements and manufacturing techniques. Carbon fibre moulding and setting was seen as being a potentially difficult process in terms of ensuring an accurate outcome as it relied on a larger degree of manual manufacturing input. It was also the only idea that required extra components to be manufacture in support, namely the mould around which it would have been formed. The other three concepts allowed for more direct CAD-to-finished-product processes and the automation involved in the manufacture of them meant higher accuracy and less manual input. Since the model was small in scale, a design choice discussed further on in this report, strength of components and the weight of other components was far less of a priority as compared to resistance to heat and level of detail.

Comparative Analysis

Table 3.1 shows the weighted comparative analysis of the body concepts.

Attribute	Weight	Carbon Fibre	Acrylic Sheet Assembly	3D Printing	Milled Aluminium
Ease of Manufacture	5	1	5	3	4
Cost of Manufacture	4	4	5	3	4
Duration of Manufacture	5	4	5	3	4
Cost of Material	4	2	4	3	3
Weight	5	5	5	4	2
Tensile Strength	2	4	3	3	5
Modulus	3	5	4	4	1
Achievable Detail	3	1	1	5	4
Achievable Accuracy	3	1	3	4	5
	Total	2.735	**4.147**	3.353	3.324

Table 3.1: Comparative analysis of the body component concepts

Suspension System

The suspension system of the rover was a critical part with respect to the traversal requirements. It was decided up front that the system replicate the feature as it was on *Curiosity* in both appearance and in operation. The Rocker-bogie mechanical principle employed for the *Curiosity's* suspension system was simple and robust and therefore made clear the decision to use the principle in the model as well. The design problem here was more concerned with the structure and material of the joints as well as how they would be fitted with the beams/rods that links the system together. Another design consideration was that of the differential cross-beam that was mounted to the top of the *Curiosity* which articulated around a center point. The choice of differential bar was dealt with in a separate analysis.

All of the concepts imply the use of shafts and bearings for free articulation between each of the rocker-bogie sections.

Concepts

- **Fully 3D Printed Assembly:** In this concept, all the parts were to be 3D printed in full. This meant that the joints and beams of the suspension system were not separate pieces, lowering the number of pieces required to be manufactured. Since the suspension system was the largest load bearer compared to that of the other subsystems, the fully printed pieces could have been reinforced with an aluminium or steel rod set down the center of the beam sections. The reinforcements could have extended partially into the joint section of each piece, as the most amount of structural risk would have been at the point where the joint and the beam meet.
- **Printed Joints with Aluminium Tubing:** Instead of printing the entire system, an option of printing the joints only and fitting them with aluminium tubing,

as the beams, was considered. 3D printing provides the benefit of being able to materialise complex objects which may contain features which conventional manufacture methods might not be able to accomplish, thus making it well suited to the unique nature of the joints in the suspension system. The beams, however, were standard in shape and would not have put this benefit to use, hence motivating the suitability of a light but strong product such as aluminium tubing. The joints would have been designed either to have the tubing fit into the joint, or have a plug onto which the tubing could be pressed.

![Render of an example plug joint and alu]

- **Sheet Brackets with Aluminium Tubing:** This concept built on the previous concept with the joints being made from sheet metal bent into bracket-type shapes onto which the tubing could have been fastened (by means of clamps). The bending process would have allowed for formation of the non-conventional angles that the suspension system required.

  ![Render of an example sheet bracket]

- **Milled Aluminium Joints with Aluminium Tubing:** Again, instead of the 3D printed joints or the sheet metal, this concept made use of milling aluminium to form the joint structures and having aluminium tubing be fitted into these joints. The milled joints would have been able to offer more surface area to features such as mounting points for the tubes and bearings, meaning that these parts would be more secure. This idea was borrowed from the OpenCuriosity project![] as highlighted in Section 2. ![Image of the machined joint of OpenCuriosity]

Discussion

The fully 3D printed concept was appealing in that it offered the most direct path from CAD design to the finished product but had much reduced structural qualities as opposed to that of the other concepts. Using a combination of tubing and manufactured joints made sense in terms of the nature of the features and aluminium tubing provided strength beyond what was required, at least as far as the tubing itself was concerned. Brackets made from sheet metal may have offered the best weight (that is, the lightest weight contribution) but required extra manual manufacture as well as would not have been suited to mounting bearings and the tubes whilst maintaining mount rigidity. Both milled aluminium and 3D printed joints solved this problem with the ability of being able to provide more rigidity for fastening tubes and fitting bearings. However, milled joints were bound in structure to the block of aluminium from which they were to be milled, meaning that in one particular plane, the axes of the joints would not have been able to be angled such as required by the suspension design.

Comparative Analysis

Attribute	Weight	Full 3D Print	3D Printed Joints w/ Tubing	Sheet Joints w/ Tubing	Milled Joints w/ Tubing
Ease of Manufacture	5	4	3	2	3
Duration of Manufacture	3	2	4	5	3
Cost of Manufacture	4	2	3	4	3
Cost of Material	4	3	4	5	4
Weight	4	4	4	3	2
Link Mount Rigidity	5	3	4	1	5
Aesthetic Accuracy	3	5	5	1	3
Suitability for Wheel Mounts	4	5	5	4	5
	Total	3.500	**3.938**	3.031	3.563

Table 3.2: Comparative analysis of the suspension system concepts

Differential System

The differential system comprised of a beam or arm that articulated about a center point on the top surface of the body and linkage mechanisms connecting the ends of the arm to the rocker pivot point on either side's suspension system. Due to the motion of the differential, strength was only required in the horizontal plane which gives reason for the thin, flat design of that on *Curiosity*. The linkages on the ends of the bar required hinges with two degrees of freedom, the detail of which is discussed further on in this report. Once again, the principle of operation of this subsystem was taken from *Curiosity* itself and therefore was not the design choice to be made here.

Concepts

- **Acrylic Sheet Bar with Steel Cord Linkage:** Since the differential bar was required to take forces in the horizontal plane, the bar did not have to be round and a conceptual idea involved cutting out the flat bar from acrylic sheet. The acrylic sheet would have been thick enough such that it be press fitted onto a bearing and shaft in the center of the body deck. The ends of the differential would then have been connected to the extensions on the main suspension joint by means of steel cord. The cord would have allowed for the degrees of freedom required given the interface between the differential bar and the suspension and each of their component axes of motion.

- **3D Printed Bar with 3D Printed Hinge Pieces:** Instead of cutting the bar from acrylic sheet, this concept envisioned the bar being 3D printed. The linkages would have also been 3D printed as two parts per hinge bolted together and each end of the hinge (one at the suspension and one on the differential bar) would be joined together using threaded bar, secured by use of fasteners. An example of this configuration is shown in Figure ![]

![Render of hinge piece design]

Discussion

Since the acrylic sheet is already flat, it suits the problem well and is easier in terms of manufacture compared to a 3D printed version. Holes for the bearings and the hinges on the ends of the bar could be included in the cutting process. Two sheets could have been glued together to form a thicker beam in the case that the bearing was thicker than the sheet. The 3D printed version, however, would have been of designed thickness thus allowing custom fitting for the bearing. Although steel cord was considered given it's flexibility and thus ability to cater for the ranges and axes of motion of either ends of the linkage, it was shortly dismissed given that it would have only been able to provide support in tension and not in compression. A fixed threaded bar, as proposed in the second concept, provides support in both tension and compression situations, therefore meeting the requirements. Threaded bar was chosen for easy fastening as well as providing the ability to adjust the extension of the linkage for fine tuning the balance of the suspension-differential system and ultimately the balance of the rover. In any case, a weighted comparison was still made in Table 3.3 since the 3D printed hinges were still compatible with the idea an acrylic sheet differential.

Comparative Analysis

Attribute	Weight	Acrylic Sheet Bar w/ Steel Cord Linkage	3D Printed Bar w/ Printed Hinge Pieces
Ease of Manufacture	5	5	3
Duration of Manufacture	3	5	2
Cost of Manufacture	4	4	3
Cost of Material	4	5	3
Weight	3	5	4
Strength	5	3	5
Mountability	5	3	5
Linkage Motion	4	0	4
Linkage Support	5	5	5
Aesthetic Accuracy	2	1	4
	Total	3.575	**3.900**

Table 3.3: Comparative analysis of the differential concepts

Wheel Hubs and Pivots

The center wheels were fixed in rotation about the z-axis and thus the mounting features of these two wheels were included in the suspension system as in the previous concept section. The front and rear wheel pairs, however, were required to rotate in order to provide steering to the rover and therefore had to accommodate for this rotation as well as actuation components for this motion. The wheel pivots were also required to be attached to the suspension system.

The concepts developed for these components followed very similar concepts to those of the suspension hinges as they offered the same principles of articulation and mounting. The final decision would therefore be in accordance to the suspension system final design.

Wheels

The wheels on *Curiosity* are signature features in aesthetics as well as, of course, in function. The wheel shape includes the characteristic curved cross-section which has benefits for terrain like that on Mars and are unique in the thinness of their outer surface or skin. It was noted that the relative strength of the wheels on the scaled model that was being developed would be required to be significantly less than on *Curiosity* and so the design choice here was based primarily on the resulting aesthetic accuracy as the wheels would serve as a great feature in which to fulfil the client requirement of the model being highly realistic.

Concepts

- **3D Printed Wheels:** The fact that the wheels had the distinct shape that they did meant that 3D printing them would render highly accurate representations in terms of their shape on those of *Curiosity*. The design would include holes and points at which shafts and/or bearings could be fitted without the need for drilling or any other type of post-produce manipulations.
- **Off-the-shelf RC Wheels:** Another option was to purchase read-made wheels and tires intended for use on radio-controlled cars. The wheels would have points for mounting by default and would offer the benefits of a rubber tire over that of plastic. Once again, this idea was borrowed from the OpenCuriosity model in ![]. The project indicated that this method was successful in function.

Discussion While the 3D printed wheels would have offered less structural robustness as ready-made wheels designed to endure high impact, gravel environments, there was no requirement for the model to traverse any faster or in any better manner than *Curiosity* and thus the added benefit of the rubber tires and strong wheels would be an over-design. Although the RC wheels would have had points at which shafts could be fitted, and potentially even bearings already installed, this would impose limitations on the size of the shafts chosen. In the case of the 3D printed wheels, holes sizes could have been chosen to work with materials and bearings that were available.

Comparative Analysis

Attribute	Weight	3D Printed Wheels	Off-the-shelf RC Wheels
Ease of Manufacture	3	3	5
Duration of Manufacture	4	2	5
Cost of Manufacture	4	3	2
Cost of Material	4	3	2
Weight	1	5	2
Traction	3	3	5
Terrain Suitability	3	4	5
Mount-type Flexibility	4	5	2
Aesthetic Accuracy	5	5	1
	Total	**3.613**	3.097

Table 3.4: Comparative analysis of the wheel and tire concepts

Neck and Head

The mast of the model required rotation about the z-axis and a joint about which an additional axis of rotation was possible to result in two degrees of freedom for the head component. *Curiosity* employed a hinge mounted to the bottom of a second, smaller box structure, the head, which rotated to provide camera pitch. The pitch actuation mechanism was situated atop a second mechanism which provided actuation for pan-axis rotation. The size of *Curiosity* allowed smart fitting of the motors in-line with the mast shaft and embedded in the head mount hinge, however, the scaled model was not able to accommodate for motors in this way. ![Put this in the detailed design, concept designs are meant to be somewhat ideal!] It was decided that it be acceptable for the mast assembly to be out of proportion, visually, in order to be able to fit the required actuation (the component choices of which were largely based on availability).

Concepts

- **Aluminium Tube Mast with 3D Printed Fittings:** This concept made use of aluminium tubing (the same material as in the suspension system concepts) which would be set and fastened into the body. A 3D printed plug with mounting points for the camera-pitch actuation mechanism would have been designed to fit into the top of the tube, as can be seen in Figure 3.2. Camera-pan actuation would have been built into the inside of the body into which the mast tube would extend. The height of the head could therefore have been adjusted since the tube was free-moving with respect to the rover deck.

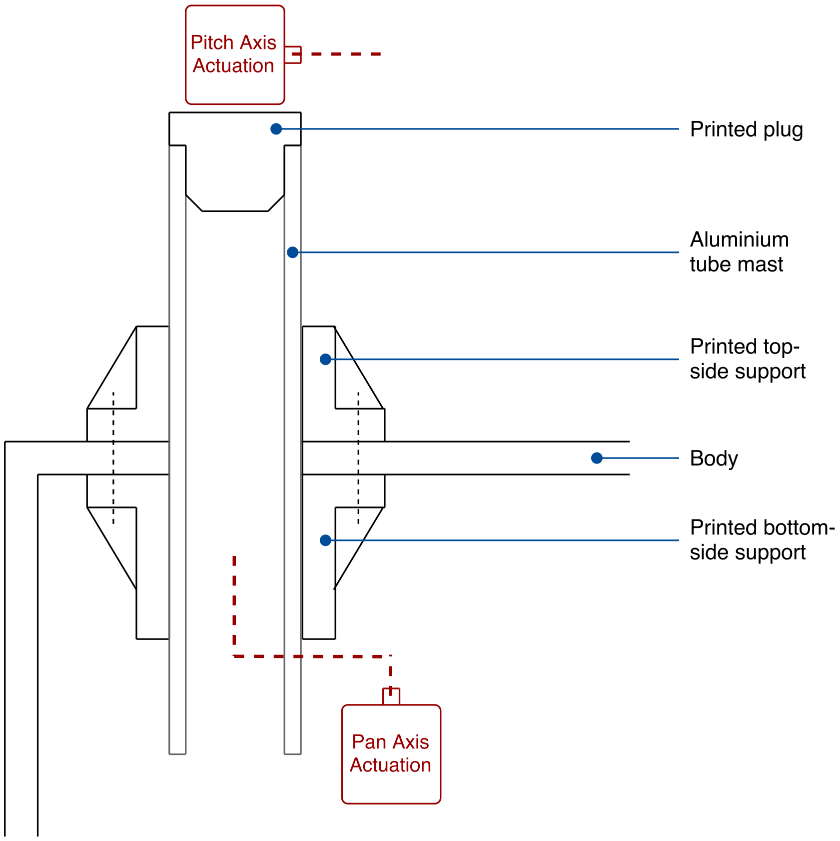


Figure 3.2: Conceptual diagram of a section view of the body and aluminium mast assembly

- **Full 3D Printed Assembly:** As opposed to making use of the aluminium tube, this concept employs 3D printing for the full assembly which would be mounted to the top of the rover body with no portion of it extending below the deck. The camera-pan actuation would be the same as in the previous concept but the camera-pitch actuation mechanism would be brought above the level of the rover deck. Further, an actuation mechanism that combines both axes of motion could ave been developed to reduce the spatial footprint that it might have incurred. The width of the base of the mast, at the mounting point, would be increased to provide structural support.

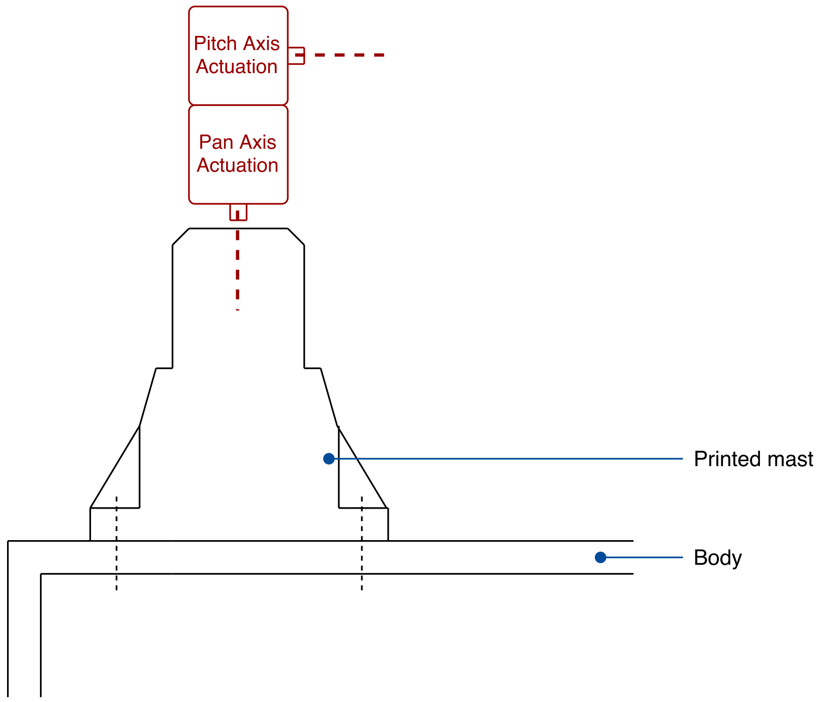


Figure 3.3: Conceptual diagram of a section view of the body and printed mast assembly

Discussion

Positioning one of the two component actuation mechanisms inside the body had benefits for the spatial footprint above the rover deck, however, the implications of taking up more space inside the body were far greater given the intended use of that area. Having the entire tube mast rotate within the opening hole from below the deck might have increased the torque requirements on the actuation mechanism, dependant on the nature of the opening. The intended use of the opening was to provide structural support and any fit tolerance introduced to improve the torque requirements of the actuation would negatively impact the effectiveness of the hole feature in its support function. This could have been solved with a bearings, however, that would have incurred addition room for mounting.

Comparative Analysis

Attribute	Weight	Aluminium Tube w/ 3D Printed Fittings	Full 3D Printed Assembly
Ease of Manufacture	3	2	4
Duration of Manufacture	4	4	3
Cost of Manufacture	4	3	3
Cost of Material	4	4	2
Weight	4	3	4
Proportion	3	4	3
Body External Footprint	3	4	3
Body Internal Footprint	5	1	5
Strength	5	5	4
	Total	3.200	**3.514**

Table 3.5: Comparative analysis of the wheel and tire concepts

Actuation

All components requiring actuation mechanisms have been covered in the above concepts. Consisting of only rotational motion requirements, the mechanisms were split into two categories based on the desired order of output motion (translated from the desired order of input control signal), namely angular position and angular velocity. Position actuation was required for rotating the wheels about their z-axis pivot for turning or steering and to provide panning and pitching motion to the head subsystem with the camera. Both of the functions involved setting a desired angular position and having the mechanism hold that position during operation. On the other hand, driving the wheels of the rover was better thought as involving an output velocity. *Curiosity* made use of high-ratio motors for all types of rotational actuation to ensure robustness of the design, higher torque outputs and to achieve precise control of each of the driven features which was acceptable in that high-speed performance was not a targeted requirement.

Concepts

- **High Torque DC Motors:** Using high torque DC motors would have been the most accurate replication of the actuation as used on *Curiosity*, as each of the mechanisms had high-ratio gearboxes attached to the brushless motors. The DC motors would have been controlled by means of PWM which would have resulted in an output angular velocity. For this reason, a control loop mechanism would have to be employed for positional motor control in the case of the subsystems that required it.

- **Analog RC Servos:** A candidate alternative to using high torque DC motors that was considered was servos, intended for radio-control vehicle use, into which a high-torque gearbox was already built. An example of this type of motor is shown in Figure 3.4. The motors operated using a pulse signal of which the width translated to a specific position as a percentage of the motor's rated angular range.

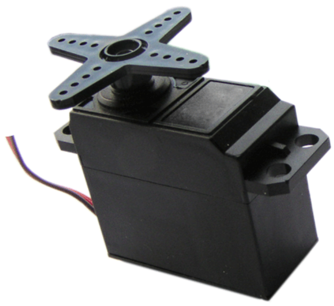


Figure 3.4: Image of an example of an RC servo motor [45]

Discussion

The two candidate actuation devices were in fact similar in that they both offered high torque output, however, the inclusion of a built-in analog position control system differentiated the servos from the DC motors. If the DC motors were to be used, the central system would had to provide an external control system to implement position control for the head and mast subsystem as well as the pivoting of the wheels. Further, this would have required output state capture by means of an encoder or an analog-to-digital converter adding complexity to the system. The fact that the servos had this control functionality built in meant this solution would have greatly reduced the incurred complexity of the actuation of the rover as a whole, as all that would have been required is for the system to provide a power rail and PWM signals.

The choice of actuation mechanisms was highly dependant on the chosen combination of subsystem concepts, specifically that of the power supply, the central control system and those that needed actuation themselves. No weighted comparison was performed for the above concepts as the choice was heavily affected by these subsystems.

Central Control System

The central control system was a critical component not only to the rover, but to the conceptual design process as it was an enabler/disabler of many of the candidate solutions. Discussed here are the electronic hardware comparisons made with respect to the central control system. The software design process took on a secondary priority approach and as such, the hardware choices were driving of the design (not without consideration of implications in the software system). As will be mentioned in full in the detailed design section, it was intended to follow a COTS design approach as far as possible given the time-frame of the project as well as the notion of keeping the design open to others who might be familiar with the hardware components chosen with respect to the aim of open sourcing. As far as education and outreach is concerned, familiar hardware is well suited to helping users and those involved in the project learn the principles of a rover design.

Conceptual candidate systems included popular, small, single-board computers, sized appropriately with the intention of fitting the system in the body of the model. Note that the lower-level device class suited to deeper embedded software applications was considered and would have proved suitable if it was not for the video streaming requirements. It was anticipated that the video feed would require on-rover encoding and compression and thus imposing the need for a better performing device capable of running a high-level operating system. The requirements for this system, which included wireless communication and embedded interfaces, were kept in mind when performing the comparative analysis. Notable specifications in accordance with the requirements are shown for each of the boards.

Concepts

- **Raspberry Pi Model B:** The Raspberry Pi was a credit-card sized single-board computer which was developed with the intention of aiding computer-science education. It made use of a well-performing CPU as well as an on-chip GPU making it suitable for low-end, media-based computational applications. Raspberry Pi computers have a very large online community from which vast resources were available.

  Notable specifications (for the 3rd generation model):

  - **CPU:** 1.2 GHz 64-bit ARM Cortex A53 (Broadcom BCM 2837 SoC)
  - **Memory:** 1 GB
  - **Storage:** None, microSD Card Slot
  - **GPIOs:** 40 pins,
  - **Network Connectivity:** Bluetooth 4.1 and Bluetooth Low Energy, 100 Mb Ethernet, 2.4 GHz wireless
  - **Other External Interfaces:** 4x USB 2.0, Camera Serial Interface (CSI)

- **Orange Pi:** The Orange Pi, an open source variant to the Raspberry Pi, was considered as it offered much the same capabilities as the Rasberry Pi. It was able to run many open source operating systems such as Debian and Ubuntu.

  Notable specifications (for the Plus model):

  - **CPU:** 1 GHz 64-bit ARM Cortex A7 (AllWinner H3 SoC)
  - **Memory:** 1 GB
  - **Storage:** None, microSD Card Slot, SATA 2.0 Connector
  - **GPIOs:** 40 pin header,
  - **Network Connectivity:** 1 Gb Ethernet, 2.4 GHz wireless
  - **Other External Interfaces:** 4x USB 2.0, Camera Serial Interface (CSI)

- **Beaglebone Green Wireless:** The Beaglebone Green is another small board as part of the Beaglebone device family, a range of single board computers that have been developed to bridge the gap between embedded electronics and computers. The green version is better suited for embedded applications compared to that of the black version and was the only Beaglebone device that had wireless connection capabilities.

  Notable specifications [46]:

- **CPU:** 1 GHz 32-bit ARM Cortex A8 (TI Sitara AM3358)
- **Memory:** 512 MB
- **Storage:** 4 GB eMMC
- **GPIOs:** 65 pins,
- **Network Connectivity:** Bluetooth 4.1, Bluetooth Low Energy, 2.4 GHz wireless
- **Other External Interfaces:** 4x USB 2.0

- **Intel Edison:** The Intel Edison is less of a single board computer and more of a complete system on chip mounted to a small board intended for use in the Internet-of-Things industry as well as for mobile and wearable products. The tiny module can further be mounted to a breakout board which provides USB interfaces and a GPIO through-hole grid.

  Notable specifications ![cite]:

  - **CPU:** 400 Mhz Intel Quark x86 (Intel Atom)
  - **Memory:** 1 GB
  - **Storage:** 4 GB eMMC
  - **GPIOs:** 28 pins,
  - **Network Connectivity:** Bluetooth 4, 2.4 GHz wireless
  - **Other External Interfaces:** 1x USB 2.0, 1x USB Serial (UART), as provided by the breakout board

- **Intel Edison w/ Arduino Breakout Expansion:** The Intel Edison had available a second breakout board which was developed to make the SoC compatible with the large variety of Arduino-compatible modules and add-ons.

- **Intel Galileo Gen 2:** The Intel Galileo is a development board that better aligns with the single-board computer principle, compared to the Edison. The processor and board are fixed and allows for connection of Arduino-compatible hardware as well as supports a range of other interfaces.

  Notable specifications ![cite]:

  - **CPU:** 400 Mhz Intel Quark x86 (Intel Pentium)
  - **Memory:** 256 MB
  - **Storage:** None, SD Card Slot
  - **Network Connectivity:** 1 Gb Ethernet Port
  - **Other External Interfaces:** 3x USB 2.0, 1x USB Serial (UART)

Discussion:

After careful research into each of the above candidate products, it was decided that all of the boards were suitable for the central computing system of the rover. All of the devices were capable of running high-level operating systems as well as had some means of connecting to a video capture device as well as providing hardware interfaces that might have been required. However, caution was taken to choose a device that would not be over-powered for the application nor provide breakouts and interfaces that would have been left unused. At this point in the design process, it was difficult to determine the exact computational requirements and so the design choice was made based on anticipative measures. It must also be noted that the choice was largely influenced by availability and cost of the devices.

Attribute	Weight	R-Pi 3	Orange Pi	Beaglebone Green Wireless	Intel Edison	Intel Edison w/ Arduino Breakout	Intel Galileo Gen 2
Cost	5	4	4	3	2	2	1
Weight	3	4	3	4	5	5	4
Availability	5	3	1	2	5	4	5
Size	4	4	3	4	5	4	3
Wireless Support	5	5	5	5	5	5	0
Provision for Video Capture	5	5	5	4	1	3	3
Suitability of Processing Power	3	3	3	3	5	5	3
Add-on Compatibility	4	3	3	2	1	5	5
Power Consumption	3	1	1	3	5	4	2
	Total	3.703	3.243	3.351	3.622	**4.000**	2.811

Table 3.6: Comparative analysis of the central control system concepts

Camera

An important item in the list of requirements and specifications was the capture of a video stream to broadcast to the connected clients. The camera was required to be above VGA resolution (640 × 480 pixels) and have a means of connecting to the chosen central computing system. The available camera modules were categorised by connector type, listed below.

Concepts

- **CSI Compatible Webcam:** Many of the central computing system candidates provided support for a Camera Serial Interface (CSI) connected camera for video capture. CSI is a camera interface standard maintained by the Mobile Industry Processor Interface Alliance (MIPI Alliance) that is at its 3rd stage of revision at the time of writing. An example of a CSI camera was the R-Pi Cam, produced specifically for use with a Raspberry Pi.
- **USB Compatible Webcam:** The majority of external webcams were USB connected, allowing them to be easily connected to a laptop or computer. The USB webcams that were investigated as being candidate devices varied in their class of drivers which was a potential issue for compatibility with the central control system, specifically the operating system that would be used. The chosen device, if of type USB, would have had to have been a USB Video Class (UVC) compliant device due to the fact that UVC devices are driverless and thus are compatible with a far greater range of host computers and operating systems.
- **I^2C Webcam:** Since the central control system would be capable of allowing serial connections, cameras that were I^2C connected were considered.

Discussion

The performance benefit of candidate cameras was not possible to determine based on their interface type, but rather the manufacturer and the designed specifications. It was decided that the camera be chosen based on compatibility with the central control system and availability of such a device.

Proximity

![Fill out]

Final Design Choice

At this point, the ideas and concepts in Section 3.2.1 had been explored in detail and final choices for each of the subcomponents had been made. This section indicates the outcomes of these choices as well as gives a brief overview of the final concept to be developed. The subcomponent concepts in Section 3.2.1, shown visually in Figure 3.5, that included weighted comparisons were finalised primarily by the outcome of those comparisons (i.e. the concept that achieved the highest score, denoted in the Tables 3.1 through 3.6 by bold numbers) and the few that did not follow the same structure of analysis were chosen by compatibility with relevant subcomponents.

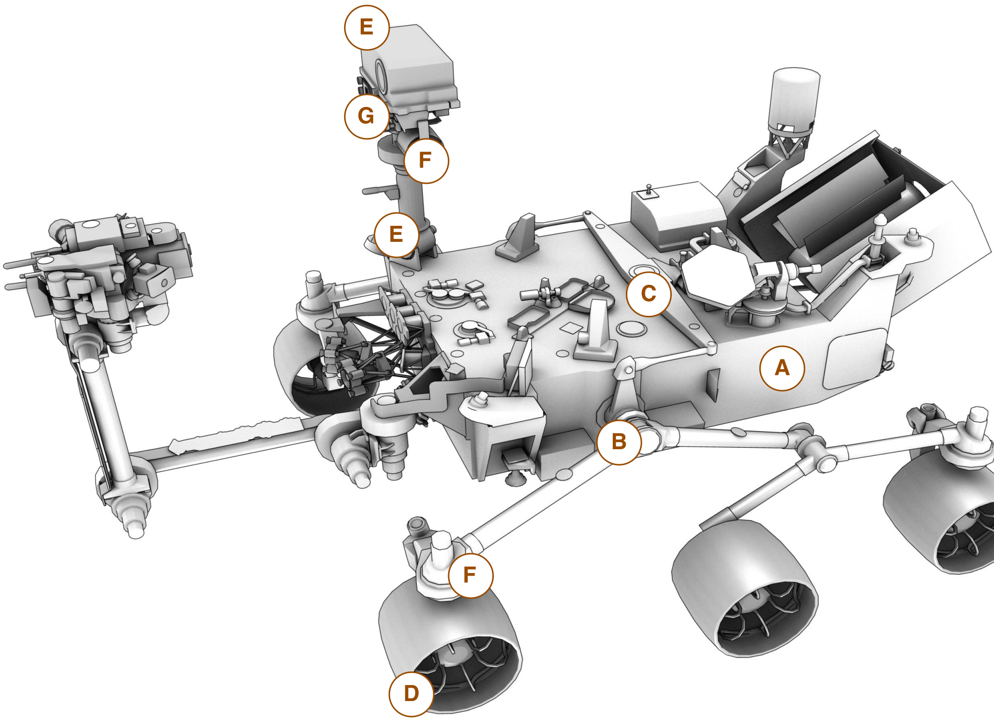


Figure 3.5: Adapted render of a model of the rover indicating the subsystems considered in the conceptual development [47]

A. It was decided that the body be made from acrylic sheet panels glued together to form the box structure required. The panel design, cutting and assembly was considered easier compared to the manufacturing of carbon fibre and 3D printing as well as being strong enough to provide the central structural support.

B. The suspension system was to be constructed from 3D printed joints and aluminium tubing for the superior total weight of the assembly and the concept's compatibility with fittings to be made for mounting the wheels. The fact that the joints were to be 3D printed meant that it would become easy to model and print the arbitrary angles of that of the suspension design without the manufacture limitations imposed by other methods and materials. The joints allowed for the design to maintain an accurate representation of that on *Curiosity* without sacrificing function and meant that close fit parts such as bearings could be easily incorporated into the design without imposing constraints on the choice of those types of parts.

C. A full 3D printed bar with printed hinges was to be used for the differential system due to the acrylic sheet and steel cord not being suitable for the required function. As mentioned in the concept's discussion, the 3D printed differential bar meant that a bearing could be correctly mounted for the motion required. The hinge on the differential bar side would be connected to the suspension side hinge by a threaded bar. As will be discussed, the connecting threaded bar could be used to adjust the distance between the hinges thus providing the ability to finely balance the rover during assembly.

D. The wheels were to be 3D printed which would allow for superior aesthetic accuracy and custom fit design for bearings and actuation. The 3D printed wheels would be lighter than bought wheels and was deemed worth the incurred manufacture time and cost.

E. The head and neck (mast) was to be fully 3D printed to make it more suitable to being mounted to the top of the rover deck without any portion of it extending into the body of the rover, taking up space required for the electronics. 3D printing meant the ability to accommodate for the chosen means of actuation. The head would be designed to consist of two parts so that access to the internals of the head was possible. This sub-assembly was then to be mounted to parts connected to the actuation and further parts for mounting on the rover deck.

F. Choice of actuation settled upon the use of RC servos. The servos were to be of a suitable size, preferably "sub-micro"[1], and compatible in interface with the central control system. The servos chosen were highly geared and were to provide the required torque for actuation of the head and wheels. The servos would have standard mounting holes making incorporation into the design an easier process.

G. The camera was to be a USB (UVC-compatible) webcam chosen based on availability. The camera would be suitable for use with the chosen central control system and significantly lower in cost compared to the other concept options. It was decided that a webcam be physically altered to be suitable for incorporation into the design of the head.

Not shown in Figure 3.5 is the central control system, which was to be mounted on the inside of the body structure. The Intel Edison with the Arduino breakout expansion was chosen due to availability of the product as well as its compatibility with add-on hardware, the advantage of which was in the increased development process as a result. The Intel Edison was regarded as being better suited to the performance and computational requirements over the other boards and provided the necessary hardware interfaces for the primary functions and associated hardware for the system throughout.

As discussed in the functional analysis, *Curiosity's* robotic arm subsystem was not included in the model due to time and cost constraints on the project. The design processed aimed to make the addition of this type of a feature possible in potential future work on the project.

[1] A "sub-micro" servo motor is one of a range of standard sized servos for robotics and radio-controlled vehicle applications

Vehicle Design and Development

Finalisation of the chosen concepts for the development of the rover meant that the project could progress to the detailed design stages. It was discussed in Section 3.2.1 that the mechanical design of the vehicle would be driving of the project, specifically the software aspects, and thus the report will deal with the mechanical and electronic detailed design first.

Mechanical Design

The mechanical design was initiated by planning the basic layout of mechanical subsystems and components and from that point developing each system further. In this section, the choice of scale (and hence dimensions) is followed by the overall plan of mechanical layout. Subsystems that were peripheral to the body structure are then covered, which include the suspension, differential and mast subsystems. Finally, the design of the body structure is described as well as detail surrounding the model as a whole.

Scale and Dimensions

Replication of *Curiosity* on an aesthetic level was a project aim to increase the viewers' and users' sense of familiarity with the model, a way of promoting the engaging experience. The replication process identified that proportion was an effective and achievable starting point and it was decided that as many of the parts as possible be based off the dimensions of the corresponding part on *Curiosity*, brought down to scale by a predetermined factor. Scale was constrained primarily by the cost and manufacturing time of parts that were required to be 3D printed; the larger the model, the greater the amount of material required and the longer it would take to print it. The print bed size was also a constraint in this regard. More details pertaining to the use of 3D printing facilities can be found in Section 3.5.1.

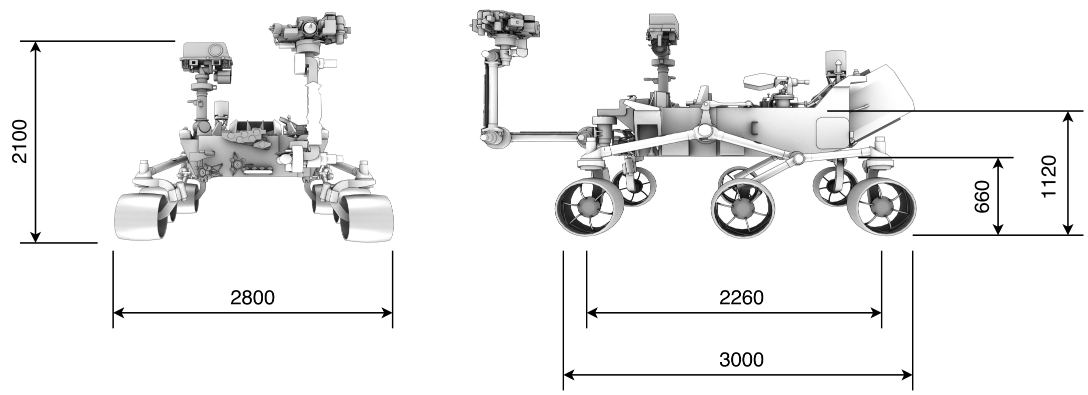


Figure 3.6: Diagram indicating the external dimensions of *Curiosity* in millimetres [47]

The dimensions shown in Figure 3.6 were retrieved from [17] and [48] as guideline, external dimensions and no other dimensions were available that might have provided a more detailed insight into each of the subsystems and components. A 3D model of a small scale, static, printable model of *Curiosity* published by NASA was found and used for extraction of proportion of the individual components [49]. While this model was not ideal in terms of representative accuracy, it provided the much needed basis on which to generate the designs of parts with an acceptable level of similarity. From these details, it was decided that the rover be built at a 1:10 scale, making the total length and width of the model, including the wheels, 300 mm and 280 mm respectively. This scale took into account allowing the model enough space to be used within the typical exhibit size outlined in the problem definition as well as 3D printing capabilities. The scale ensured that anticipated electronic internals would fit into the body structure and that mounting of bearings and the chosen standard size of servo motors was reasonable.

The chosen scale gave rise to a set of external dimensions for each of the subsystems, highlighted in Table 3.7. The guideline full-scale dimensions in Figure 3.6 were used against the 3D model in [49], here-onwards referred to as the reference model, to derive the scale of this reference. This scale was then used to obtain external, high-level dimensions for all of the subsystems and components ensuring that they remained in proportion. The dimensions were used for positioning of components and aided in the management of space allocation thereof. There were certain cases whereby external factors influenced component dimensions to result in these components not abiding by spacial allocations as well as proportion, the cases of which are dealt with within their respective sections.

The reference model, which was in Standard Tessellation Language (STL) format, was imported into a CAD package with millimetre units and evaluated in that state to result in a scale of 1:1.7037 (reference model as to *Curiosity*). The dimensions shown in Table 3.7 are of priority components and subsystems only, omitting details related to components that were intended to serve aesthetic purposes only (such as a mock-up of the RTG).

Feature	Dimension	Code	Value (mm)
Rover	Height	A1	210
	Width	A2	280
	Depth	A3	300
Body	Height	B1	46
	Width	B2	136
	Depth	B3	190
	Ground Clearance	B4	66
Suspension	Height	C1	122
	Width	C2	72
	Depth	C3	271
	Wheel Pitch	C4	119
	Center-pivot to Body Front	C5	71
Wheel	Diameter	D1	50
	Depth	D2	40
Mast	Height	E1	98
	Width	E2	62
	Depth	E3	50
	Position from font deck edge	E4	28
	Position from right deck edge	E5	28
Head	Height	F1	30
	Width	F2	60
	Depth	F3	50

Table 3.7: Table showing the external dimensions of components and subsystems obtained from the reference model

Layout Plan

The dimensions in Table 3.7 were used to construct a plan of the layout of subsystems to be used for further detailed design. The plan can be seen in Figure 3.7 along with selected dimensions from the table.

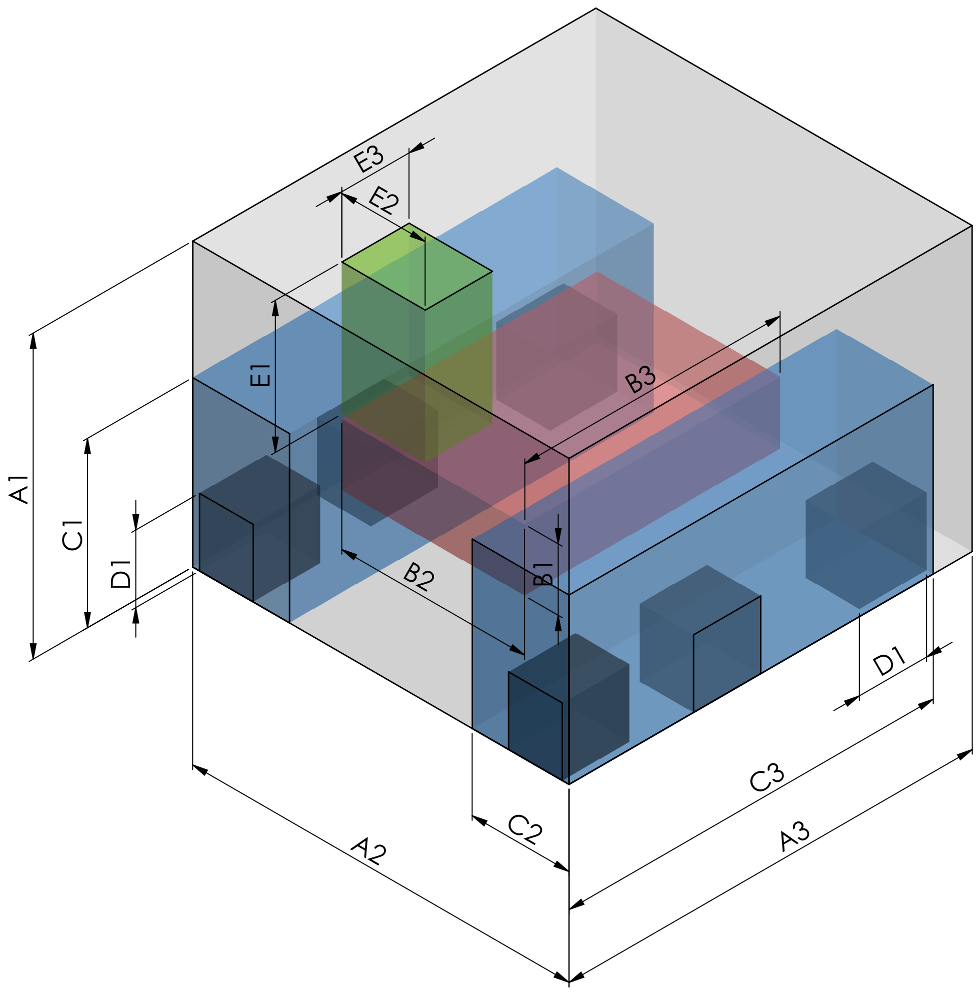


Figure 3.7: Isometric view of the 3D layout plan with a subset of the external dimensions shown

Standard Features

Prior to designing and developing the components and parts in detail, standard feature dimensions and sizes were set up to maintain a level of consistency throughout the process. This included features such as holes, walls and fasteners and served as a general guideline allowing for variation of these parameters if required. Table 3.8 highlights these feature details.

Feature	**Size**	**Comments**
Fasteners	M2 - M3	Full pan-slotted screw, hex nut and flat washer stack. M3 as first priority dropped down to M2 if the part dimensions or circumstances did not allow
Holes	M2 - M3	The holes were to match the fasteners in terms of size
Hole Clearances	0.5 mm	The clearance was made to be over a standard fit clearance in anticipation of spread of the surfaces of the part during the 3D printing process
Wall Thicknesses	Major: 5mm Minor: 3mm	Major walls were used where significant structural integrity was required, whereas minor walls were used both for less significant areas or areas where available space was a constraint

Table 3.8: Table indicating standards for common features across the entire design

Suspension

The collection of joints, pivots, struts and wheels was collectively referred to as the suspension system, one positioned on either side of the body structure. Each side of the suspension system included two fixed link mechanisms, the “rocker” and the “bogie” as part of the Rocker-bogie principle as highlighted in Section 2.2.3. During the conceptual design phase, it was decided that this mechanism be constructed by connecting aluminium tube pieces to 3D printed joints, on the ends of which the pivots and struts could be attached for the wheels.

The design started with the identification of the components required and a map of how they would be fitted together which included the names of each part for identification throughout the process. Figure 3.8 shows this mapping, which can be considered as a lower-level conceptual plan of the system.

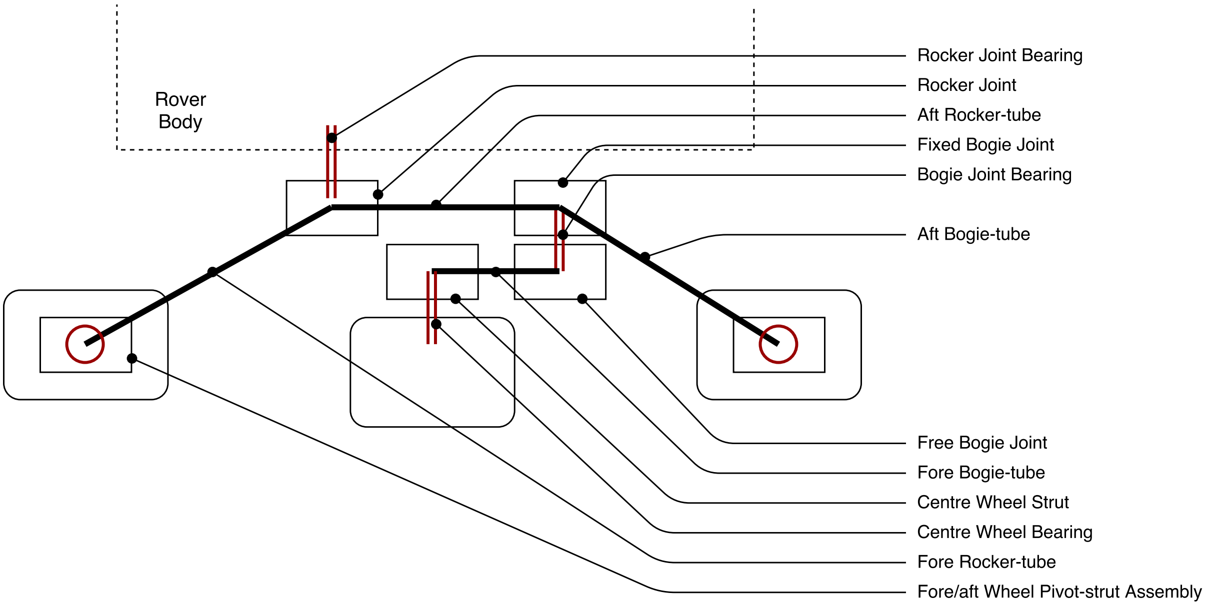
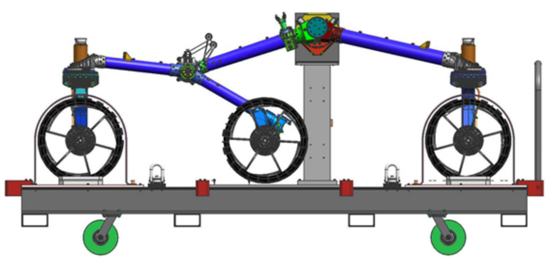
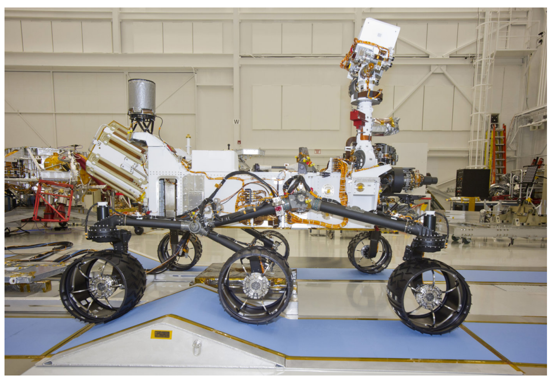


Figure 3.8: Schematic diagram of a top view of the suspension system

It was noted that the ratios of the tubing or beams on *Curiosity* (and rocker-bogie mechanisms in general) were important since it determined the system's range of motion, affecting the rover's ability to traverse the terrain. The reference model in [49] was not able to provide this kind of detail, and so the angles and positions of the centre-points of joints and axes of pivots and wheels had to be constructed from reference images of the rover. What was known was the distance of the wheels away from the side of the rover body, that the pivot centre-points were directly above the centres of the wheels and that the aft rocker-tube and the fore bogie-tube were parallel to the body of the rover in the x-y plane. Figure 3.9 includes the images that were used to find these details.



(a)



(b)

Figure 3.9: The two images used for obtaining the positions of joints and pivots of the suspension system in 3D space. [50] and [51] respectively.

A skeleton layout generated from the positional data obtained is shown in Figure 3.10 where a 2D sketch was created as a starting point from which a 3D sketch of the layout was formed. The skeleton sketch was rigid in the position whereby all three wheels were at rest on a flat, horizontal surface parallel to the rover body.

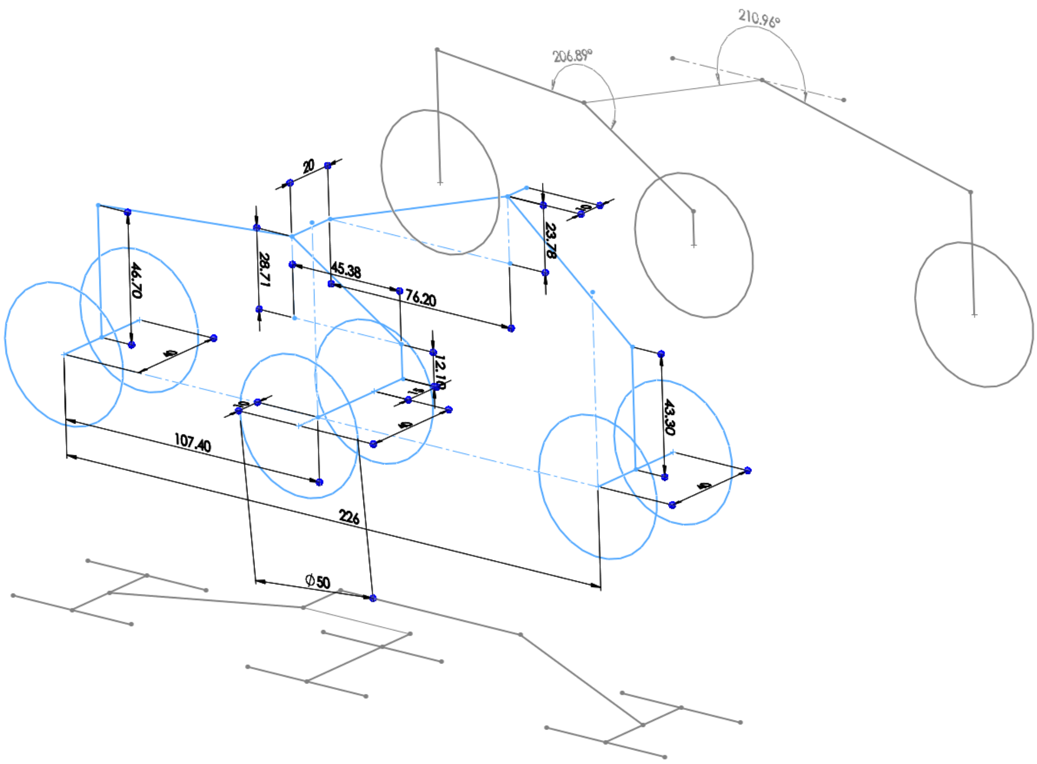


Figure 3.10: Isometric view of the 3D sketch of the generated suspension system skeleton used for positioning of designed parts

The joints, pivots and struts were then developed around the axes and centre-points in the sketch, a work-flow typical of the CAD package used.

Joints

One side of the suspension system required three different joints: the rocker joint and fixed and free bogie joints. The bogie joints were the simpler of the three and provided a means for the bogie to pivot about one of the ends of the rocker. The fixed joint was fixed in rotation on the end of the rocker while the free joint rotated about a point on the free joint. The rocker joint allowed for the entire mechanism to pivot about a point on the side of the rover body as well as allow attachment of the differential bar in order to keep the two sides of the suspension system coordinated.

It was decided that the rotation of the joints be aided by use of bearings mounted on aluminium shafts. The aluminium would not add excessive amounts of weight to the system but still provide the rigidity required between the joints. Bearings were then required to be fixed into the rocker and free bogie joints with a shaft extending from the side of the body for the rocker joint bearings and another shaft mounted in the fixed bogie joint. Various methods of mounting bearings and shafts into 3D printed parts were considered, however, the most commonly employed technique involved press-fitting

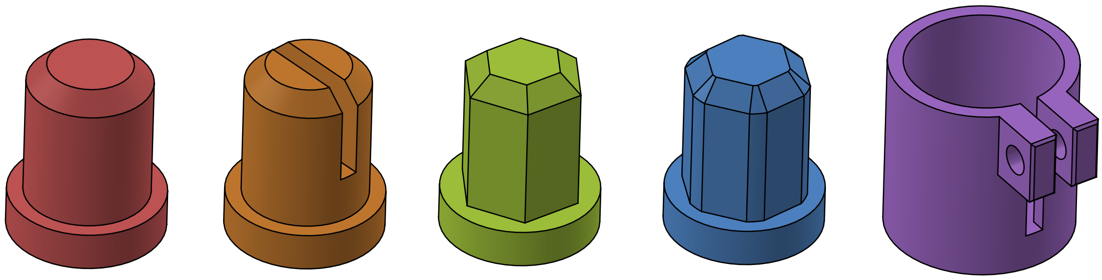


Figure 3.11: Render of the plug concepts considered for the attachment of aluminium shafts onto joints and pivots

both types of components. At this point it was clear that printing the parts from a material which allowed for a certain amount of flexibility (i.e. less brittleness) would suit press-fitting bearings and shafts and reduce the chances of parts cracking when doing so. The press-fit holes and bores were introduced into the design after modelling the joints.

The joints were to host the aluminium tubes and thus a way of mounting them was required. Aluminium tubing dimensions were decided upon based on availability, cost, weight and strength and the aim of keeping the suspension system in proportion was a contributing factor in this design choice. The size of aluminium was chosen to be a standard extrude of 15.88 mm outside diameter with a 1.62 mm wall thickness (making the internal diameter 12.64 mm). Two methods of fixing the tubes to the joints were considered: the first of which was to design a plug onto which the tube could be pressed and fastened and the other involved a bracket into which the tube would be placed and the bracket could have been tightened using a clamp or nut and bolt. The plug concept was chosen over the bracket due to size constraints which would have been exceeded if the latter were used. The plugs took advantage of the fact that the aluminium was tubular and minimised use of space outside of the diameter of the tube. However, using a plug might have introduced a weakness into the design in that cross-axis forces (bending moments) on the plug could damage, if not, tear the plug from the joint part. This would not have been the case with a bracket where these types of forces would have translated into forces parallel to the plug main axis. Despite the possible weakness, the plugs were used and care was taken to ensure that typical use would not affect the part in this way. Another reason for not using a bracket was due to anticipation of the plastic material used for the printing possibly deforming when tightened with the suggested fastenings. Plastic, among most other materials, offers greater robustness when compressed (as in an internal plug feature) as opposed to if it is put under tension [52].

Multiple plug shapes were considered, as a range of which are shown in Figure 3.11. The aim was to have the plug not require glue, as aluminium is not well suited to being glued using adhesives that work well with plastic parts. An ideal plug was one where just the press-fitting process was satisfactory in order to obtain a rigid attachment.

Chosen was the plug that was hexagonal in shape but had edges which were filleted to match the inside surface of the aluminium tube. This was a hybridisation of the cylindrical plug, which introduced a very low window of tolerance in the manufacture of the joints, and the simple hexagonal plug. The filleted edges increased the contact surface area with the inside of the tube, improving the effectiveness of the fit, whilst allowing for greater manufacturing tolerances. In case the plugs proved to be lacking the required strength, a hole could have been drilled down the centre of the plug and a steel rod could be glued into place to strengthen the joint, specifically at the intersection of the middle body and the plug. A nut and bolt was added to the plug-tube assembly as in Figure 3.12 to improve the fitting and prevent rotation of the tube around the axis of the plug.

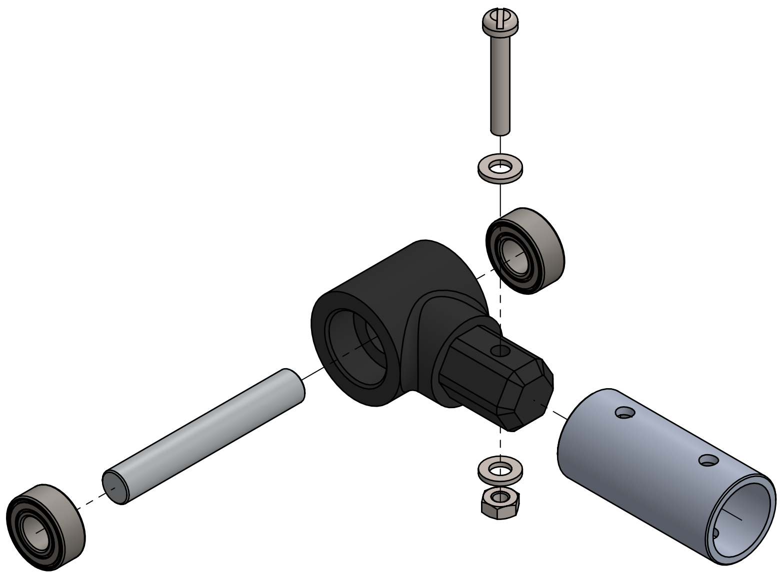


Figure 3.12: An isometric exploded view of the plug-tube-bearing assembly concept for the suspension system

An extension to the rocker joint was made in the form of a “fin” feature to allow for the connection of the differential system. The feature was added “in-place” in the 3D model after the differential has been added to the assembly so that correct alignment was ensured.

Finally, features for the press-fitting of bearings were added to the joints that required them. Bearings were chosen at this point to be of dimensions shown in Figure 3.13 in which the shaft diameter is also shown. A single bearing alone was not suitable to provide support against bending torques brought about when the shafts were to be put under load, thus each free-moving joint had two bearings on either extremity. A hole through the centre of the bearing bores of $\varnothing 8$ mm was included to allow the shafts to extend to the outwards facing bearings. The final designs for each of the three joints are shown in Figures 3.14, 3.16 and 3.15.

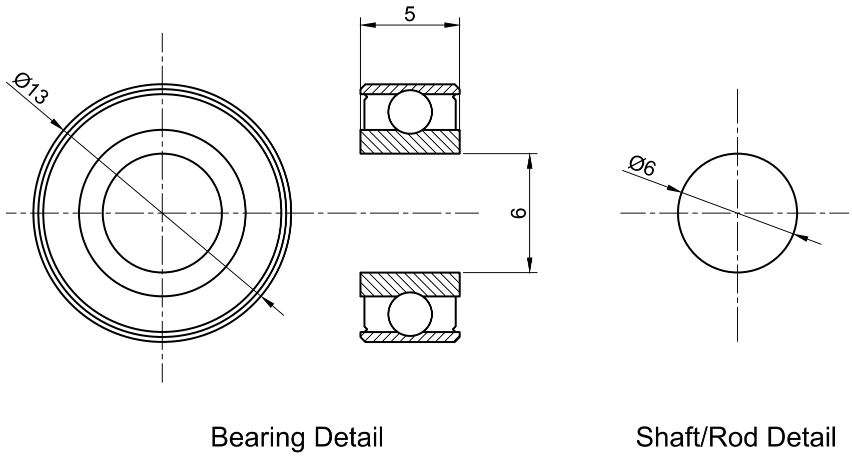
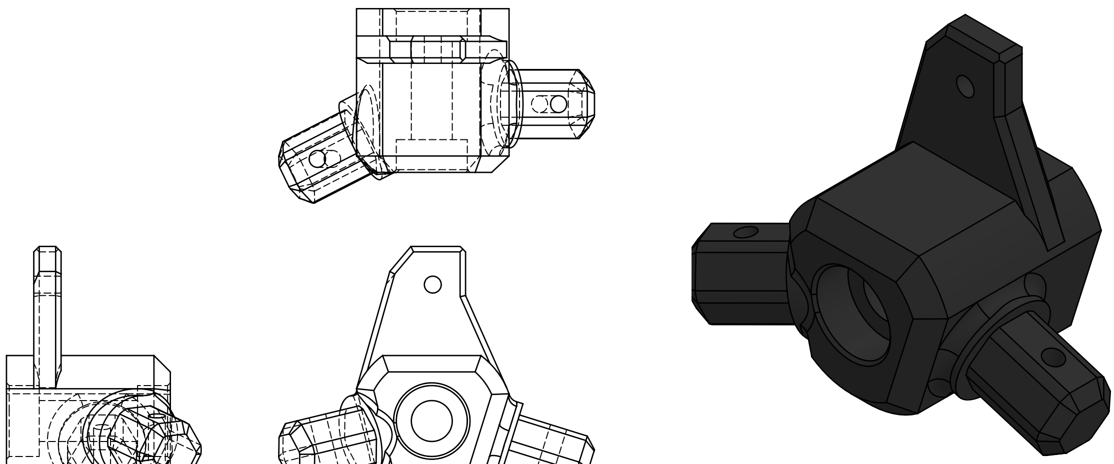
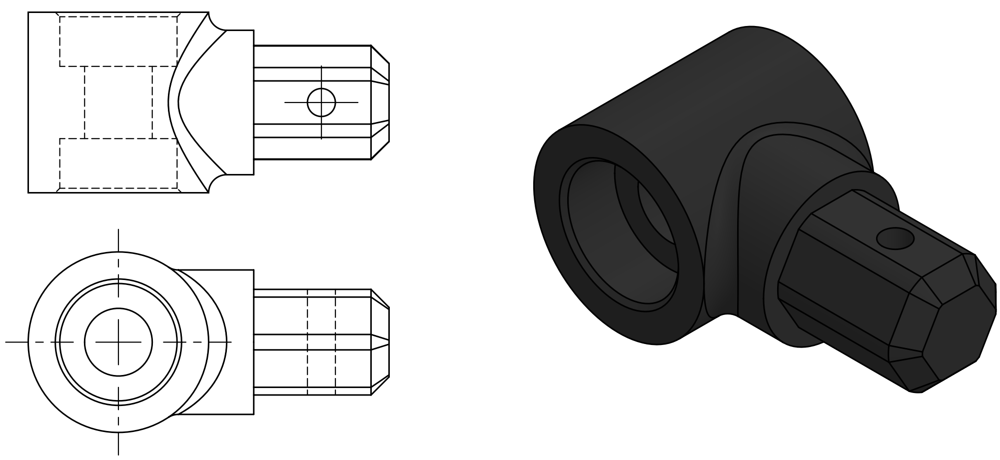


Figure 3.13: Detail of the bearings and shaft chosen for the entire design



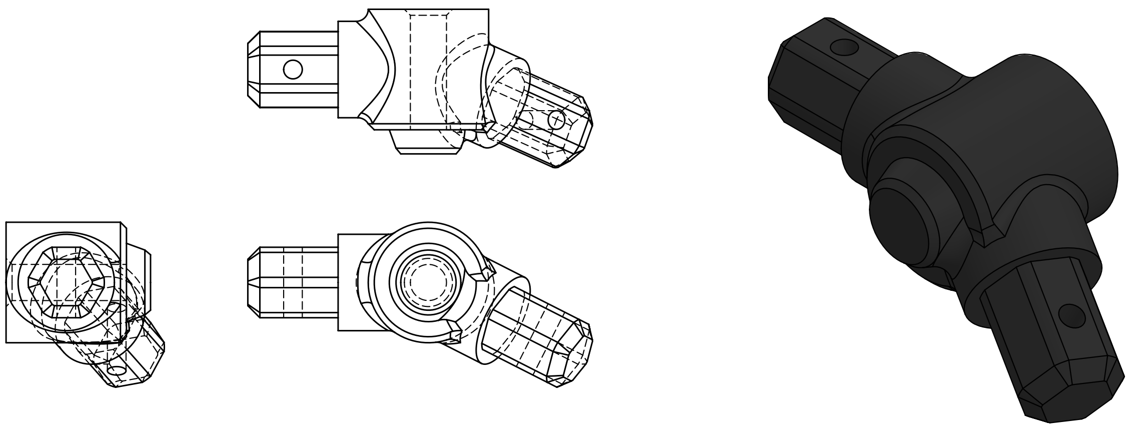
(a) (b)

Figure 3.14: Detailed drawings of the rocker joint component for one side of the suspension system



(a) (b)

Figure 3.15: Detailed drawings of the free bogie joint component for one side of the suspension system



(a) (b)

Figure 3.16: Detailed drawings of the fixed bogie joint component for one side of the suspension system

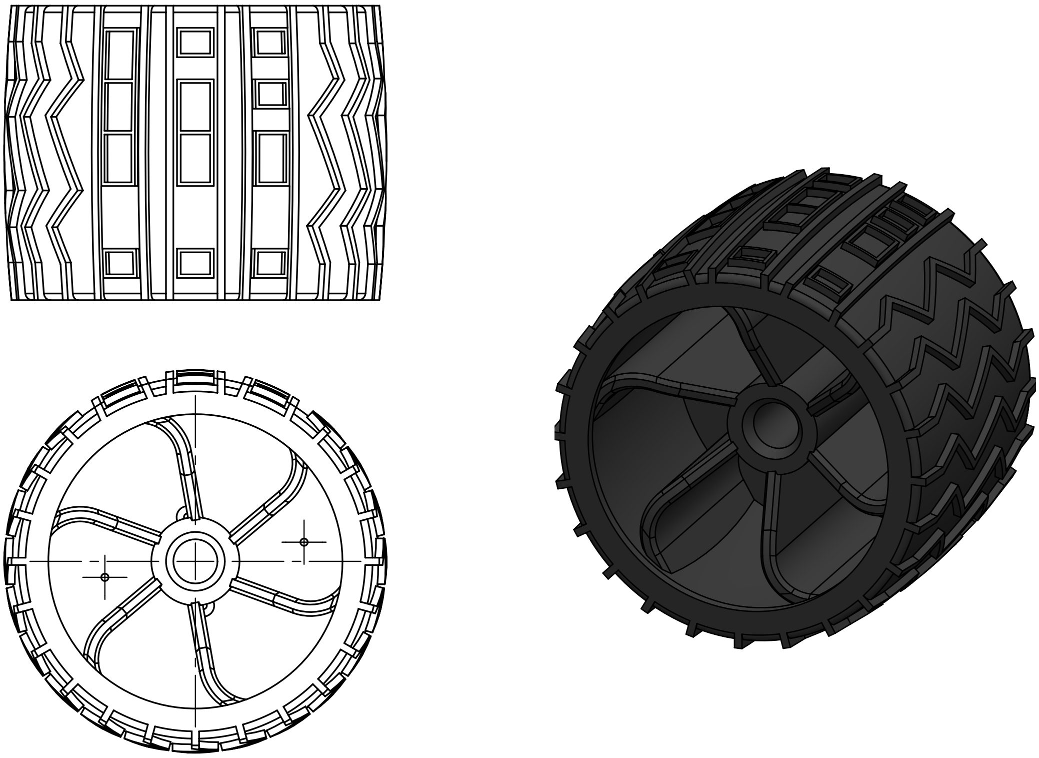
Wheels

Six wheels were to be designed, four of which were driven by the sub-micro servos (front and rear wheels) and the two centre wheels were to be mounted onto fixed shafts with bearings. All six of the wheels on *Curiosity* were actuated to ensure robustness of the driving mechanisms in a wider range of terrain types and traversal situations. It was also a feature of redundancy in that if one of the motors failed, the rover was capable of continuing operation. However, it was decided that for this model only the front and rear wheels would be actuated given the reduced power to weight ratio compared to that of *Curiosity*. Redundancy was not an issue worth the resultant extra servos and the incurred control complexity.

As mentioned in Section 3.2.1, the wheels were a great opportunity to make use of the aesthetic accuracy of additive manufacturing thus the wheel was modelled so as to replicate the cross-sectional curve of the outer shell of the wheel. Included were the tread patterns for traction as well as the morse-code emboss which read "JPL", used on *Curiosity* to acquire optical estimates of the distance travelled by the rover. Spokes and a centre cylindrical core was added to the inside of the outer shell, keeping the wheel as a single piece.

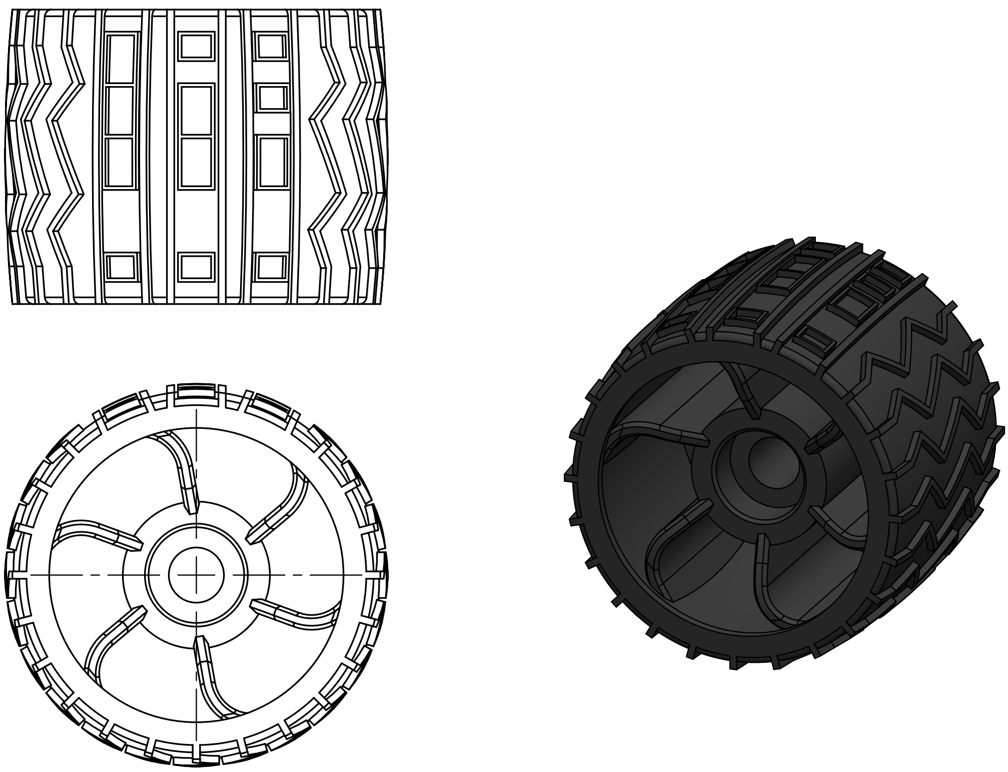
The sub-micro servos were accompanied by servo horns that fitted onto the shaft of the servo. The horns were cross-shaped, a layout of which was taken advantage to provide support in the cross-axis plane. The horns were measured and holes were added to the four wheels concerned so that they could be mounted directly to the driving servos. The need for bearings on this assembly was countered by an estimate of the forces developed due to the rover's weight and it was anticipated that the servos would be capable of taking the estimated load without damage or wear. This also provisioned for easy replacement of wheels and or servos should one of them be damaged.

The same bearing bores and centre hole as on the joint components was added to the cylindrical core of the centre wheels for mounting to the aluminium shafts. The press-fitting of bearings into the wheels was to be of the same nature as that of the joints. Figures 3.17 and 3.18 show the outer and centre wheel details.



(a) (b)

Figure 3.17: Detailed drawings of the outer wheels



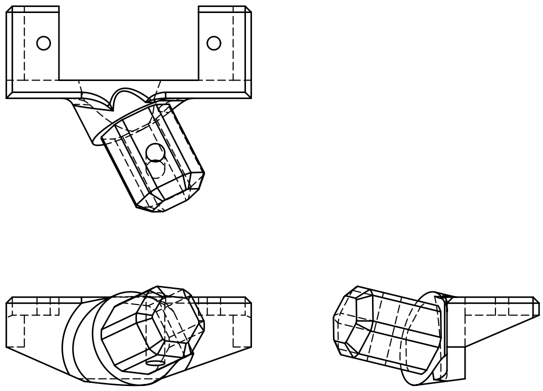
(a) (b)

Figure 3.18: Detailed drawings of the centre wheels

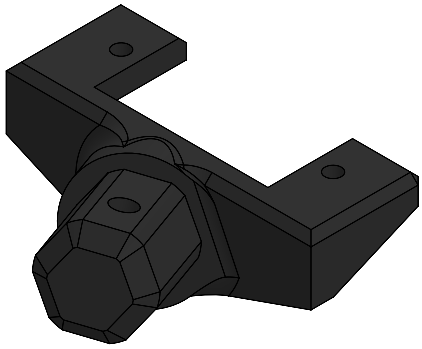
Pivots

Turning the wheel-strut assembly involved the pivot component which was required to allow for mounting of a sub-micro servo (steering servo) and to be attached to the ends of the fore rocker-tubes and aft bogie-tubes. The same concept for attaching to the aluminium tube as in the case of the joints was applied to the pivots thus the design consisted of a L-shaped extrusion with the plug extending from one of the outside flat surfaces. The other surface had a rectangular cut-out the size of the servo body, mounting holes for the servo and ribs for supporting the L-shaped extrusion. Figure 3.19 shows the pivot component detail for the front wheel assembly.

The front and rear pivots differed slightly due to the angle of entry of the rocker and bogie tubes towards the centre-points of the wheel assembly were different. Managing the differences in angles was aided by use of the 3D skeleton sketch. Again, the front and rear pivots from the left hand side were mirrored to produce parts for the right hand side suspension assembly.



(a)



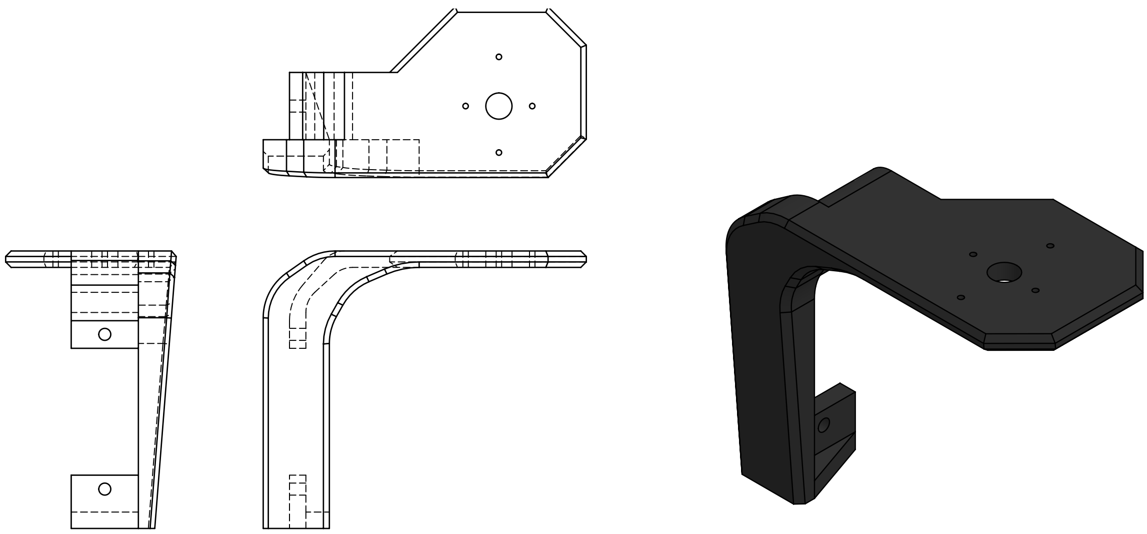
(b)

Figure 3.19: Detailed drawings of the wheel pivot component for one corner of the suspension system

Struts

Curiosity had and arcing “strut” for each wheel which curved from above the wheel, underneath the pivot motor, over the side and into the inwards facing threshold of the hollow of the wheel. The strut was attached to the drive motor on the inside of the wheel, as close to the centre of the wheel for balance and minimisation of bending stress. The sub-micro sized servos would not fit inside the wheels of the model at its chosen scale, thus they had to be mounted on the outside of the wheel. The strut was required to provide a place to mount the driving servo and to be mounted to the servo horns of the steering servo.

The strut was designed to maintain the curved appearance as on *Curiosity* but to take into account the strength of the component. A flat platform above the wheel included holes for mounting of the steering servo’s horn and this curved downwards into the strut section of the component. The strut curve consisted of a flat section to offer strength against bending in the typical direction as loaded (the x-axis) with a rib type extrusion from the rear facing side of the strut for increased support and tabs on which to mount the driving servo. The design was then mirrored for the rest of the corners and the final detail can be seen in Figure 3.20.

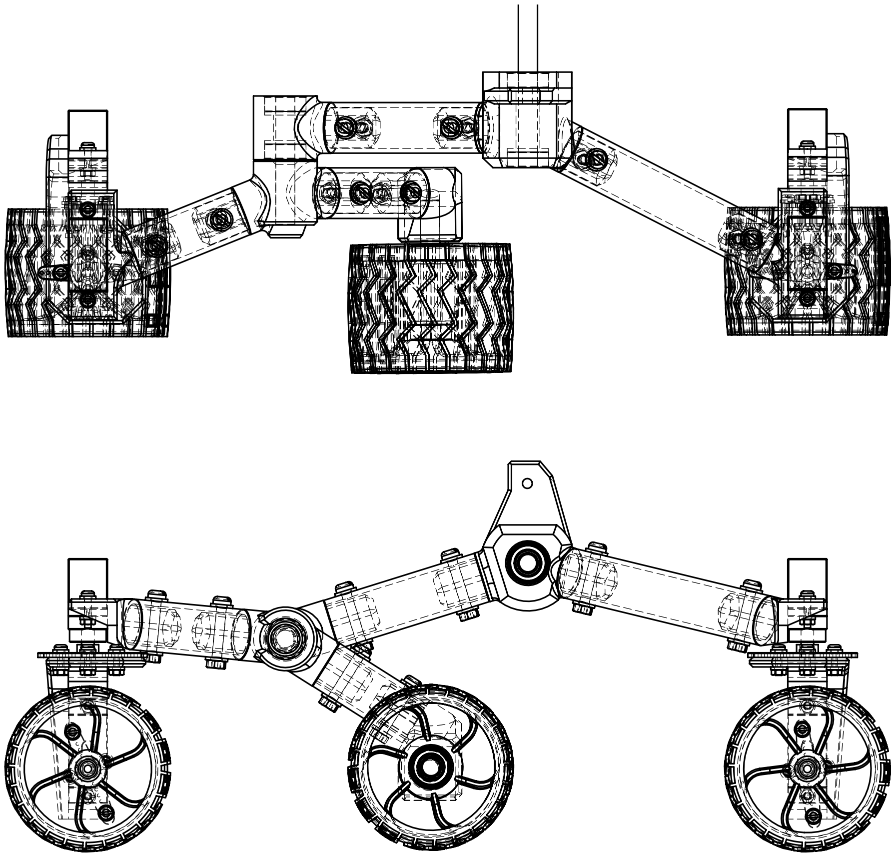


(a) (b)

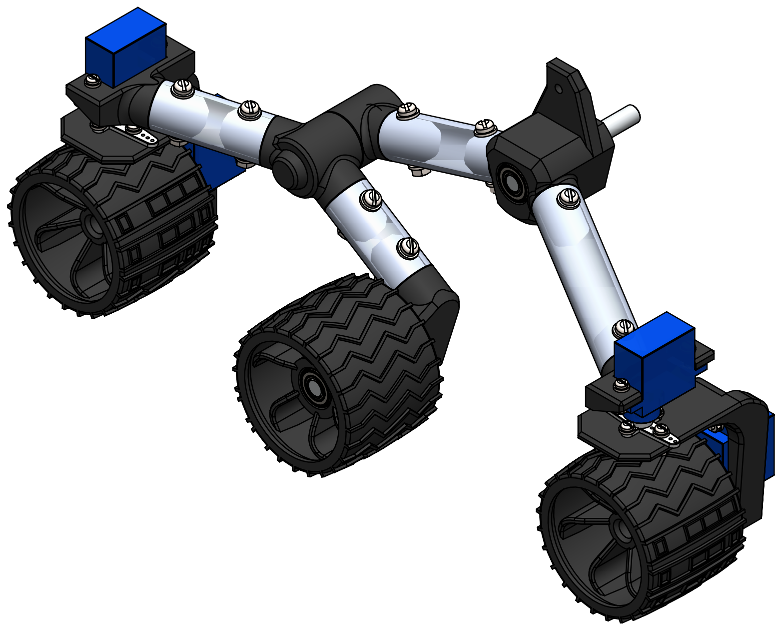
Figure 3.20: Detailed drawings of the wheel pivot component for one corner of the suspension system

Final Sub-assembly

Having designed the parts around the skeleton sketch, where they were kept fixed to preserve the angle details linking them, another assembly was created into which the parts were re-added and mated in a manner more typical of the way that they would be assembled. The assembly allowed simulation of the movement and this functionality was used to analyse the assembly for interferences and to ensure that the structure moved the way it was required. Figure 3.22 shows the linkages positioned as if the subsystem was navigating over an obstacle. Each individual part was then mirrored and assembled to form the opposite side of the suspension system. The CAD package ensured that the mirrored parts were dynamically updated should one of the original parts have changed.



(a)



(b)

Figure 3.21: Detailed drawings of the working, dynamic assembly one side of the suspension system

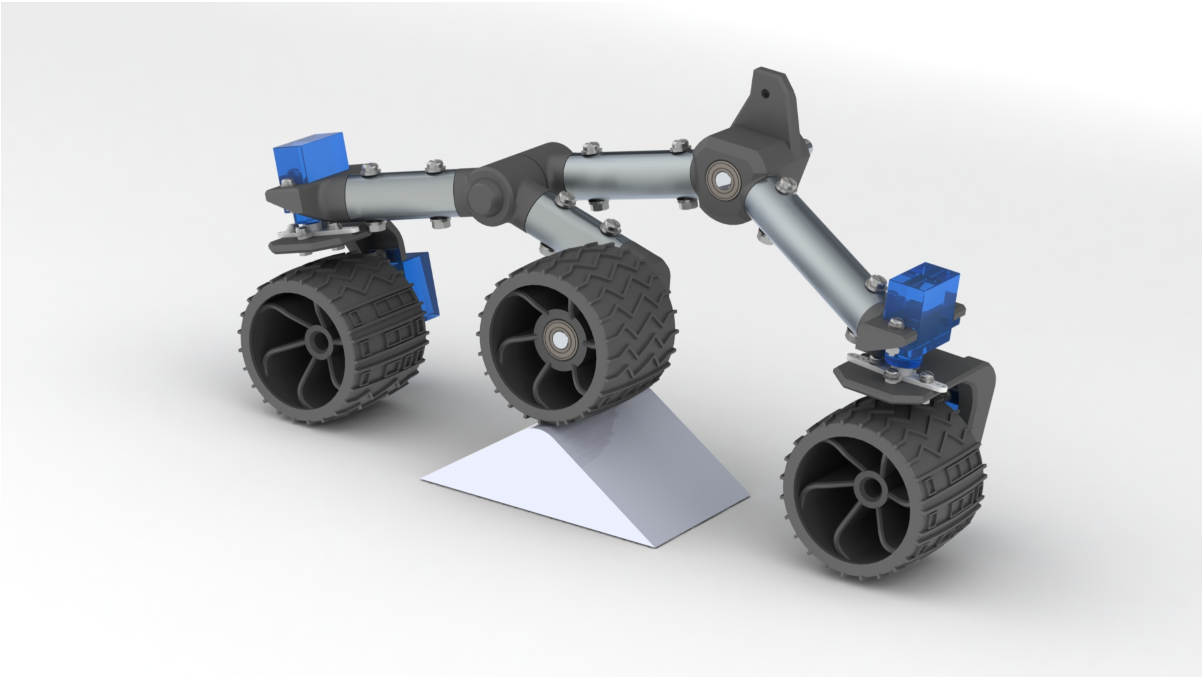
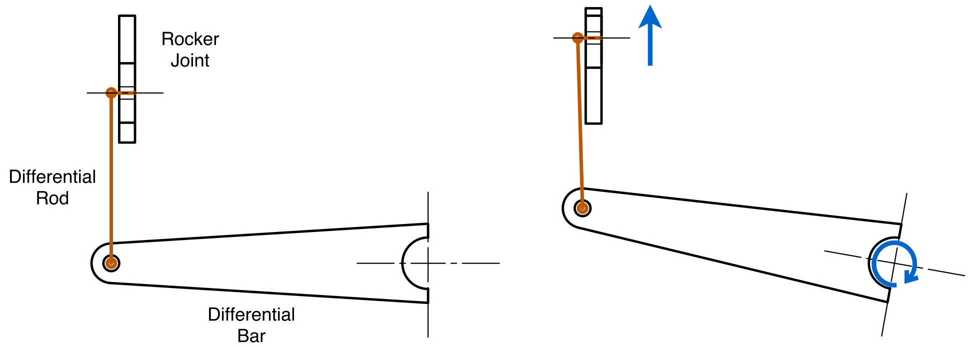


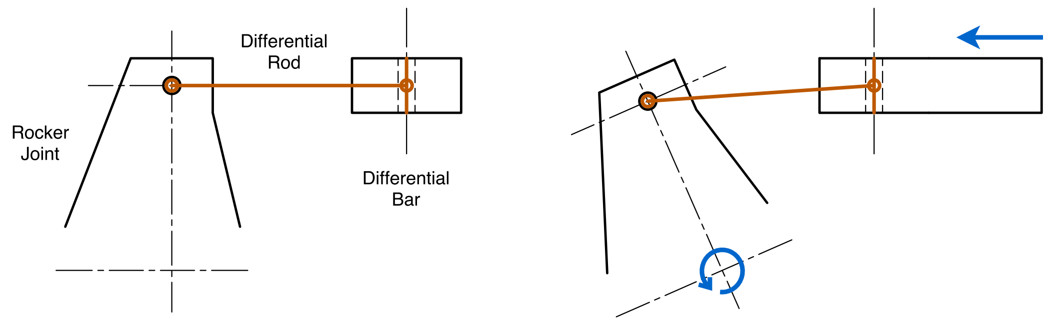
Figure 3.22: Render of one side of the suspension system navigating over an obstacle

Differential

Design of the differential involved a partially completed design of the body structure which contained details of the mounting points of the suspension system and thus the position of the connection point on the rocker joint, as well as the centre point of articulation of the differential bar as acquired from the reference model. The concept chosen for this subsystem included a 3D printed differential bar, printed hinges and threaded-bar (rods) attached to the hinges to link the differential to the rocker joint. The need for hinges was to provide the rods with the degrees of freedom required taking into the account the arced motions of an end of the differential bar in the x-y-plane and rocker joint in the x-z-plane. The articulation of the differential system and the resulting motion of the rods is depicted in Figure 3.23, each of the two views showing two positions in the motion.



(a) Top view

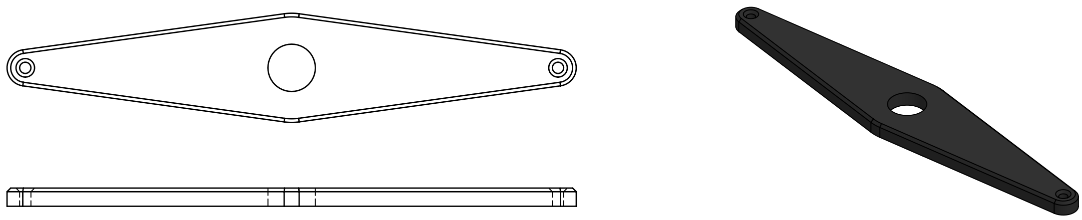


(b) Side view

Figure 3.23: Diagram showing the motion of the differential and the resulting motion of the differential rod

Differential Bar

The design of the differential bar stemmed from the partially completed rover deck, specifically with respect to the width of the body and therefore the span of the rocker joints' differential connection points. The bar took on the tapered shape as on *Curiosity* with the wider section in the centre and narrower ends. A hole was added for the addition of a bearing in the centre of the bar and holes for the hinges added to the ends. The bearing was to be mounted to a short shaft which was to be fixed into the deck of the rover. Figure 3.24 shows the detail of the differential bar.



(a) (b)

Figure 3.24: Detailed drawings of the differential bar component in the differential system

Hinges

Hinges were designed for each end of the rods, one end on the rocker joint side and the other for the differential bar. The hinges allowed rotation about specific axes, the y- and z-axes on the bar side and the y-axis on the joint side. Figure 3.23(a) demonstrates that the bar also rotates about the z-axis which would require the hinge at the rocker joint to allow for this motion. However, this was not included in the design after confirming through calculation that the amount by which the bar would have rotated in this direction at the maximum angle of articulation of the differential bar ($\approx 9°$) did not justify the resulting added complexity in the hinge design.

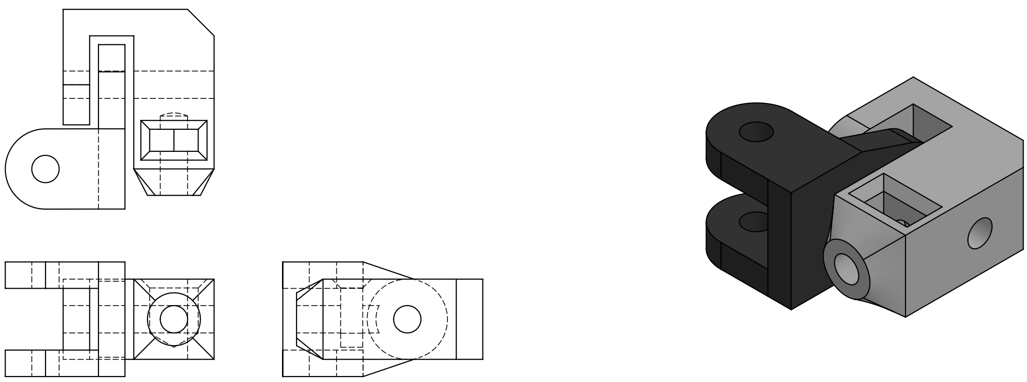
The single axis hinge on the rocker joint side amounted to a right-angled piece with a hole in one of the flat sections for fastening it to the rocker joint and another hole on the other flat section for fastening of the threaded-bar rod component. Slotted bolts and nuts were used for the joint hole with washers between the joint and the hinge part to minimise the friction between the parts despite small degree of motion that would be effected on this coupling. For the rod, two nuts on either side of the piece were used to fix the threaded-bar.

The two-axis hinge on the differential-bar end included a part with two tabs with holes, one above and one below the end of the bar and a flat section extending perpendicular to the axis made between the two tab-holes. The additional section included a third hole to allow attachment of the second part responsible for mounting the rod. The second component included a blind hole into which the rod could be place and a cutout halfway down the length of the hole to allow for a nut to be pushed into place. This meant that the rod could be screwed into the piece, the purpose of which included easy assembly and breakdown if required as well as allowing the extension of the rod to be adjusted. Therefore, the differential system could be adjusted to balance the rover body about the rocker joint pivot points.

Detailed drawings of both hinge assemblies can be seen in Figures 3.25 and 3.26.

(a) (b)

Figure 3.25: Detailed drawings of the single axis hinge component in the differential system



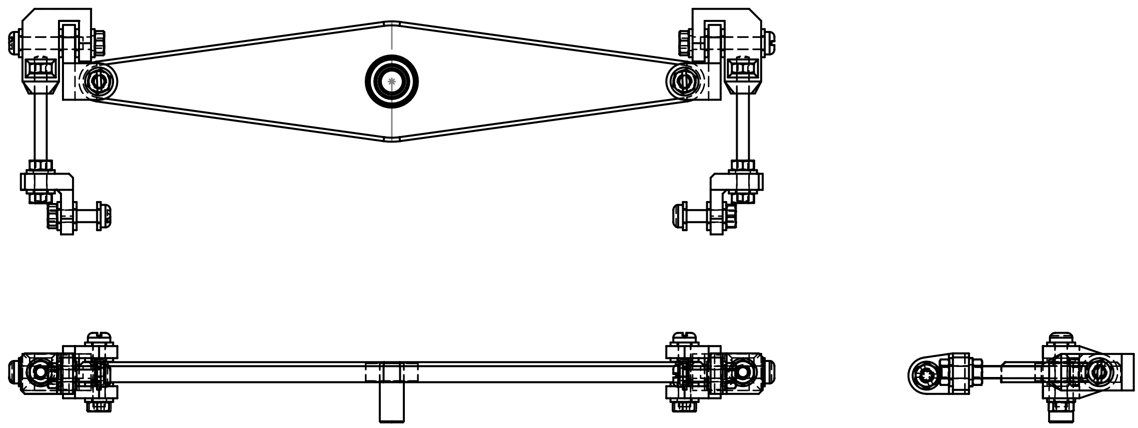
(a) (b)

Figure 3.26: Detailed drawings of the two-axis hinge component in the differential system (without fasteners)

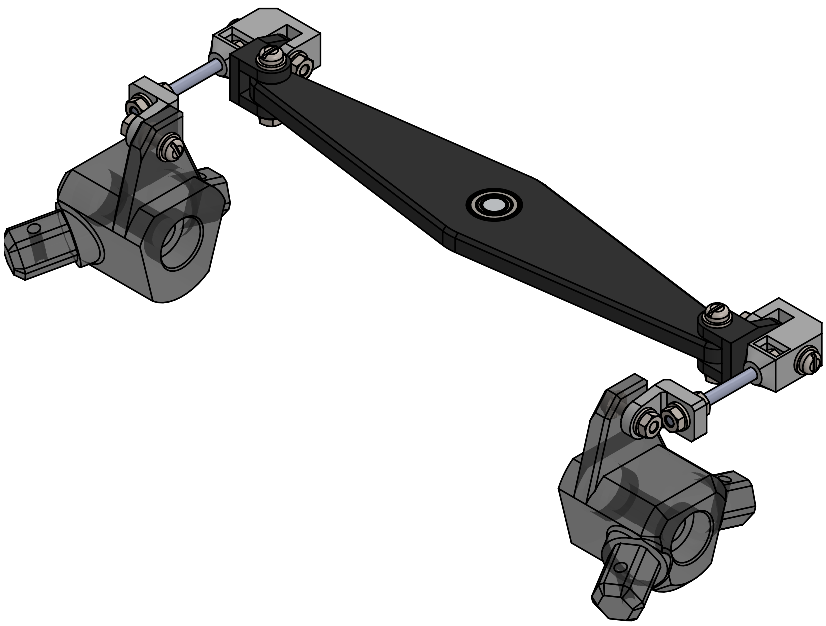
It must be noted that other hinge techniques were considered for this subsystem, one of which included a ball and ring-socket joint which would have provided the required axes of rotation in a single coupling (for each end). The idea was not used for the design due to unavailability of the joints, particularly of the size required. The hinge technique was simpler in design and leant itself well to the chosen manufacture method.

Final Sub-assembly

Figure 3.27 shows detail of the differential sub-assembly as generated in the CAD package used and was analysed for interferences and functional integrity.



(a)



(b)

Figure 3.27: Detailed drawings of the working, dynamic assembly of the differential system (included in the isometric view in (b) are the rocker joints as part of the suspension system)

Head and Neck

- Neck mount - Neck Hinge and Actuation - Head

Body

Aesthetic Details

Electrical Design

Actuation

Sensors

Camera

Power

System Interfaces

Integration of Mechanical and Electrical Designs

Internal Electronics Mounting

Cables and Wiring

Software Design

Overview of Requirements in Context

Plan of Structure

System Architectural Structure

RSVP Servers Plan

RSVP Client Plan

RCE Plan

Technology Choices

Common Platform Flavour

Embedded Software Platform

Data Communication

Media Streaming

Front-end web Platform Framework

Vehicle Build and Manufacture

Overview of Manufacturing Techniques

Additive Manufacture

Laser Cutting

Manufacturing Plan

Analysis of 3D Components

Bill of Materials

Vehicle Assembly

Software Development

Development Environment

Build Processes

Dependencies

Target Platform Requirements

Rover Sequencing and Visualisation Program Servers

Rover Sequencing and Visualisation Program Client

Rover Compute Element

Chapter 4

Electro-mechanical Integration

Chapter 5

Testing and Results

Chapter 6

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 7

Conclusions

These are the conclusions from the investivation 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 8

Recommendations

Make sensible recommendations for further work.

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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

Ethics Forms