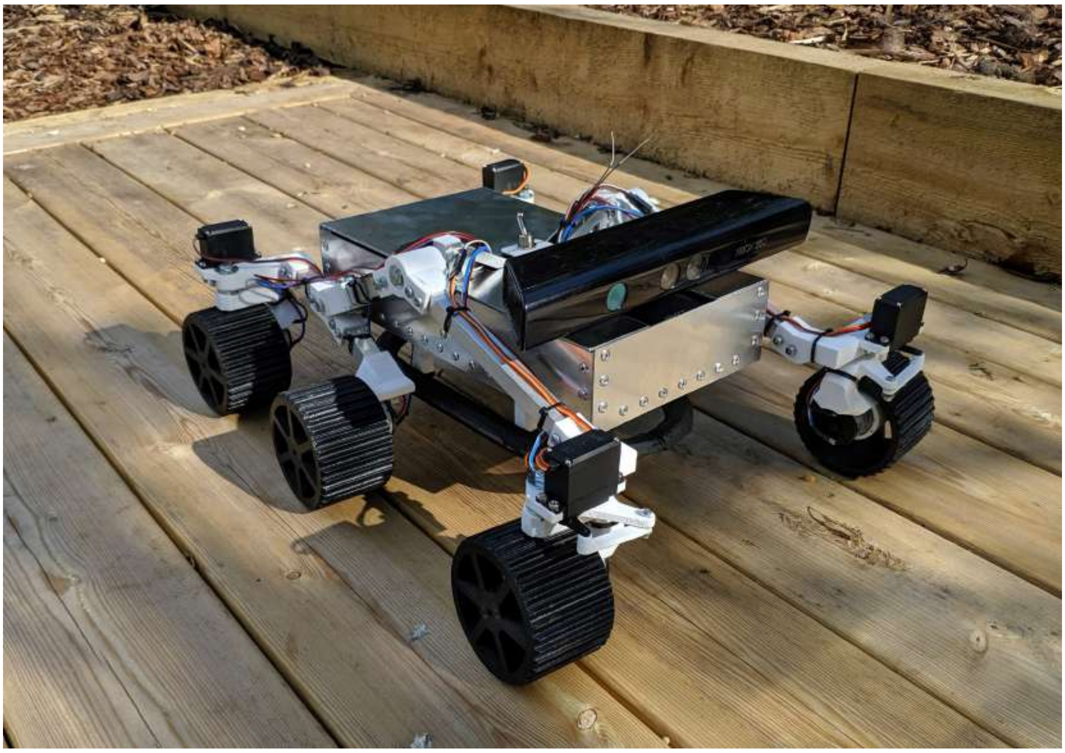
EDT Engineering Education Scheme Project Report

Pluto Rover

Watford Grammar School for Boys
with Leonardo UK



Dominic Dale, Pallav Hingu, Daniel Baars, Tim Hire, Ben Post and James Turvey

Centre lead: Mr Chase

Leonardo mentors: Anthony Phillips and Dan Bouchard

2019/20

Abstract

This report details our Engineering Enterprise Scheme (EES) project which ran from October 2019 to April 2020.

Our team compromised of six lower sixth students from Watford Grammar School for Boys selected by our centre lead and sponsoring company, Leonardo MW Ltd (Leonardo). The team was mentored by two engineers from Leonardo who came to our school for a weekly meeting.

This report details all aspects of our project, from the initial brief from the initial briefs we had to choose from and our development of a detailed specification, to the final design and evaluation. It also outlines all the technical hurdles we encountered and the skills that we applied to overcome them. In discussing these, we describe the design solutions we developed to solve our problems, showing the inventive ways we tackled the challenges. Our report also includes an evaluation (Chapter 17) and our own personal reflections of the project (Chapter 19), wherein we will discuss our own development throughout the project, the skills we learnt and the challenges we overcame.

The EES project we selected was to create a prototype of a rover capable of searching for metals on the surface of Pluto. This brief forced us to think about not only the main function of the rover, but also how could we design a vehicle with the appropriate forms and functionalities to deal with the terrain and conditions of Pluto. Such a task involved research into potential issues and the conclusions from this research informed the design of our prototype and adaptations for the final product.

During our project, we visited Loughborough University, in order to build our project and make use of the University's equipment. We also visited our sponsor's Luton site. These visits gave us an understanding of how engineering is carried out in the modern world, both as an academic subject at universities and in industry.

Even though our project is now finished, there are still small improvements that we could make (Chapter 16), in order to make the functionality of the rover better suit the brief requirements.

Acknowledgments

Our team would like to thank all those who have helped us through our project, allowing us to achieve our goal and giving us support throughout the design, planning and manufacturing process.

Firstly, we would like to thank Mr Chase, who has kept our school in contact with both our sponsors Leonardo and with the Engineering Development Trust (EDT). He ensured that we remained focused on our project and helped us think clearly about how to develop our design. Due to the fact that he had seen many other projects progress, he was able to guide us through the project and ensured our project remained realistic within the timeframe.

Secondly, we would like to thank Leonardo, our corporate sponsors, for helping us with our project. Not only did they provide us with two mentors, but they also paid for some of our materials and components for our project. Leonardo also allowed us to visit their premises in Luton. This allowed us the opportunity to see what a day in a STEM-based employment setting was like and the kind of work that Leonardo does.

We would also like to thank our two mentors from Leonardo, Daniel and Anthony, who held technical conversations with us during our weekly meetings. They stimulated us to have our own original thoughts and due to their experience were able to get us to focus on the potential issues that they saw could occur. This insight allowed us to ensure that our project was moving in the right direction and we did not get stuck in unnecessary dead-ends.

We would also like to thank our parents for providing financial support to us, which allowed us to complete this project, and our days out including the residential visit to Loughborough.

We also extend our gratitude to Loughborough University who allowed us to use their facilities to construct our prototype, along with providing space to complete other activities organised by the EDT. Loughborough provided us with excellent machining facilities and expert advice in all sectors of manufacturing, with staff on hand to help us with the manufacturing of our parts, as well as help with using the machining equipment.

Finally, we would like to thank the EDT itself, which is the charity that facilitates the whole scheme. Without them, we would not have had the opportunity to undertake this project. Their competition's scheme also allowed us to learn about and apply engineering conventions, such as report writing. This not only meant that we produced our own project by the end of the process, but we also learned skills about working in a STEM career along the way.

Contents

1 Introduction

Our report discusses the development of a prototype for a rover to be sent to Pluto in order to discover metals, in it, we address how we designed a prototype that would be able to achieve these goals and what techniques and skills we implemented in order to achieve this. We also detail the systems we designed and the computer hardware and software we used in order to complete our prototype to be a functioning representation of our future design for a rover.

The final aim of the project was to create a rover that could discover metals on Pluto, but we also aimed to improve our ability to carry out an engineering project and improve our application of our learning and understanding of mathematics, physics, computing and design. In this report, we outline in detail everything we learnt in this process and our experiences during this process, such as our visits to Loughborough University and the Leonardo Site in Luton. The purpose of this report is to communicate our experience and the engineering process that we undertook.

This report is structured to outline our process in a near-chronological description of our design, manufacturing and evaluation process.

2 The Team

2.1 Dominic Dale

Creating elegant solutions to complex problems by applying mathematics and physics is what excites me about engineering. Unlike other disciplines, the end goal of projects is a functional product that can have a real impact on people's lives. I have experience working with electrical circuits, including using microcontrollers and designing PCBs from scratch. Furthermore I have knowledge of the programming languages running atop microcontrollers (mostly C) and the various protocols often used to communicate between devices. I hope to apply these skills in designing the rover control module along which will also be an opportunity to gain a deeper understanding of power electronics and motor control systems.

2.2 Pallav Hingu

Maths, physics and computer science have always interested me and are the A-Level subjects I most enjoy. I am passionate about engineering, particularly software engineering, and I continually work on programming projects. In the past, I have had work experience at technology companies such as Capgemini and the Civil Aviation Authority. I hope to bring my computer science and engineering knowledge gained from these experiences to the team. Being the programming leader, my job will be to ensure that the software controlling the rover is robust and functional. This will include ensuring that the rover handles errors and unexpected events smoothly while continuing its activity.

2.3 Daniel Baars

As an A-Level student studying physics, maths and geography, I hope to help understand some of the challenges that the rover would face in such an extreme environment. I personally have an interest in the societal benefits of space exploration and therefore want to ensure the data this rover would collect . With my knowledge of product design, applied physics and mechanics, I also will be able to assist in the structural design of the rover so it can withstand the stresses of Pluto's environment.

2.4 Tim Hire

I am an A-Level student passionate about maths and engineering. I am going to utilise the skills that I gained doing GCSE design and technology to help design the rover in CAD, to make sure that the rover is functional and to ensure the rover can be built to high tolerance levels. I am interested in the RC hobby, having both RC cars and helicopters, so I hope I can use some of my knowledge associated with this field to aid the designing of the rover. I studied Astronomy for GCSE, so I am also interested in learning more about Pluto while on the rover designing journey.

As design leader, I will be responsible for pulling together all the different ideas the team comes up with, whether for an overall design or a design for one sub-system of the rover, to create a finished overall design. I will also be responsible for making sure the design has been created with sufficient tolerance to allow for construction, whether by hand or with computer aided manufacturing. Furthermore, my role will include making sure the team avoids design fixation, as this can curb innovation and originality which we want to see in our finished product.

2.5 Ben Post

I am an A-Level student taking maths, further maths, physics and history. I have always been interested in the application of maths and physics so engineering has caught my attention. As the team leader, my job will include assigning jobs week by week, making sure that all parts of the project are completed to the team's best ability and that we stick as close as possible to our schedule. My diverse skill-set also means that I will be involved in many different aspects of the project and I hope to use my problem-solving ability to creatively approach problems we encounter. I look forward to presenting the final project and hope my confidence paired with my interest in the field will help to communicate our project to our audience.

2.6 James Turvey

For me maths, physics and engineering have always been the most interesting subjects in school. I have experience in astronomy and so I will mainly be ensuring that the rover meets all design requirements to survive and function on Pluto. I also have an interest in mechanical engineering and will be helping to design some of the key components that will allow the rover to fulfil its functional requirements. Furthermore, I have some knowledge of programming so will be assisting with the control software development. Due to my wide range of skills I hope to be able to act as a bridge, linking many different aspects of the project together.

3 The Brief

3.1 Choosing our project

At the scheme launch event, we were presented with a choice of project briefs and after a short evaluation of each, we narrowed the choice down to three: the Pluto rover, Fox detector and Unmanned Aerial Vehicle (UAV) hanger. One week later, after initial presentations of ideas on the three projects, we used a decision matrix (Appendix 1) to summarise our opinions in project feasibility; complexity; possibility to utilise of our skills; scope; group interest; time scale; project cost; and the possibility of research in the project. We further weighted these factors, identifying group interest, project scope and our existing skills to be the most important factors in successfully completing the project. Based on this we chose to pursue the Pluto rover project.

3.2 Design Brief

The Pluto rover project brief given to us by Leonardo can be viewed in its original form in Appendix 1. It is quite short but gave us some key details. The main points of the brief can be summarised as

follows: Build an unmanned Pluto rover prototype capable of

- Scaling the icy terrain of Pluto
- Detecting the presence of metals in the crust

From the project brief, we wrote an initial set of project criteria for the rover as follows:

- Must detect metals (particularly iron)
- Must survive the harsh conditions and traverse the terrain of Pluto
- Must record the position of metals detected
- Must be able to log and transmit this data

4 Initial Project Analysis and Plan

It was clear from our requirements that the rover must be controlled remotely (preferably with autonomous driving to avoid objects), it must be able to drive effectively over Pluto terrain and it must be able to detect metals. Additionally, the data about metal detecting must be logged and transmitted. The main aim was, of course, to fulfill these requirements and the project brief (Appendix 1). We also analysed the shareholders, including us, Leonardo and the school (Appendix 1).

We broke down the project into four sections: planning, building, implementing and evaluating. Using this, we designed our Gantt Chart (Appendix 2), which we had based on a previous group's attempt, feedback from teachers, our own ideas about timings and the rough flow of the Engineering V-diagram (allowing time for iterations). We also made progress points (Chapter 17) from the Gantt Chart to ensure that we were on target for the project, as well as a parts and budget sheet (Chapter 9) to ensure we remained within the budget (up to £200).

The first thing that we planned to do was conduct a detailed plan of the project to help us fulfill the requirements in the five key sub-sections of structural, locomotion, metal detection, electronics and coding. Our planning section also involved gathering information about the task specific to Pluto (such as terrain) and space travel (such as weight requirements), as well as a rough design plan for the rover.

We decided to leave further planning of the project until after the "planning section". However, we decided that we would work in sub-teams or as individuals for certain tasks. We also decided that the person with the most experience about each subsection would take the lead and help the others to learn new skills.

5 Requirements

The process of creating the requirements was much more work-intensive than first envisaged. The basic requirement overview was able to be extracted from the very general instructions on the briefing document given to us by Leonardo. We had to revise these requirements multiple times as each time we thought we had a comprehensive set of requirements our mentors were able to find issues with them. One major problem was avoiding solution based requirements as we had many ideas on originally seeing the brief and unintentionally added requirements such as 'must-have six wheels' which were not present in the brief anywhere. Additionally, it was challenging to ensure each requirement fitted the criteria set out by Leonardo. The mentors were crucial in this process, as while this was the group's first interaction with professional standards, the mentors had a deep understanding of what made good requirements given that they were both Systems Engineers. In order to ensure we covered all aspects of the project, we split the requirements into sections that best describe the key functions of the rover. However, this did result in repetition of requirements which then had to be removed meaning that the division into sections was not as useful as first anticipated.

1. **Movement of the rover**
   (a) *Motion*
      i. The rover shall be able to travel a distance of at least 1m
      ii. The rover should be able to travel a distance of at least 50m
      iii. The rover shall be able to travel at a speed of at least $1cms^-1$
      iv. The rover should be able to travel at a speed of $5cms^-1$
      v. The rover shall be able to travel for a duration of at least 5 minutes without any significant systems failures
   (b) *Terrain*
      i. The rover shall be able to traverse over flat terrain
      ii. The rover shall be able to traverse over terrain with a high coefficient of friction
      iii. The rover should be able to traverse over an incline of at least 20 degrees
      iv. The rover should be able to travel at a speed of $5cms^-1$
      v. The rover should be able to traverse over terrain with a low coefficient of friction
   (c) *Mechanics*
      i. The rover should stay level over bumpy terrain
      ii. The rover shall keep all components in working order after a significant distance travelled
      iii. The rover should be able to maintain at least four points of contact with the terrain at all times in normal operation
2. **Electronics**
   (a) *Components*
      i. The rover shall contain a Raspberry Pi
      ii. The rover shall contain a power source
      iii. The rover shall contain a method of communication
      iv. The rover shall have a method of identifying metals
      v. The rover shall have a method of navigation
   (b) *Power*

i. The Power source shall provide enough power for all components to function effectively for at least 5 minutes
ii. The Power source shall be connected to all components in the rover
iii. The Power source shall be safe for use in a non-controlled environment

(c) *Function*

i. The rover shall be able to store or transmit the data received from the metal detection process
ii. The rover should be able to report its location
iii. The rover shall be able to avoid objects
iv. The rover shall be able to regulate its speed

3. **Structure**

(a) *Abilities*

i. The rover shall be strong enough to withstand the impact of inversion
ii. The rover shall be self-supported at all times
iii. The rover shall be resistant to temperature changes

(b) *Limitations*

i. Shall contain all components within the boundaries of the rover
ii. The rover must be able to fit inside the landing module
iii. The rover shall be 200mm high
iv. The rover shall be 500mm long
v. The rover shall be 300mm wide

4. **Communication**

(a) *Type*

i. The rover shall be able to communicate with an exterior device

(b) *Method*

i. The communications shall be interpretable by another system
ii. rover shall be able to communicate with the external device over a range of at least up to 50 meters

5. **Assumptions**

(a) All the parts needed were available
(b) All the parts needed were within the budget

6 Initial Research

6.1 Climatic conditions and their impacts

The climatic conditions on Pluto can be summarised as very cold with typical light levels similar to sunset on Earth and a very thin, tenuous, atmosphere comprising primarily of nitrogen.

The temperature present on the dwarf planet ranges from approximately 33 to 55 Kelvin depending on its orbit of the sun; which varies from 30 to 50 times further away than the earth's orbit. This prevents the use of hydraulics mediums other than hydrogen or helium as any other element is at risk of freezing into an unusable solid. Furthermore, this temperature does not allow the use of any rubber as it will freeze and crack. Therefore, the selection of materials will be dependent on temperature first and foremost.

Thereafter, Pluto's nitrogen-rich atmosphere and extremely cold temperatures present two main challenges for the design and operation of the rover. According to the American Geophysical Union's Journal of Geophysical Research: Planets[1], "during the day, some of the nitrogen surface, which is what mainly comprises the surface of the planet, evaporates into the thin atmosphere and subsequently condenses once again at night forming another layer of nitrogen ice." This process is known as the "nitrogen ice cycle".

The cycle drives the strong winds that are found "on" Pluto; although research suggests that the majority of these winds are found more than 4 km above the surface of the planet and will not interfere with the operation of the rover on the surface. Those fast-moving surface winds that are generated by the nitrogen ice cycle should not interfere with the functional capabilities of our rover because the 'air' on Pluto is estimated to be 100,000 times less dense than the Earth's counterpart, providing little force or resistance.

However, the repeated freeze–thaw cycles do run the risk of freezing some of the rover's mechanical parts together, thereby preventing further operations from taking place. The 6.4 earth-day-long night (one rotation lasts 153.3 hours) could be particularly challenging because there is a lot of time for ice to reform around the rover or some of its components. Potential solutions to this problem include:

- Heating the rover to prevent the ice from condensing
- Completely sealing the rover to prevent condensation from taking place on the inside and damaging the electronics
- Continue mission functionality throughout the night so the components of the rover do not cool sufficiently for ice to form

The first solution has implications for the rover's energy supply and the last solution would require testing to establish whether the operational rover would be cold enough for nitrogen ice to form. Furthermore, night operation would also require different parts of the EM spectrum to be used for navigation purposes.

The tenuous atmosphere on Pluto could pose a risk of cold welding[i]. Although this is unlikely on Pluto (there is some atmosphere all of the time) it is much more likely to occur on the transit from Earth (as happened with the Galileo space craft) so this must be taken into account when designing the spacecraft in which the final rover will travel.

Theoretically, it is possible for nitrogen to flow as a liquid on the surface, presenting a potential hazard for the rover were it to land in 'a pool'.

[i] Two flat parts of identical chemical composition fuse under pressure in a vacuum as atoms cannot differentiate between the two identical materials[2]. This can be prevents by building the rover from different alloys which will not cold weld with each other.

There is very little research data available on the radiation levels Pluto is exposed to, although NASA's Chandra's X-Ray Observatory detected X-ray emissions from the planet above what would be expected from solar wind generated by the Sun[3]. This finding suggests there may be an unknown radioactive source on the planet, although this is unknown. However, with no magnetic field and very little atmosphere it may be wise to assume that the levels are significantly higher than they are here on Earth.

6.2 Terrain on Pluto

Pluto has very varied terrain, some of it being extremely treacherous for our rover to traverse. The most extreme terrain is thought to be a jagged terrain with knife-like projections over 30m from the surface[4]. There are also mountains several kilometers high in some regions which would be impractical to attempt to climb. However, there are large areas that are reasonably flat such as the Cthulhu Macula which is only lightly cratered and could be traversable (this area also contains hydrocarbons which is interesting).

The terrain should not be 'slippery' as almost every element is solid at these temperatures but the nitrogen could be difficult to traverse as it is the closest to it's freezing point. Glaciers present such as the Sputnik Planatea show that nitrogen is not quite at the temperature where it is completely solid as the glacier still moves like a fluid. This could mean the rover will suffer traction issues, however, if it moves slow enough there is little risk of this causing a significant issue.

We can be sure that the solid nitrogen will be able to support the weight of the rover as tests calculate that solid nitrogen has an Ultimate Tensile Strength[ii] of 1.43 MPa[5] at 40K. If we estimate the area of each wheel of the rover prototype in contact with the ground being 0.09×0.01m, then we can calculate (using Pluto gravity of $0.62 ms^{-2}$) that the rover would have to have a mass greater than 2100kg to risk the solid nitrogen not being able to support the rover.

A major issue of landing on Pluto is that we have very little data about the finer details about the dwarf planet and one whole side is nearly completely unobserved and so could provide much more suitable landing areas of more interest to our research. Additionally we do not know what specific hazards lie at each part of the surface.

For the purposes of our project, the agreed requirements are linked to distance, speed and maintaining traction on "bumpy" terrain. It is assumed that the landing site will be pre-selected and appropriate to the rover such as the Cthulhu Macula.

6.3 Existing designs of celestial rovers

We reviewed the design of past rovers to assess what features were successful and those that were not; this influenced our design decisions. Planetary rovers have been used by the major space agencies such as NASA and ESA to aid sample collection and scientific analysis of rocks found on different planets. This is similar to how we need to test for the presence of metal on Pluto. The following section focuses on the most recent and, therefore, most technologically advanced NASA Mars rovers in order to glean information about which features we should implement into our own design. More information about the history of rovers can be found in Appendix 3.

[ii] The maximum stress that can be applied to a material before failure

6.3.1 Case study: Mars Exploration Rovers Spirit and Opportunity

Spirit was the first of the two twin Exploration Rovers that took off to study the geology of Mars in 2003. The primary goal of the whole project was to try and determine whether Mars had ever had the conditions required to sustain life. Unfortunately for Spirit, after one drive motor failed, the rover got stuck in soft sand and NASA scientists were unable to free it, although the rover was used for a period of time as a stationary Martian laboratory.

On the other hand, Opportunity, also launched in 2003, far surpassed the expected lifetime of 90 days and finally broke down after a dust storm in 2018. This marked a more than 14-year lifespan in which it drove over 45km[6] on Mars, the longest of any celestial rover ever, during which time it transmitted 217,594[7] images back to Earth. This does, however, highlight planetary rover's dependence on solar energy to function, as neither of the rovers had a backup source of energy after the sandstorm covered the solar panels with sand. Perhaps looking at alternative sources of energy generation could be important for the success of our rover.

Both of the rovers had the same design, with six wheels on a rocker-bogie suspension system and 4-wheel steering for maximum manoeuvrability. They each weighed 180kg and had a top speed of 5cm/s, although their average speed was closer to 0.89cm/s[8]. The rovers were designed to operate at tilts of up to 30°, at which point onboard gyroscopes would halt the forward travel of the rover and search for an alternative route to take instead. Like all other rovers, the electronics were kept at a reasonably warm temperature by multiple Radioisotope Heating Units (RHUs) and kept in a box insulated by gold film and silica aerogel (more information about thermal insulation and regulation in section6.5). The electrical power was generated from the suite of solar panels on the top of the rover which charged the lithium-ion batteries inside the chassis. Communications with the Earth took place using a single direction steerable high gain antenna, which communications with the local orbiting spacecraft were completed using an omnidirectional low gain antenna which could communicate at a low data rate[9].

The design of the rovers were completely identical, as the array of scientific instruments on each rover were also the same. Both rovers featured a controllable arm which contained many of the scientific instruments located on the rovers.

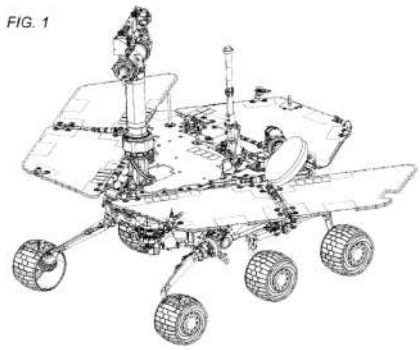
The main chassis holds the following scientific instruments[10]:

- Panoramic Camera - for visual data recording the texture, colour, mineralogy and structure of the terrain around each of the rovers
- Navigation Camera - a monochrome camera with a large field of view but low image quality to allow the feed to be used for driving the rover from Earth
- Miniature Thermal Emission Spectrometer - an infrared spectrometer used for determining the chemical composition of rocks from afar by making measurements based off the infrared part of the electromagnetic spectrum being reflected by the sample in 167 different wavelengths allowing analysis to take place
- Hazard Cameras - wide field of view cameras in known positions on the rover to allow the onboard computer to create a digital 3D model of the surrounding terrain to influence navigation decisions made by the rover

The arm of the rovers contain the following scientific instruments:

- Mössbauer spectrometer - uses the recoil of nuclei of atoms in samples when gamma rays are fired at them in order to work out the mineralogy of any iron-bearing samples
- Alpha Particle E-Ray Spectrometer - analysing the chemical element composition of samples, which is commonly used on space missions because the equipment is lightweight and has a low power consumption
- Magnets - used for collecting magnetic dust particles for further analysis

- Microscopic Imager - allows for close up high-definition images of rocks or soils to be taken, which could reveal signs of any previous life (e.g. fossilised remains)
- Rock Abrasion Tool - used for grinding and brushing rocks to reveal more samples from beneath the surface of the rock samples



(a) One of NASA's patent images of the Opportunity rover

(b) Render of the Opportunity or Spirit rover on the martian surface

Figure 6.1: The fold-out solar panels on the size of the rover are clearly visible, and maximise the solar panel area of the rover to increase power generation

When comparing Opportunity or Spirit to the Sojourner rover (more information in Appendix 3) which was launched in 1996, the point of rotation of each corner wheel is further from the centre of the wheel, whereas Soujourner has the axis of rotation directly above the centre of the wheel. This would mean more energy is required for the wheels to be turned on Opportunity and Spirit, however, the force required is still significantly less than what would be required on Earth due to the reduced gravity on Mars. The main physical difference seen in the more modern rovers (Opportunity and Spirit) is the tall protruding tower which allows for a better view of the surrounding landscape to improve navigation.

6.3.2 Case study: Mars Science Laboratory Curiosity

NASA's Curiosity rover is the latest rover to successfully touch down on Mars (August 2012). It is equipped with a whole host of new instruments aimed at learning more about the planet. These include aims such as making an inventory of the different carbon compounds found on the planet, looking at the chemical makeup of rocks and determining how they might have been formed, determining the present state and distribution of the water and carbon dioxide cycle on the planet and investigating the spectrum of radiation being emitted from the martian surface.

With dimensions of 2.9m long by 2.7m wide and 2.2m high and a total mass of 899kg, Curiosity is much larger than its predecessors[11]. This allows the number of scientific instruments packed into its chassis to be much greater. Furthermore, unlike Spirit and Opportunity which primarily relied on its solar panels for power, Curiosity is powered by a new generation Radioisotope Thermoelectric Generator (RTG) called a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) (heat given off by the decay of the plutonium-238 dioxide isotope is converted into electrical voltage by a thermocouples)[12]. This ensures the rover has a constant current flowing into it, notwithstanding dust storms covering solar panels (as was the case with Opportunity) or forcing the rover to go into standby mode when night falls. However, reliance on nuclear decay for a power source does mean there is a very real limit to the lifespan of the mission unlike using solar panels which could work indefinitely (as long as they were not covered by dust). Curiosity is expected to have a lifespan of 14 years (by which time the power output of the generator is expected to have dropped to 100 watts)[13]. This is much more than the power output by Spirit or Opportunity as there are many more instruments to power.

Curiosity's increased size allows it to have 11 scientific instruments including[14]:

- Mastcam - a camera to take colour images and videos of the Martian terrain
- Mars Hand Lens Imager - a camera that takes high magnification photos of rocks to allow scientists to analyse their textures and structures
- Mars Descent Imager - a camera that took colour video during the rover's descent to the surface to provide a wide-field view of the landing site and local landscape
- Alpha Particle X-ray Spectrometer - measures the chemical makeup of rocks and soils
- ChemCam - an instrument that uses a laser to vaporise material before collecting samples to undergo an elemental composition test using an onboard spectrograph
- Chemistry and Mineralogy X-ray Diffraction - measures the amount of certain minerals in samples of rocks and soils
- Sample Analysis at Mars - an array of instruments that look for the compounds of carbon that are associated with life e.g. amino acids
- Radiation Assessment Detector - measures and identifies all high-energy radiation incident on the detector (including protons, ions, neutrons and gamma rays)
- Dynamic Albedo of Neutrons - a pulsing neutron generator used to detect minute levels of water on the surface or below the surface of Mars by measuring the hydrogen in the ground below
- Rover Environmental Monitoring Station - measures atmospheric pressure, temperature, humidity, winds and UV levels on a daily basis so seasonal weather patterns on Mars can be identified and analysed
- Mars Science Laboratory Entry Descent and Landing Instrument - collects engineering data during the entry of the rover into Mars' atmosphere

These instruments do not include the cameras which are used for hazard detection and navigation purposes. Some of the above instruments are installed into the robotic boom which allows for the instruments to get closer to the object they are trying to look at, giving more accurate results.

Curiosity communicates with Earth via the NASA Deep Space Network of huge antennas[15]. There are three antennas, each located in a different third of the globe (California, Madrid and Canberra) to allow for communication with the rover to be able to take place whatever the rotation of the Earth at that time. However, there are points when the system is busy because it simultaneously communicates with all man-made objects in space, so more commercial and domestic antennas throughout the world were used at the critical landing phase of the mission, to ensure that there was no risk of a signal with the landing module being lost. Curiosity often communicates data with the Mars Reconnaissance Orbiter or Mars Odyssey orbiter, which can then relay data back to Earth. This is beneficial and it means more powerful antennas can be used (the ones on Curiosity are not as good at long range communication as on the orbiters) and the transmission can be sent from outside Mars' atmosphere instead of inside it. The rover communicates using X-band radio waves which have a much higher frequency than those waves used by radio stations on Earth, meaning the DSN does not need to fight against much interference on the same frequency[16].

Like the two previous exploration rovers, Curiosity features the now-standard rocker-bogie suspension design on 6x50cm diameter wheels, with 4 wheel steering. Each of the wheels on the rover has an individual pattern, which allows the images of the tracks in the soft sand to be used by an onboard computer to estimate how far the rover has travelled, and therefore its location on the planet's surface. The rover can easily climb slopes of 12.5°in the soft sand, and although the rover can go to 50°before tipping over, onboard sensors restrict the rover from tilting any more than 30°. The rover has a 60cm ground clearance so it can avoid many small obstacles allowing it to easily traverse the terrain.

Conclusion:

The review of these two successful designs influenced our design in a number of ways:

- Implementation of the rocker-bogie suspension design
- Autonomous navigation using a dedicated depth camera

- Use of an MMRTG for power and thermal energy generation
- 4-wheel steering for maximum manoeuvrability
- Design of requirements regarding mission length, maximum speed, tipping angle and climbing angle (up a slope)

6.4 Communicating with the rover from Earth

Curiosity used X-Band Radio Waves to communicate with the NASA Deep Space Network[15]. New Horizons which recently flew past Pluto also uses an X Band radio wave system. A 2.1-meter antenna transmitted the data it recorded including high resolution images to Earth at a speed of just 1 to 2 Kbps[17]. The data transmitted by the spacecraft is picked up by the distributed Deep Space Network satellites across the Earth as the signal is so weak.

Implementing a similar system on our rover could present many challenges:

- The antenna on the New Horizons craft[18] is huge and while backup antennas are smaller high bandwidth transmissions require a large antenna.
- The rover will likely be shielded from signals at times, for instance when on the side of Pluto facing away from Earth.
- The signals will take a minimum of 4 hours to reach the rover if transmitted from Earth. This means to be efficient with time, the rover will likely need to have some sort of 'self pathfinding' capability similar to that found on the Mars exploration rovers.

Another option would be to deploy a satellite transmission station into Pluto's orbit: this would mean the rover itself would not need as large antennas and that the rover would likely be reachable from Earth for a greater time period. This satellite could be transported in the same spacecraft as the rover.

Ideally any system implemented has a backup in place for critical mission signals; the New Horizons spacecraft has a backup system to ensure data transmission can always take place[19].

6.5 Thermal regulation of the rover

section 6.5 Due to the very low temperatures present on Pluto, it is very important that the rover maintains a temperature within certain boundaries. If the rover gets too cold then the batteries will no longer work and some electronics will fail, meaning the rover will no longer be operational. It is difficult to design our prototype to cope with these conditions as we cannot test in the required operating temperature range. Therefore, it is important to ascertain what insulation and heating mechanisms are required so that the rover could meet the space and energy requirements of these systems.

One of the main ways that rovers sent to Mars have maintained a reasonable operating temperature even through the harsh martian nights is through the use of Radioisotope Heater Units (RHUs). A RHU is a box with a small amount of an unstable element in it[20]. This element will slowly degrade and emit radiation, providing a small amount of heat that does not require additional electrical power to function, thereby reducing the power constraints of the rover. However, these are fairly ineffective as they only provide one Watt of heating and so conventional electric heaters may be needed during the night if the RHUs alone are not able to provide enough heating power.

In order to maximise the efficiency of any heaters installed, the rover will have to be thoroughly insulated to prevent as much heat loss to the environment as possible. The first method to achieve this is a material called Multi Layer Insulation (MLI). MLI is made up of lots of thin sheets of alternating reflective layers separated by a layer of perforated plastic called a scrim[21]. The aim of MLI is to insulate against heat loss by thermal radiation alone and it does this my reflecting the thermal energy back towards its source. The parallel layers of reflective material are separated only by the scrim and this means that radiation gets reflected back to the surface that emitted it, for example if the first layer emitted 100 W then the second layer would reflect 50 W back so the first layer only loses 50 W in total. The effect of this quickly builds up as more layers are added until very little energy is emitted to the outside of the insulation. Each layer is very thin and so depending on how many layers are desired the MLI can be very thin.

Another way to insulate against thermal radiation escaping is to use gold. Gold is a highly reflective material and so is very good at reflecting thermal energy back at the source[22]. When it is painted around the outside of a body, normally by spraying it, it is able to prevent a large proportion of the infra-red radiation from escaping that body. Gold is also very useful in this application as it is very inert and so is not going to be removed by some chemical process where another material would be vulnerable. Furthermore, the coating of gold is very thin and so does not contribute much mass despite gold being a very dense metal. There are limitations to gold as an insulation material; it cannot be placed anywhere with moving parts as it will be worn away; while the layer is thin, a large amount of gold must be used to cover the whole area which will make the rover more massive and finally gold is still gold and so is extremely expensive to cover a large area with as even as little as 5g is worth £200 (March 2019).

However, while the two materials (gold and MLI) are able to insulate against thermal radiation they do not insulate against electrical conduction, especially gold which is an excellent conductor. One alternative to these two materials is Aerogel. Aerogel is composed of 99.8% air with a small amount of plastic forming the structure in which the air sits[23]. Due to the poor thermal conductivity of air it is an excellent insulator. The structure of Aerogel prevents the air from moving around and conducting the heat through convection and this means that it is highly efficient at insulating while also being extremely light.

6.6 Transportation to Pluto

The rocket used to launch the rover could be almost any rocket currently in use, from Soyuz to Atlas, however, the cheapest option may come from the rise of private space companies such as Space X or Blue Origin, set up by Elon Musk and Jeff Bezos respectively. Their reusable falcon heavy would provide enough thrust to launch the rover and its thruster into space without the extra cost of having to design and build our own rocket design. The rover would only need a small engine to provide enough thrust to propel it to Pluto after it has left the Earth's atmosphere. However, to maximise the mass of the rover able to be propelled, a more efficient engine powered by a fuel that will not freeze during the journey would be needed. Falcon Heavy also has the highest launch payload of any launch system currently in use, and the second highest ever, only eclipsed by Saturn V. However the only other similar launch to Pluto, New Horizons, used the Atlas V launch vehicle to propel the payload into interplanetary space. Atlas V has a much lower launch capacity though and would be much more expensive as it is not partially reusable as the Falcon Heavy is.

The second and third stages are up for much more debate as many of them are essentially the same. They would most likely be solid fuel boosters that will take the rover out of Low Earth Orbit (LEO) and into its course towards Pluto via a Hohmann transfer orbit (the most fuel efficient method to exit LEO). In order to speed up the journey, the spacecraft would likely follow a trajectory towards Jupiter to take advantage of the Jupiter Gravity Assist. This was successfully employed by New Horizons and increased the velocity of the craft by 9000 mph[24]. The rover itself and its landing vehicle could have another solid fuel booster that will burn in order to slow the craft down enough to enter an orbit around Pluto before being jettisoned as a less powerful and more controllable booster takes over and takes the craft carefully to the surface.

Due to how far Pluto is from Earth, the journey would take between 9 and 12 years[25] based on previous spacecraft such as New Horizons. Therefore, the spacecraft would have to be able to keep the rover inside at a temperature which prevents damage to electrical components, especially the lithium ion batteries, using methods detailed in the previous section. Furthermore, the large transit time puts

6.7 Testing for metals

For our prototype, we focused on remote metal detection methods. This differs to the methods used on Opportunity, Spirit and Curiosity as they used their arm to bring samples into the rover for analysis using methods such as flame emission spectroscopy[iii]. This focus is because most of these more accurate methods require expensive equipment that we are unable to obtain. Furthermore, the solid nitrogen crust of Pluto is harder to penetrate that then tholeiitic basalt of Mars making sample collection more difficult[26].

Remote detection methods, as detailed below, are less accurate at determining types of metals than chemical methods. However, post-processing of data can give an estimate of the metal type.

6.7.1 Traditional metal detectors

Metal detectors work by transmitting an electromagnetic (EM) field from the transmitter coil into the ground. Beat Frequency Oscillator (BFO) detectors use a transmitter coil to send low frequency signals into the ground[27]. Metal objects within the magnetic field become energised and create an electromagnetic field of their own in the form of eddy currents. The receiver coil registers this new electromagnetic field makes and alerts the user to a target response. A high frequency detector is more sensitive to smaller objects and a low frequency is able to detect larger objects at greater depth. Some metal detectors can use both frequencies simultaneously. The other common type of metal detector uses Pulse Induction (PI) technology. A high voltage pulse is emitted from the detector. The decay of this pulse is recorded, as the presence of metals will increase the time for the voltage to decay allowing the user to be notified[27].

Ground balance will need to be constantly adjusted depending on the surface the rover is on. This is mainly to avoid fine particles which give out "ground noise". This increases detection depth in mineralised ground and would vary for different conditions. We would have to adjust the ground balance to prevent a false alarm for the metal on the rover itself and also if we want to block out "ground noise".

Discrimination allows the EM signal to be interpreted to suggest the type of object based on conductive and ferrous (containing iron) properties. Iron has a conductivity of 1.04×10^7 Siemens per meter (electric conductance per meter) which can be picked up by a metal detector, allowing a positive identification to be made.

6.7.2 Induced Polarisation and resistivity

Induced polarisation (IP) is extensively used in base metal mineral exploration for identifying low grade deposits, and works similarly to PI metal detectors. Usually induced polarisation and resistivity are measured at the same time. Resistivity is the resistance across a metre cube of a material and is measured by passing a current through two electrodes pushed into the ground. The current is then

[iii]Flame emission spectroscopy is a chemical method for accurately identifying the chemical composition of materials by analysing the energy emitted by the natural decay of a particle following its excitement to a higher energy level using photons.

shut off and the IP is measured. The induced polarity is caused by the current “charging” mineral phases, which temporarily store electrical energy. The decrease in potential difference is measured over time to get a reading for IP. This is called Time Domain Induced Polarisation. The values obtained are then compared to existing measurements to estimate what type of metal is present[28].

This method is mainly used to measure disseminated minerals instead of larger clumps of metal. It also has a depth limitation - maximum detecting depth is $\approx 20\%$ distance between the electrodes, which is turn is limited by the current being applied to the electrodes. The electrodes also need good electrical contact to the ground which is usually achieved on Earth using water. We cannot assume we can make good electrical contact with the solid nitrogen of Pluto, making this method unviable. The electrodes themselves may also be a struggle for the rover to be able to carry. Furthermore, we may lack accuracy in measurements, especially resistivity measurements, as many elements and minerals are superconductive[iv] if found in solid nitrogen.

6.7.3 Ground Penetrating Radar

Ground Penetrating Radar (GPR) is normally used to detect mines. Electric permittivity (ability of a system to store electric charge) is the most important parameter of GPR. When encountering a high frequency wave, any material becomes dielectric (domains line up and the object becomes polarised). Interpretation of readings is easier as the diffusion effect is less than on a metal detector as the electromagnetic field is transmitted as a wave. However, the amplitude of the wave decreases quicker. The receiving antenna measures the reflected electromagnetic wave (some is also refracted, transmitted or scattered) from the subsurface structure and is therefore able to determine the type of object, shape and depth[30]. It can detect both metallic and non-metallic objects and is capable of imaging the target shape.

Limitations: Performance is limited in high-conductivity materials such as clay or salt contaminated soils and varied condition e.g. soil with large rocks. It also has a high energy consumption and must be constantly moved making it unviable for this environment. There is a need to calibrate sensors by knowing the surface material to measure depth. It can't detect specific materials - separate analysis would have to be carried out, therefore, it is not a viable option

6.7.4 Laser-Induced Breakdown Spectroscopy (LIBS)

LIBS detects the spectral signatures of plasma light emissions from materials when they are excited using high-energy laser pulses. The spectrum can be analysed and compared to laboratory results to determine which elements are present[31]. LIBS has the major advantage of allowing the spectroscopy to take place in situ without the need for sample preparation. While this method may be more accurate than other remote detection methods (accuracy[v] better than 10%), this technique requires the sample to be on the surface of Pluto. Furthermore, the high price of instruments (generally more than $20,000) makes this an unviable option for this prototype, although their relatively small size could be accounted for in the design to allow LIBS to be present in future prototypes.

6.8 Other sensors that can be used on the rover

In order to increase scientific capability, we explored other sensors and instruments that could also be integrated on the final rover to allow for additional experiments to be carried out.

After NASA New Horizons flyby of the Pluto System on the 14th July 2015, a number of observational

[iv]Superconductive materials have a resisitivity of 0, due to the clumping of electrons into Cooper pairs (BCS theory)[29].
[v]Accuracy refers the the variation in results of the same sample.

hypotheses were generated by the scientific community from the large amounts of images and data collected. Therefore, additional instruments positioned on the rover could potentially be aimed at investigating some of the following areas further:

- Pluto may have a subterranean ocean of liquid water[32]
- Pluto has a complex terrain including icescapes, mountains and flat plains[33]
- There are a variety of ice sheets on Pluto, including methane, water, nitrogen and carbon monoxide
- It is thought that composite ice structures that have very different properties to any of the ices on their own
- Ice formations around Pluto's equator are jagged, like knives pointing upwards These are methane ice formations that are like penitentes on earth, which are jagged ice formations of water, however on Pluto these can be a few hundred feet (around 100m) tall
- Pluto includes a variety of ices and snows, such as nitrogen snow and methane ice. There is also a variety of formations of frozen materials, such as icebergs of water ice floating on denser nitrogen ice
- It is believed that Pluto has a centre warmed by radioactive decay, leading to a lot of movement of nitrogen (it is thought that nitrogen moves down into the subsurface and is then heated and moves back up to the surface)
- It is thought that Pluto has a nitrogen atmosphere[34]
- It is not known whether Pluto has a magnetic field

How can our rover prove or disprove some of these ideas and what instruments would be required?

Topics under investigation	**Required instruments**
Subterranean ocean of liquid water	A ground-penetrating radar would prove to be the optimal way of detecting a subterranean ocean, as GPRs work best when they are penetrating through ice. This would make it easy for the rover to study the presence of water in Pluto.
The nature of difference ice sheets on Pluto	In order to find out about different ice sheets we would have to take samples of the ice. We may then be able to figure out the composition of these pieces of ice by melting them and using Thin Layer Chromatography or another method. We could also find out how these ice masses accumulated, and we could do this by taking layered samples of the ice.
The shape of features on Pluto	Many of the features on Pluto were seen by New Horizons, however, the images had a low resolution. We could map parts of Pluto better by using Synthetic Aperture Radar, which is used to create 3D images of landscapes.
The intensity of radioactive decay under the surface of Pluto	It may be difficult to detect radioactive decay underground, due to the size of equipment that would be required. However, we could use a Geiger-Müller tube or a Dosimeter to detect radiation above ground.
The atmospheric makeup of Pluto	Usually to test the atmosphere around Earth, either a Light Detection and Ranging[35] (LIDAR) sensor or a laser is used. However, this system requires a lot of infrastructure so is not viable on Pluto. Instead, a Mass Spectrometer could be used on samples directly from the atmosphere.
The temperature of Pluto	A low-temperature thermometer that measures in the range 33-55K.

Topics under investigation	Required instruments
Whether Pluto has a magnetic field	We could include a magnetic compass to detect whether there is a consistent magnetic pole that does not change location as the rover moves.

Other instruments that could be considered:

- Alpha Proton X-Ray Spectrometer - used on the Sojourner rover to work out the chemical composition of rocks. An alternative to this is Infrared Spectroscopy. This uses the idea that different molecules absorb different frequencies of EM radiation that correspond to their chemical structure. The absorptions only occur at resonant frequencies, which is when the frequency of the radiation that the particle absorbs is the same as the vibration of the molecule. An onboard reference is often used in order to eliminate the instrument influence. However, using a reference adds weight. Also, the process of infrared spectroscopy may be too resource intensive to carry out away from earth, as it requires a form of solvent in order to be carried out on a solid sample. Furthermore, samples would have to be taken into the rover. This would require an arm containing mining equipment which is not currently included on the rover design.
- Antenna for communication - There are two types of antenna we would be able to use, either a High Gain Antenna (HGA) or a low gain antenna (LGA). HGAs generate precise radio signals that can travel a long distance to a more precise location, whereas LGAs do not travel as far, but can travel around mountains and other features. The two are sometimes combined, as HGAs can be used to increase the intensity of signals from LGAs.
- Cameras for navigation and taking photos of the samples we collect. We would have to investigate which part of the EM spectrum would be best to take photos in on Pluto (is there enough visible light for it to be used). The orbit of Pluto is elliptical, between 30 and 50 AU (or 30 and 50 times the distance between the Sun and the Earth. This means the light intensity of the sun on Pluto is between 1/900 and 1/2500 times less intense than it is on Earth[36], or around 264 times brighter than a full moon; this is a brightness known as civil twilight[37] which is bright enough to read by. It might be best, therefore, to maximise the light entering the camera by using an ultrawide lens or creating artificial light. However, the atmosphere of Pluto is blue and hazy which may reduce light entering the atmosphere.
- Mössbauer spectrometer - this process involves the firing of a stream of gamma rays at a sample. Since the chemistry of the absorbing item is different to the gamma ray emitter, there are very small shifts in the nuclear energy levels. T resulting spectra is plotted and corresponds to one particular result allowind accurate chemical composition to be determined. This process would also be reliant on the rover having an arm with mining equipment to be able to bring samples from under the surface into the rover for analysis (as the surface is covered with nitrogen).

6.9 Navigation on Pluto

On Earth we can use GPS satellites to triangulate precise locations but on Pluto this is clearly not possible. Another way of navigating is by using the magnetic field of the Earth to find North then mapping a route based on that: again this is likely not possible on Pluto as it is unclear whether Pluto has a magnetic field and even if it does it is likely weak[32].

On the Spirit and Opportunity rovers three key systems were used to log the rover locations:

- Odometers in the wheels to tell how far the rover had travelled.

- Inertial Measurement Unit (IMU) with accelerometers and gyroscopes to find which way 'down' is and determine heading
- Use of sun direction scanning to determine the direction the rover is facing.

The drawback of odometers is that if the wheels are turning but the rover is not in full contact with the ground or the rover is slipping, the rover may still compute a move forward; the Spirit and Opportunity rovers used various systems to detect these cases.

A similar system could be used in a Pluto rover, though using the sun to determine location would take much longer. The Pancam used on Opportunity and Spirit tracks the sun for $\approx$ 10m (2.5 degrees) to determine location. Days on Pluto are much longer ($\approx$ 6.4 Earth days) than Mars, so the sun would likely need to be tracked for up to an hour. More research into the orbit and how the sun tracks across Pluto's sky would need to be carried out to determine if this is fully possible.

Another potential navigation option is star tracking. As Pluto has a thin atmosphere (much thinner than Earth), stars can be easily observed as there is less scattering of light upon entering the atmosphere. However, this method would require telescopic equipment for accurate measurements which would increase the weight of the rover (as mirrors are heavy). This method would also be relatively slow as a discernible change in the apparent position of certain stars must be recorded in order to calculate position. The method could be improved by using more expensive higher resolution observing equipment that require smaller changes in relative star positions to determine accurate location.

6.9.1 Potential for autonomy

Due to the inevitable time delay communicating with the rover (4 hours 27 minutes for a one-way radio signal[38]) some sort of autonomous system to track around the surface without human input seems appealing.

NASA have used pathfinding systems in the past such as the Hazard Avoidance system on board the Mars Exploration Rovers (MER)[39]. This system took input from 'waypoints' that could be set from Earth and the rover would traverse the terrain to that waypoint; it stopped every 10s and assessed its situation for 40-50s before continuing. Pancams (RGB) and Navcams (stereoscopic (depth) 3D imagery, grayscale) on the front, back and sides of the rover were used to generate a 3D model of the terrain which was analysed to determine the best route.

A similar system could be implemented on our Pluto rover, perhaps with even less human interference due to advances in technology. Many robots use a SLAM (Simultaneous Localisation And Mapping) system with LIDAR, RGB-D[40] (RGB depth images) or other systems; this allows the control software on the robot to visualise elevations and potential hazards, avoiding them. Transmitting data back to Earth will also use lots of energy which is limited on the rover; an autonomous system is advantageous in this sense as it reduces the amount of data transmission that is necessary.

The key requirement for autonomous navigation is depth imaging. To an extent this can be extracted from standard RGB images but the reliability of this on Pluto cannot be relied upon. One other depth sensing option would be to use two cameras in a stereo setup as used on the MERs. This is, however, impractical for our situation; stereo cameras require fine tuning and a huge amount of processing to convert the two video feeds into a depth image. Furthermore, this type of depth imaging does not work well on smooth surfaces, although we do not think this will be an issue on Pluto. Finally the depth reliability largely depends on the quality of the cameras, and for this prototype our budget is limited.

Another way to record depth would be with the use of an RGB-D camera[40], as found in devices such as the Xbox Kinect. The Kinect uses a textured infrared (IR) laser projector and a Complementary Metal-oxide Semiconductor (CMOS) sensor to detect depth under any lighting conditions. Due to the textured projection; the surfaces being recorded can be smooth and still be correctly processed.[41] The

CMOS input is processed on the device to a depth image and paired with a simple RGB image before being exported at a rate of up to 30Hz. Because an IR projector is on board, depth images can be captured regardless of ambient visible light.

One final depth imaging option is a LIDAR system. The benefit of a system such as this would be a much larger range of imaging, though that would add to the processing load. A laser is fired and distance is measured by timing how long it takes to return. This happens at up to 150,000 pulses per second and the system is often mounted to a rotating base to provide 360°depth imaging. Even this can only capture depth on a 2D plane and more complex, and more expensive systems are required to map depth in 3D space, making it impractical for this prototype. This may be optimal for the final design as it is highly accurate over huge distances.

6.10 Power sources

The power source for the Pluto rover will be a crucial part of the electronics, which would need to be highly reliable and be adapted to the atmosphere of Pluto. For this, it would need to be able to run in extremely cold temperatures. At such low temperatures, electrons tend to lose their energy and do not flow well. This means that we would need to use an electric heater to heat all the components.

6.10.1 Lithium Batteries

Lithium batteries are used by NASA a lot; they were used in the Curiosity, Mars Pathfinder and other rovers[13]. They are a reliable source for main and backup power. NASA uses "2 lithium-ion rechargeable batteries to meet peak demands of rover activities when the demand temporarily exceeds the MMRTG's steady electrical output levels"[42] (more information on MMRTG's in 6.10.3). But, these lithium batteries face an obstacle on Pluto due to the extremely low temperature. Cold temperature increases the internal resistance and lowers the capacity of the battery. A battery that provides 100% capacity at 27°C (80 °F) will typically deliver only 50% at –18°C (0°F). The average surface temperature on Pluto is far below -40°C, which is the temperature that lithium ion batteries freeze, so there is no way that they can be used as a standalone power supply for the Pluto rover. A solution for this would be to use an electric heater, as mentioned above. This would prevent the lithium batteries from freezing.

Lithium batteries would be the primary go-to options for use in the rover. They would be very useful as primary power stores as well as backup options. For energy backup, primary batteries should be used as they have "high specific energy, long storage times and instant readiness that give primary batteries a unique advantage over other power sources."

6.10.2 Solar Power

While solar power seems like the go-to option for space, it is not the best option for a Pluto rover. NASA uses solar power on Mars exploration rovers and Mars Pathfinder as Mars is very close to the sun. But as Pluto lacks sunlight and is a very cold and dark planet, solar power would be highly inefficient. Solar panels are very readily available and can be pretty efficient compared to other methods used by NASA. An innovative addition to past rovers is Triple Junction Gallium Arsenides cells. These are 3 layered solar cells and made their first trip to Mars aboard the MER rovers[43]. Used on NASA's Deep Space 1 mission, these cells are able to absorb more sunlight than the single cell versions sent on Sojourner. These solar panels are able to supply much more power to the rover's rechargeable Lithium batteries.

6.10.3 Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)

The Curiosity rover is carrying a nuclear power source to charge its batteries[13]. The system uses heat from the decay of plutonium-238 to generate 110 watts of electrical power to charge the rover's batteries. This is an effective method to generate electricity which would be extremely useful in Pluto. This method utilises the Seebeck Effect (named after Thomas Seebeck), which is a phenomenon in which a temperature difference between two dissimilar electrical conductors or semiconductors produces a voltage difference between the two substances. In the rover, a radioisotope is used to make the hot element in the circuit, and the atmosphere is used to make the colder element. This effect is used to power the rover, but for certain cases, the rover has rechargeable batteries to meet peak electrical demand from rover activities, as mentioned above.

The Radioisotope Thermoelectric Generator (RTG) could also be used to heat all the components in the rover. This heat can be used to prevent the lithium battery from freezing and losing all stored energy as well as making sure circuit components do not become superconductive changing the functionality of the circuit or suffer cold welding issues.

Although we cannot implement this technology into our model rover, we can potentially use the Seebeck Effect without the radioactive element. We can use the very cold atmosphere of Pluto for the colder element of the circuit, and we can potentially use the heat generated by the motors and the circuit. As the motors will be running for a prolonged period of time, it would be useful to replenish as much energy as possible. Further testing would be required to see whether this method has potential for energy generation.

6.10.4 Conclusion: Powering the real rover

Powering the rover using solar panels would be a bad option as in past Mars rovers, solar panels have limited their operating range as they have been forced to remain within a few degrees of a planet's equator. The rovers have not been able to operate in any area in any season, and they require all their energy from the sun. This would also have further disadvantages on Pluto as it is around 40 times further from the Sun than Earth is. This means that solar radiation is 1600 times less intense than it is on Earth, meaning solar panels would fail to generate enough power for the rover.

The Spirit and Opportunity rovers, which were both operated in a geological context, similar to our rover, were able to use their solar array to generate 140 watts for 4 hours per day or 2016kJ over that time. The distance between Mars and the Sun is 1.524 astronomical units, whereas Pluto is 39.5 astronomical units from the Sun, which means that the light intensity is 672 times weaker on Pluto than it is on Mars. Therefore, if we were using the same solar technology, the solar array on a Pluto rover would have to be 672 times larger for the same power output. Even with a more advanced solar array, obtaining a large share of the energy from solar would not be feasible. This is because the sunlight is not intense enough to generate the power required. There is also a risk that the batteries would be limited due to the intense cold on Pluto. Therefore, solar power is not an option.

Previous Mars rovers have therefore been powered by Plutonium-238, which releases heat in its decay that is turned into electricity, this is using RTGs which generate electricity using the Seebeck Effect, where the difference in temperature brings about a voltage. This would be very efficient on Pluto due to the large temperature gradient when compared to that of Mars. The lack of moving parts would also be beneficial for a Pluto rover due to the need for reliability.

Typically, the power generated is then used to charge batteries. The batteries that are used are lithium ion batteries, though these become less able to store energy as the temperature decreases. Batteries will be used on the 2020 Mars rover to meet short times of high energy demand, it might be useful also to use a few ultracapacitors on our own vehicle to meet the energy demands of any short-term energy uses such as beaming a large amount of data back to the communications centre.

An essential way to avoid temperature decreases such as these is to use some form of temperature control from the nuclear fuel source.

Traditional nuclear fuel rods are highly inefficient, generating only 4% of the energy they could from a nuclear fuel rod, furthermore, RTGs are also highly inefficient, at between 3 and 7%.

A new way of increasing the efficiency of terrestrial nuclear power plants is by using a dissolved nuclear fuel, in liquid form, with this method being far more efficient than traditional fuel rods. However, it may be difficult to find a liquid that would act as a solvent at such low temperatures. A major benefit of a higher efficiency power source is that it would be able to last longer, extending the rover's life cycle. The difficulty with finding a solvent that could act at low temperatures could be remedied with using a RHU to produce heat. These only weigh a few grams and can generate about a watt of heat for several decades. Therefore, using these could keep a far more efficient nuclear power source active for far longer. Since temperatures on Pluto are between 33K-55K, heating and heat management is likely to be a far greater priority than for other rovers.

The 2020 Mars Rover uses many layers of insulation in order to protect both the fuel during launch and the rover upon entry into Pluto's atmosphere. The material used is the same as those used on the cones of intercontinental ballistic missiles, which serves as heat shielding for re-entry to the Martian atmosphere. However, this may not be an issue on Pluto as the atmosphere is so much thinner, reducing the buildup of atmospheric drag and aerodynamic heating. The 2020 Mars Rover's fuel was in ceramic form to prevent fragmentation, which may not be an option with a dissolved nuclear fuel. Therefore, testing of ceramic nuclear fuels is required.

On the 2020 Mars Rover, the power source was a cylindrical RTG with a diameter of 64cm and a length of 66cm. It weighs 45kg and produces 110 watts of energy at launch, with the amount of energy it produced reducing by a few percent every year. This power source being used on the 2020 Mars Rover has been used on many other NASA missions, including the Apollo missions to the Moon, the Viking missions to Mars, and on spacecraft that flew to the outer planets and Pluto, including the Pioneer, Voyager, Ulysses, Galileo, Cassini, and New Horizons missions. Due to the large amount of time to get to Pluto ($\approx 12 timeslongerthantogettoMars), anRTGforthePlutoroverwouldhavetobemuchlargerthanfoundinthe 2020 Mars$

6.11 Drivetrains

For the drivetrain, we can transfer energy to the wheels in a number of ways:

- If a motor is to be shared - use shafts and gears made of metal to share and transfer energy to each of the wheels.
  - When doing this, it is extremely important to consider the Coefficient of Thermal Expansion (CTE) of the metal used for the gears as this metal can expand and shrink as temperature changes. This can cause many issues on the rover. Also, testing this would be hard on Earth as we would not be able to achieve temperatures like those of Pluto for a prolonged period of time economically, therefore we would need to do calculations, and if possible, computer simulations to test that the gears work in all conditions.
- Use individual motors for each wheel - this would be more power consuming but would increase the available torque and overall control of the rover.
  - Done by NASA on the Curiosity rover as well as many other rovers.
  - This would reduce our need to use gears, decreasing complexity and increasing overall control of the rover. But, on the other hand, this increases the difficulty of keeping all the components warm using the core heater. One way we can get around this is to use liquid heat transfer. We can use N,N-Dimethyloctylamine which has a freezing point of around -190 °C. This liquid can be heated by the core and transferred to the motors to heat them. A pump would need to do this constantly. But, this may not reach the temperature that we need so testing is required.

- Use individual hydraulic motors for each wheel and use helium to power these motors as it has the lowest boiling point of -268.9 °C, and this would decrease further as the atmospheric pressure decreases. Using a hydraulic system is extremely beneficial when transferring energy throughout the rover.

6.11.1 Rocker Bogie Suspension

Rocker Bogie Suspension is used on every rover and allows the rover to have mobility passively without needing any external components. For this system to work, we need to have good structural integrity and ensure that the bearings/joints do not freeze in the cold temperature. This would be a challenge as most metals shrink in the cold temperature tightening joints, making linkages vulnerable to jamming. "Aluminum is used in space because it retains so much strength at cryogenic temperatures[vi] (it doesn't get brittle like most steel, and actually gets stronger; austenitic stainless being an exception). Aluminum has a higher coefficient of thermal expansion than steel"[44], meaning that we should use aluminium for the drivetrain but the joints would need a metal with a low CTE.

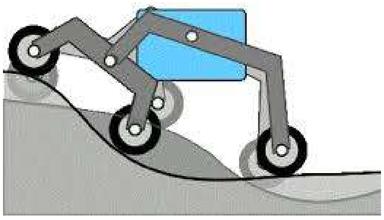


Figure 6.2: Diagram illustrating how the rocker bogie design operates over variable terrain. A video showcasing the abilities of this design can be found at `https://www.youtube.com/watch?v=3Zx7tGtwF5g`

Invar-36 is a nickel alloy that has the lowest CTE as it "exhibits a near zero rate of thermal expansion" and would be most suitable for the joints. Invar-36 also "offers a high retention of strength and toughness at cryogenic temperatures"[45], which means that it may be the best metal to use for the rover and would be ideal for the conditions on Pluto. Although it is difficult to get and is comparatively expensive, I think that it would be the best metal to use for our purpose. Realistically, if we cannot buy enough Invar-36 to manufacture the whole rover, I believe that it would be best to buy Invar-36 screws and nuts, which would not shrink to tighten joints, helping with the rocker bogie suspension system.

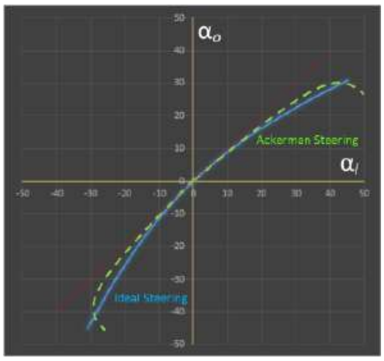
Two other cheaper alternatives to Invar-36 are graphite composite carbon fibre and Beryllium. Composites have been used in spacecraft since the 1970s, but suffer from microcracks[vii] which affects structural rigidity[46]. Specific testing would be required to investigate the mechanical properties of individual composites at 33-55K. Another option is Beryllium. Even at cryogenic temperatures, Beryllium has a very high strength to weight ratio and suffers from minimal thermal expansion[47]. As a result, it has been used for the mirrors on the James Webb telescope. This material could, therefore, be used as an alternative to Invar-36 on the rover.

The rocker bogie suspension system also allows hydraulic systems to work better as flexible pipes can also be lined along the system without the risk of tangling, with the actual structure arms acting like pipe supports. Care needs to be taken to ensure pipes or electrical wires are not pinched or stretched by the rotating hinges in the system.

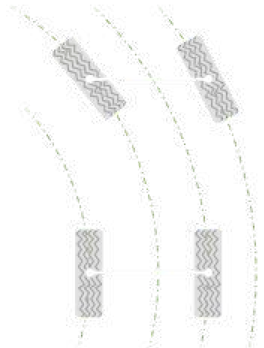
[vi] Low temperatures where molecule activity come as close to stationary as is theoretically possible. Definted as temperatures between -150°C and absolute zero (-273°C).

[vii] Caused by the difference in thermal expansion between the fibers and resin.

6.11.2 Ackermann steering



(a) Steering offset (α_o) against angle of wheel turned (α_I)



(b) Effect of Ackermann steering

Figure 6.3: Ackermann steering diagrams[48]

We will need to use the Ackermann steering principle for the rover. To prevent the wheels from slipping to make it around a corner, each of the wheels must turn at a different angle and rotate at a different speed when turning. Ideally, the front wheels would be independently steerable to set them to the perfect angle to be a tangent to the circular arc with a common centre to the arcs for the other tires. This would mean that there was no slip as the tires moved in a circle.

Ackermann's solution was to make a trapezium shape between the wheel and another pivot. This means that the outside wheel for any turn will turn to a lesser degree than the inside wheel. This reduces slipping for the tires and approximates to the ideal steering (see graph). We may also be able to find software to change the inside and outside wheels at different rates for corners. This would have the advantage of not having to link together the front wheels, which would limit the rocker-bogie suspension and may even be closer to ideal steering than Ackermann steering, reducing slipping even further.

7 Further Research: Metal Detection

7.1 System requirements about the metal detector

What do we need to make sure the metal detector can do?

- The detector shall be able to detect metals up to 3m below the crust of Pluto
- The detector shall not interfere with, or be interfered by, the electronics in the rover
- The detector shall be able to detect ferrous and non ferrous metals

7.2 Types of metal detectors

7.2.1 Beat frequency oscillation detector

Considered to be among the most basic of metal detectors, these detectors usually feature two coils of copper wire rolled around a ring of iron or steel (a ferrous and therefore magnetic material). One coil is located at the bottom of the detector and another slightly higher, with both of the coil being attached to the same signal generator. However, both of the coils operate at slightly different frequencies, with the difference between the two frequencies being the output of the metal detector. This detector is considered to be a weak detector, with a maximum range (of a handheld-sized detector) being about 60cm.

7.2.2 Very low-frequency detector

Like the beat frequency oscillation detector, the very low-frequency detector also features two different copper coils which work together in order to detect metals. The first coil is the transmitter giving off intense electrical current at the same frequency as produced by the signal generator, while the second coil is the receive picking up the signal and amplifying it to produce a discernible output.

The transmitter coil loops a magnetic field above and below the ground, using the coil as a solenoid that acts as an electromagnet when a current passes through it, which is then disrupted when it tries to pass through metal. The secondary receiver coil, therefore, looks for discrepancies between the signal produced by the transmitting coil and the magnetic field received by the second coil, known as the interference. It is this interference that is outputted from the detector. One large benefit of this detector, and why it is the type of detector most commonly used by detecting hobbyists, is that the interference produced by each type of metal is slightly different, meaning the type of metal can often be identified solely from the output signal of the detector. Additionally, more magnetic metals such as iron and steel produce a more powerful interference and are therefore easier to be identified by the detector. This is useful for our design, as the primary metal we are searching for is iron.

7.2.3 Pulse induction detector

This type of detector uses the theory of echolocation to detect for metals, by sending a short burst of current through the coil, which quickly disappears generating a magnetic field in the opposite direction (as it opposes the change in current). This reverse in magnetic field induces a short electric current which also quickly disappears. The size of this current is what is used to detect metals, as magnetic objects buried beneath the ground will interfere with the current that is generated. This type of detector has some advantages, namely that it is very accurate at detecting objects and is of a reasonably simple mechanical design as it only requires one coil of wire to operate. However, it also has some disadvantages, such as not allowing the type of metal to be identified from the output and the high risk of external noise affecting results. This could be an issue on our rover, due to the onboard computer (Raspberry Pi) operating the rover in the chassis above the detector.

7.2.4 Why type of metal detector are we using and why?

We are using the pulse induction-style metal detector on our rover because it has a more simplistic design as a result of the detector only working with one coil. Furthermore, out of the three most common detector designs features above, the pulse induction is the most accurate at detecting metals according to a number of sources, which is important to make sure that we can be sure we can detect minute traces of metals on Pluto. However, this type does have electrical noise issues, as written above. This means we are going to have to implement some source of magnetic insulation into our chassis, in order to prevent noise from the electronics interfering with the metal detector and visa versa.

7.3 Pulse induction metal detector in detail

7.3.1 A brief explanation of inductance

Metal detectors work on the principle of inductance. Inductance is "the tendency of an inductive circuit [electrical conductor] to oppose any change in electric current flow."[49]

Where capacitors store energy in the form of a static charge, resisting sudden changes in voltage, inductors store energy in the form of a magnetic field and resist sudden changes in current.[50]

Energy storage in an inductor is a function of the amount of current running through it, this property results in the tendency of an inductor to maintain current at a constant level.[51]

A good analogy for this is a water wheel in a circuit. When a pump (cell) starts pushing water through our loop, the waterwheel (inductor) starts to slowly spin, slowing down the water at the same time; this can be considered a large resistance. When the waterwheel picks up speed and eventually reaches the limit of the pump it can be considered to have a resistance of 0. If the pump is switched off, the waterwheel will continue to push water round the loop, resisting the change in the rate of flow, and slowing down in the process.[52]

An inductor has inductance 1 Henry if a current change of $1A/s$ produces an (opposing) voltage of 1v in the circuit. When a current runs through a wire a magnetic field is induced.

When the current flowing through an inductor is increased or decreased, a voltage is formed across that inductor. This is because energy is either being transferred from electrical energy to kinetic energy to store in the form of a magnetic field, or from kinetic energy to electrical energy. Inductors act as a source when current through them is decreasing, or as a load (resistance) when current through them is increasing.

Inductors do not have a stable resistance like conductors. Instantaneous p.d. across an inductor can be calculated by:

$$v = L\frac{di}{dt}$$

Where v is instantaneous voltage across the inductor, L is the inductance in Henrys and $\frac{di}{dt}$ is the instantaneous rate of current change.

Factors affecting inductance are:

- Number of turns in the coil; more turns means a greater amount of magnetic field force therefore **greater inductance.**
- Coil area (as measured looking down through coil); larger area means less opposition to formation of magnetic field therefore **greater inductance.**
- Coil length; shorter path for magnetic field flux to take then less opposition to the formation of that flux for a given field force therefore **greater inductance.**
- Core material; magnetic permeability of core, a more permeable core (e.g. iron) will result in a greater magnetic field therefore **greater inductance.**

This gives us:

$$L = \frac{N^2 \mu A}{l}$$

Where:
- L is inductance in Henrys
- N is the number of turns (where a straight wire = 1)
- μ is the absolute permeability of the core material
- A is the area of the coil in m^2
- l is the length of the coil in m

This yields approximate figures; one reason being permeability changes as the field intensity varies.

One way of working out which materials give the most inductance as a core material is by looking at a $B-H$ curve. You can see that for part of the curve there is a (fairly) linear relationship. It is within

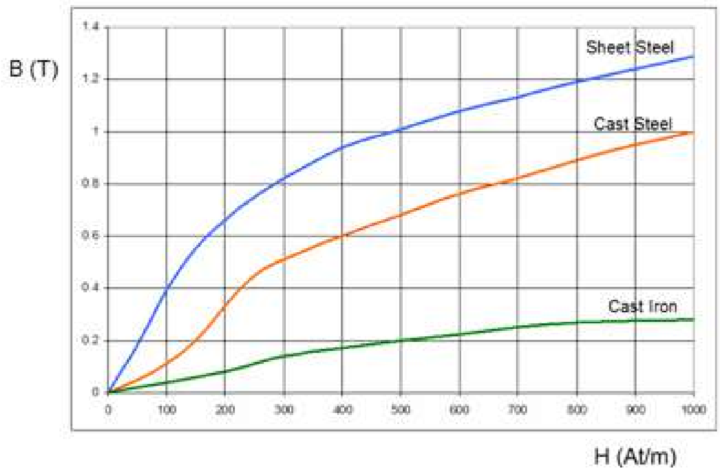
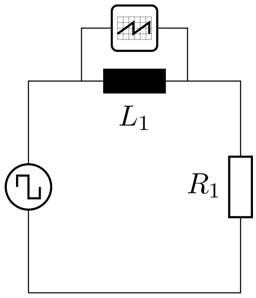


Figure 7.1: $B-H$ curve of a few materials (flux density plotted against the magnetising force)

this section ('linear zone') that inductors are designed to operate as beyond this zone ('saturation') behavior can be unexpected.

7.3.2 Use in metal detectors

Metal detectors harness the behavior of inductors with the use of AC circuits and Faraday's Law of Induction. As the current is constantly changing the magnetic field around the inductor is also constantly changing. When ferromagnetic metals are brought near an inductor the induced magnetic field aligns with that of the inductor's field increasing inductance. When non-ferromagnetic metals are brought near an inductor Eddy currents are induced which create magnetic fields that oppose the inductor's magnetic field leading to a lesser inductance.



(a) Simple LR circuit. A square wave is applied across the inductor and resistor (i.e. continually connecting and disconnecting a DC source).

(b) The p.d. across the inductor acts as a differentiatior.

Figure 7.2

This means metal detectors can differentiate between ferrous and non-ferrous metals by measuring the inductance of the detector coil.

7.3.3 Measuring inductance with an Arduino[53]

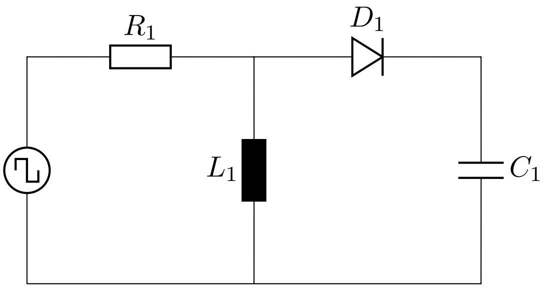


Figure 7.3: Arduino based metal detector circuit. The square wave is produced by the Arduino, voltage spikes similar to those visible in 7.2b can be measured across L1.

There are many expensive tools which can be used to measure inductance, but for our application keeping costs low is important. A simple relative inductance measurement can be taken by using an arduino, diode, resistor and capacitor. The inductor in this setup is our detection coil. When the arduino sends a pulse through the circuit shown above, the p.d. across the inductor spikes in proportion to the inductance of the coil. This spike subsides very quickly, but it can be used to charge a capacitor. If we do this multiple times the capacitor reaches a voltage capable of being read by the arduino ADC, giving a quantitative value for the inductance of the coil. If we know the ADC reading of the coil when only the hull of the rover is near, we can simply detect any deviation from this and we know a metal is present near the coil.

7.3.4 Testing the pulse induction principle

Initially, when choosing the type of metal detector we would implement on the rover, we conducted some simple tests to ascertain whether the pulse induction metal detector design was realistic. To do this, we made a simple circuit compromising of a resistor in parallel with an inductor. The inductor acted as a miniature coil as would be normally found in a metal detector. The input to the circuit was a bench signal generator to provide a changing potential difference and current to the circuit. This was plotted on the oscilloscope alongside the potential difference over the resistor.

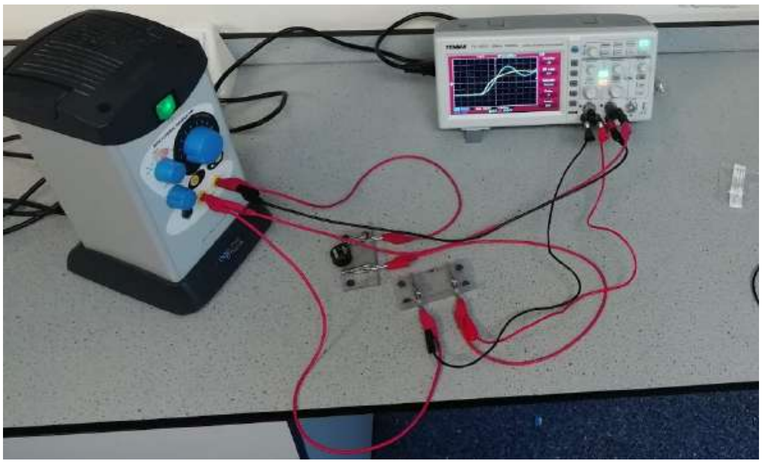


Figure 7.4: Using the oscilloscope to detect changes in the decay of current flowing through the circuit

As a pulse induction metal detector works by detecting delays in the change in direction of current flowing through the coil caused by the interference from the magnetic field of the metal being detected. We could, therefore use the oscilloscope to see how the time for one direction of current to decay is affected by the presence of a metal (iron) near the coil. This test was successful as it proved it was reasonable to be able to detect changes in inductor behaviour caused by the presence of metals.

7.4 Detector interference

7.4.1 How will the detector's reading be affected by onboard electronics?

Due to metal detectors relying on inductance to detect metals, the electromagnetic interference generated by electrical circuit can potentially register incorrectly on the detector. This is usually found in the form of a small amount of 'chatter', depending on the frequency of the electrical device. The primary sources of electrical interference are electric light dimmers or transformers, however, small electrical circuits and bluetooth connections such as those being used on our rover will interfere with the metal detector to a smaller degree.

According to Dave Johnson, a leading metal detector designer for the past 25 years, there are a number of methods of reducing the impact of electrical interference, such as might be found on our rover, on the results of the metal detector. The first is to reduce the sensitivity of the detector, so that is does not register a result for the small changes in inductance generated by the electrical devices. While this does marginally reduce the potential measuring depth of the detector, it eliminates electrical interference from the results of the detector. Another method is to shift the frequencies being measured out of the range of those produced by the electrical devices, especially the flow of current through the power cables in the rover.

The potential for disruption from electrical interference is lower because the sensitivity of our detector is lower, as we are using less sensitive electronics to those found in professional metal detectors, for example, along with a lower current and smaller radius of the coil. This means out detector will affected less in comparison to expensive more sensitive detectors.

The rover chassis being made out of aluminium will reduce the magnetic fields being able to travel from the wires in the chassis of the rover to the coil. The chassis of the rover will, therefore, act as a shield to the magnetic fields produced by the electronics. As a result, the electronic disruption received by the metal detector will be reduced. In order to assess to what extent electrical disruption is an issue in our rover prototype, we will integrate all of the systems and then conduct testing, before altering the settings as detailed above.

7.4.2 How will the onboard electronics be affected by the detector?

Due to the relatively small current flowing through the coil of the metal detector, the magnetic field created by this will not be strong enough to affect the flow of current flowing through the electrical components. The field is further reduced because of the aluminium chassis. With aluminium being non-ferrous and, therefore, largely non-magnetic, the magnitude of the interference of the changing current in the metal detector coil on the electronics of the rover will be minimal.

7.4.3 How can we insulate the rover from the detector?

In order to protect the rover's electronics from magnetic fields from the metal detector, there are a few materials we can use.

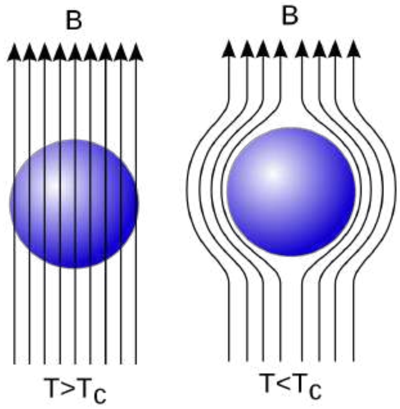


Figure 7.5: Illustration of how the Meissner effect changes the magnetic fields properties in superconductive materials

One of these methods utilises a superconductor in the Meissner Effect. This occurs when a superconductor is cooled to below its critical/transition temperature. Below this temperature, the electromagnetic field lines are expelled from the superconductor, and they run around the outside of it, meaning that the electronics inside the superconductor do not get affected by the flow of the magnetic field. The temperature of Pluto ranges between 33 and 55 kelvin, so we would likely need to use either a cuprate (such as bismuth strontium calcium copper oxide, critical temperature 140k) crystalline, (such as yttrium barium copper oxide, critical temperature 120-250K) that would act as a superconductor on the surface of Pluto. Metal-based superconductors have too low a critical temperature to be useful on Pluto.

Another alternative is to use a casing with high magnetic permeability (this is when a material becomes highly magnetised due to the creation of a magnetic field. This draws the magnetic field up and around the magnetically permeable shielding, and this serves as a form of shield around the object. Metals with a high magnetic permeability include permalloy or mu-metal, both of which are iron-nickel alloy. However, the effectivity of these is increased when many layers are used, which successively reduces the strength of the magnetic field in each layer.

Apart from this passive shielding, active shielding can also be used, which is when another field is used to cancel out the one that would have had damaging effects in the first place.

The best form of magnetic shielding is a fully enclosed box around the protected instruments.

On our rover to Pluto, it is likely that we used a crystalline or cuprate insulation, as these materials have a greater critical temperature than the whole range of surface temperatures of Pluto. The use of passive shielding is not effective at high magnetic field strengths, meaning that it may limit the capacity of the rover in its task of searching for metals. In the actual rover, the shielding would be separated from the power source, which would be radioactive, as this could otherwise cause the shielding to become ineffective at higher temperatures. The radioactive power source would also have insulation so that it only heated the parts of the rover where heating was necessary and not the shielding materials.

7.5 Placement of the detector on the rover

There are three key options for the location of the metal detector on the rover:

7.5.1 Metal detector around the rover

Figure 7.6: Option 1 putting the metal detector in a ring around the outside of the rover

Advantages	**Disadvantages**
Coil is located outside of the central chassis of the rover, reducing the electrical noise interfering with detecting Increased radius of the coil increases the distance at which the detector can detect metals	Cannot go up hills without the detector hitting the ground, which makes all the advantages of the rocker-bogie suspension void Makes it difficult for the Kinect to map a wide enough area for the coil to pass through without colliding with obstacles Requirement for the coil to have structural rigidity increases the weight of the coil Increased current is required due to increased wastage of energy

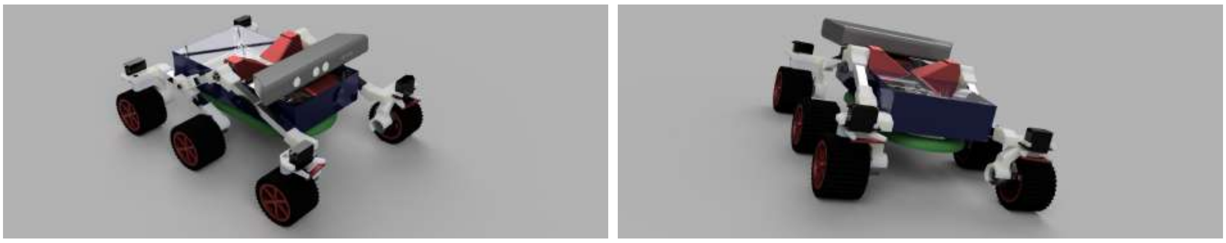


Figure 7.7: Option 2 putting the detector under the rover

7.5.2 Metal detector under the rover

Advantages	**Disadvantages**
Small and compact	Smaller radius so less penetration distance, meaning it has to be closer to the ground to successfully detect metals
Does not compromise any of the function of the rover	The metal chassis of the rover could interfere with the detector
Can be easily integrated onto the chassis after construction	
Requires less current to operate	

7.5.3 Metal detector at the back of the rover

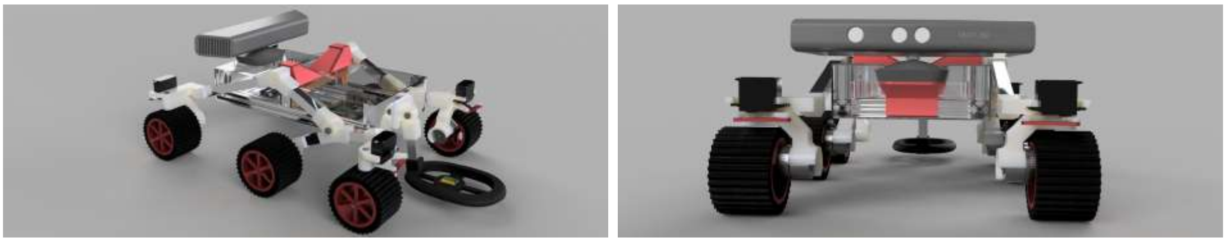


Figure 7.8: Option 3 putting the metal detector at the back of the rover, where it can be lifted up and dropped depending on whether the rover is travelling or detecting

Advantages	**Disadvantages**
Could introduce hinge to easily lift up / down	Would have a much smaller radius so would have a lower working range
Behind the rover so less electronic interference	Could easily snap off - with or without a hinge
	Would negate rocker-boogie suspension advantages over rough terrain as would make contact with the ground when in down position
	Would make the rover back-heavy (suspension originally designed for front-heavy weight distribution because of the Kinect)

7.5.4 Conclusion

The metal detector under the rover is definitely the best option for us. However, if the electronic interference from the rest of the rover was too severe, our fall back option is to locate the metal detector at the back of the rover.

8 Final Design

8.1 Design of the system as a whole

As a result of our research, we decided to use the rocker-bogie suspension design due to its simple construction and easy maintenance. This heavily influenced the overall design of a number of components, because their position in relation to the wheels was dictated. For example, we have to purchase and design mounts for motors that could be attached directly to the suspension arms rather than using drive shafts that are commonly found on modern automobiles.

The rocker-bogie design also means the suspension arms connect to the rest of the chassis at a single central brace. Therefore, the central brace was designed to be slightly off-centre from the centre of gravity of the chassis to account for the asymmetrical (front heavy) weight distribution of the Xbox Kinect, batteries and other electronics in the chassis. As a result, the overall moment acting on the brace, and therefore the force going through the right-hand suspension arm, is reduced, perhaps making the rover less likely to fail structurally.

Due to having the motors outside the main chassis, in which is located the battery and other electronic circuits, cable management became an issue. Although in the real design these would be run through the hollow suspension arms, we were unable to do this while ensuring structural rigidity. Therefore, we used cable ties to attach the wires to the suspension arms to make sure they were tidy and could not come loose. Care was taken to make sure the wires were never under excess load, for example, caused by the turning of the wheels.

When it came to the positioning of the Kinect in the rover chassis, there were a number of factors we considered. Due to the Kinect having a limited field of view, as mentioned in the research section, we had to make sure to maximise what view it had. Therefore, we raised the Kinect up out of the front of the chassis to ensure it had a clear view of the terrain that is directly in front of it. As we were still using the original Kinect case, we chose to use a dedicated aluminium bar and bracket to lift up the Kinect, using temporary fixings such as double-sided tape to attach the Kinect to the bracket. This allows easy access to both the Kinect and the inside of the chassis while getting rid of the need to interfere with the Kinect case.

As the rover featured a large amount of 3D printing, we made design choices to maximise the strength and quality of the parts. The strength of the 3D printed parts was maximised by designing the bolts to be perpendicular to the layers printed by the printer. Therefore, when the bolts were done up, the primarily splitting force being applied to the weakest axis of the plastic parts, along the layers, was reduced. Care was also taken to try and design a flat face into parts to print on. This gets rid of the need for supports in the printing supports which improves the print quality while also reducing the amount of plastic and time required for the print.

In order to make .stl files ready for 3D printing, the whole rover was designed on the CAD software Fusion 360. This program had the advantage of allowing renders to computed, tracking changing design over time. Some of these renders can be found in Appendix 7.

8.1.1 Tracks vs. Wheels

Tracks and wheels are both very viable methods for propelling the rover across the surface of Pluto however both have significant advantages and disadvantages

Wheels have been used on a lot of rovers that have come before such as Curiosity and the Apollo Moon buggies that the astronauts used during the Apollo missions of 1971 and 1972. They are very simple to design and manufacture as they are simply a cylinder of material that grips onto the ground. Using wheels also simplifies the steering processes as it is very simple to turn wheels enough to get a good turning circle, especially with four wheel steering. It is also easier to design a suspension system for wheels as each wheel can have its own suspension assembly. On the other hand, tracks have to have a much more complex system in order to ensure constant contact between the track and the ground. The wheels can also have individual motor control allowing for a higher top speed and six-wheel drive so that it is easier to traverse rougher terrain.

However, tracks do have some benefits as they have a higher surface area allowing for greater traction when traversing slippery ground. This may be highly relevant on the plains of frozen nitrogen that exist on Pluto. The tracks also exert a lesser pressure due to their larger surface area, but this may not be relevant as surface pressure is only relevant in the ground is a fluid or acts like a fluid.

Therefore, wheels would be much better suited to our rover as they are simpler and offer better reliability as the rover would be able to continue to operate even if one wheel stops working.

8.2 Design of the rover chassis

The primary influence of the design of the chassis was the aluminium monocoque that featured in many early Formula One cars (early 1970s) and is still found in many other vehicles today. The design utilises the strength of the aluminium panels of the rover to hold together and strengthen the aluminium frame inside the chassis. The large number of rivets connecting the side panels and the chassis frame ensures a strong connection and helps to increase the rigidity of the frame. This method also maximises the interior space of the rover, as less structural parts are required on the inside of the chassis, resulting in more space being available for the electronics.

This was a suitable design choice because it creates a lightweight but strong chassis, which is similar to those used on real celestial rovers such as Curiosity. The placement of these rivets so close together (19mm) simulates the approximate distance they would have to be when the rover is scaled up. The holes for these rivets were cut using the waterjet at Loughborough University to ensure accurate placement. This was important as adjacent panels sharing a common edge had the holes deliberately offset to ensure the rivets would not hit each other.

Figure 8.1: Fusion 360 render of the final rover design

In order to further increase the strength of the chassis, there are 11 aluminium bars that make up the sub-frame of the chassis which were attached together using 3D printed parts. The printed parts allowed the components to be effectively held together while the aluminium panels were being attached. However, their full functional strength was not utilised as the parts were not strong or accurate enough.

This resulted in cracks appearing through some joints when the aluminium panels were attached. For the real rover, this would be remedied, by changing the chassis design to more of a spaceframe chassis[54] which would attach the aluminium bars together using much stronger methods such as welding.

The lid of the rover was designed for easy access to the components inside the chassis. The cross brace was specifically designed with three points of contact on which the top panels could rest in the middle of the rover, while the other end of the panels could sit on the top of the corner pillars. This, combined with having the front and back panels raised so their top was flush with the top panel, allowed us to ensure the top panels could not move while not securing them directly to the rest of the frame. As a result, we could just use friction to hold the plates in place, making them very easy to remove for maintenance and access. We were planning on attaching magnets to each of the 4 corners of the top plate to ensure it would lift, but found that this was not necessary because the fit was accurate enough that the panels were held together by the pressure exerted on each other.

8.3 Design of the metal detector loop

As mentioned in the metal detector research section (Chapter 6), the depth to which a metal detector can detect is directly proportional to the radius of the detector. Therefore, the design of the metal detector loop focused on making the ring as large as possible, hence its large ovular shape and location underneath the rover's body.

After conducting tests with the new metal detector coil to work out the working range of the detector (mentioned in Chapter 12), we realised we needed to drop the coil closer to the ground so the detector had enough range to reliably detect metals on the floor. This was achieved by using 3D printed spacers to lower the coil towards the floor. This has the benefit of allowing the height of the detector to be easily changed during the testing process by changing the combination of spacers being used. For the real rover, perhaps lifting and dropping of the detector could be investigated to allow for a better balance between detecting precision and ground clearance.

Due to the large size of the coil, we chose to laser cut the base plate from 3mm plywood to create a rigid base for the coil. This made it easier to attach the whole coil to the bottom of the chassis, as there was no risk of the coil being floppy, and it utilised the precision of the CAM laser cutter to cut the part. The coil was wrapped in situ on the base plate around the 3D printed walls that were glued to the inside radius of the oval. In order to give a uniform and aesthetically pleasing finish to the coil, while still ensuring the wire would not fall out of place, we printed a shroud to hold the coil in place.

8.4 Design of the suspension assembly

8.4.1 Design of the wheels

There have been a number of wheel designs that were used on both Lunar and Mars rovers (Chapter 5.3.1). This includes those used on Curiosity which have individual tread patterns on each of the six wheels, which can be used to work out how far the rover has moved (as the number of revolutions of the wheel can be unreliable if on low-traction terrain). Due to Pluto having a harder surface compared to the sandy rock found on Mars, we used a very different wheel design. We, therefore, chose to use a track-like pattern. We evaluated that this would provide reasonable traction on the expected conditions on Pluto, however, further testing is required on model terrain to determine the optimum design. Furthermore, using continuous lateral track patterns made the wheels very easy to manufacture using a 3D printer when compared to 'knobbly' tyres used by many off-road vehicles on Earth.

We chose to chamfer the edges of the wheels to reduce high point-loads on the edges of the wheels. This reduces the chance that they may fail in extreme circumstances, which is important as the wheels are partially hollow and can, therefore, fill up with unwanted material. Even though we chamfered the wheels, we still ensured the width of the wheels was wide enough to sufficiently spread load to the ground, therefore, reducing the chance that the rover will sink into the surface it is driving on. This is particularly important as the terrain of Pluto is not known for definite, it's only estimated. As a result, contingency needs to be included in some areas such as the traction department, to ensure the rover will be able to move allowing it to subsequently detect for metals.

When it came to attaching the wheels to the motor shafts, we decided on a simple press-fit that utilised the flat on the motor shaft to stop it from spinning. After testing, we decided that the torque was low enough that friction was sufficient to stop the wheel being stripped. This meant that we did not need to implement our design for a grub screw on the flat of the motor shaft. Although this may not be too effective when screwed into the plastic, it acts as an example for the real rover, which will have metal wheels that are more resistant to wear and tear and are more suited to the temperatures found on the surface of Pluto.

8.4.2 Design of the steering system

Due to the wheels being very wide, it was important to reduce the turning force required to turn them as much as possible, so as to reduce the stress on the servo and other steering linkages. Therefore, we chose to place the pivot point of the wheels directly above the centre of the wheels, thereby requiring the minimum amount of force to turn the wheels as possible.

In order to simplify the steering system linkages, the centre of the servo pivot was placed parallel to the wheel pivot. As we needed the rover to be able to turn on the spot, the rest of the linkages were designed with large steering angles in mind, with the aim to be for every wheel to have the ability to turn 45°in each direction.

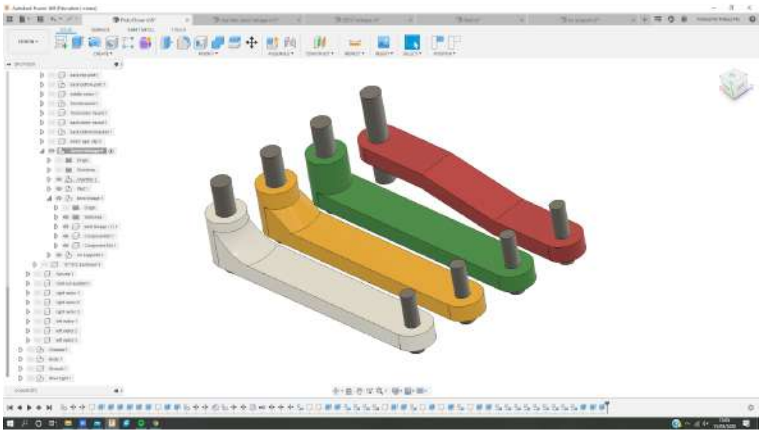


Figure 8.2: Different options for the servo linkages designed in Fusion 360

In order to work out the best design for the servo linkages, which joined the end of the servo horn the attachment on the wheel mount, we used Fusion 360 static stress testing. Detailed descriptions and results can be found in Appendix 6. The simulations calculate a numerical safety factor for each design, which represents the relative strength of each linkage when the same force is applied to the two holes. Therefore, we concluded that the yellow design (see Figure 8.2) was best as it had the greatest safety factor rating, meaning it was least likely to break under load.

8.4.3 Design of the motor mounts

When deciding how to attach the motors to the rest of the chassis, we decided there were two clear options: either use the mounting holes on the front of the motor to attach it to a plate, or to put the motor in a supporting outer structure. The first idea was difficult to implement because the screw holes would be difficult to access because the wheels were attached directly to the motor shaft. Additionally, we were limited to how thick we could make the front plate because we needed to make sure as much of the motor shaft was in the wheel to increase the amount of torque that could be applied to the joint before failure. This would, therefore, make it difficult to have a rigid and strong front plate, especially using 3D printed PETG (polyethylene terephthalate). We could avoid this problem by using machined aluminium for the real rover which has a much higher tensile strength than aluminium.

Therefore, we chose the second option, placing the motor in a 3D printed case to support the motor as this was the stronger option. As the output shaft of the gearbox was not directly at the centre, we printed the case to stop the motor from being able to turn. This meant we did not need to use the screws in the front of the motor to stop the motor spinning in its case, as this was being done automatically by the 3D printed bracket.

9 Design of the electronics

9.1 Electrical systems breakdown

Name	**What will the component do?**
Raspberry Pi	Odometry, autonomous navigation
Arduino Nano	Motor physical control, connects to H bridge, connects to metal detector circuit, connections to LEDs, connections to servos, interfaces with Pi via I2C
Metal detector circuit	Detects metal, with coil
DC-DC buck/boost circuits	Regulates battery voltage to usable 5V and 12V
H-bridges	Flip motor direction based on logic input
Battery (made up of 4x 18650 rechargeable) cells and protection/balance circuit	Power the rover

9.2 Schematic design

Once we had determined we needed a circuit, we had to determine the requirements for it. From the beginning these requirements were made assuming we would have the circuit manufactured as a PCB.

The core requirements were finalised as:

A	The circuit must be able to control rover motors, including independent control of the left and right motors, speed control, and direction control.
B	The circuit must be able to provide a steady 12v and 5v output to power the Kinect and Raspberry Pi respectively, stepped down from the 14-18v battery. It must also provide a stable power source for its logical components and the servos.
C	The circuit must be able to provide an interface between the onboard microcontroller and the Raspberry Pi.
D	The circuit must be able to control four servos independently and provide an output connector.
E	The circuit must be able to integrate all metal detection wiring from the prototyle, except for the inductor coil.

9.2.1 Motor Circuit: requirement A

For our motor circuit we require the ability to change the direction of the motors, and also require the ability to control motors on each side independently. To do this we will use two H-bridges; these are circuits allowing control of a DC motor in both directions with two control signals.

Two of four mosfets have a control signal applied to their gate, allowing flow of current from the

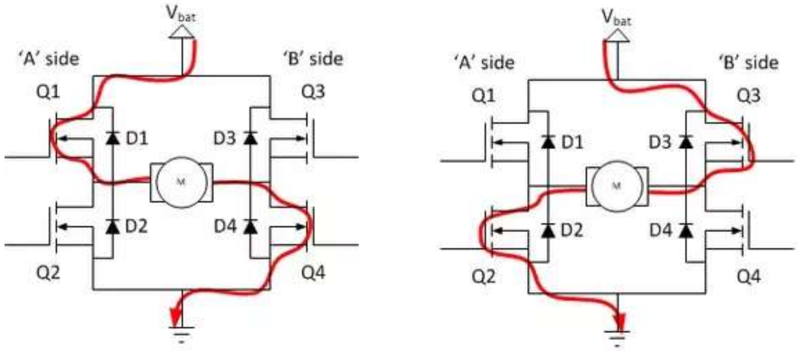


Figure 9.1: H-bridges for independent motor control

battery through the motor in one direction. If the direction is to be flipped the control signal is switched off to the initial two MOSFETs and applied to the other two MOSFETs. Current then flows through the motor in the opposite direction. The flyback diodes eliminate flyback, the sudden voltage spike across the inductor (motor) when the control signal is turned off and the current through the inductor changes.

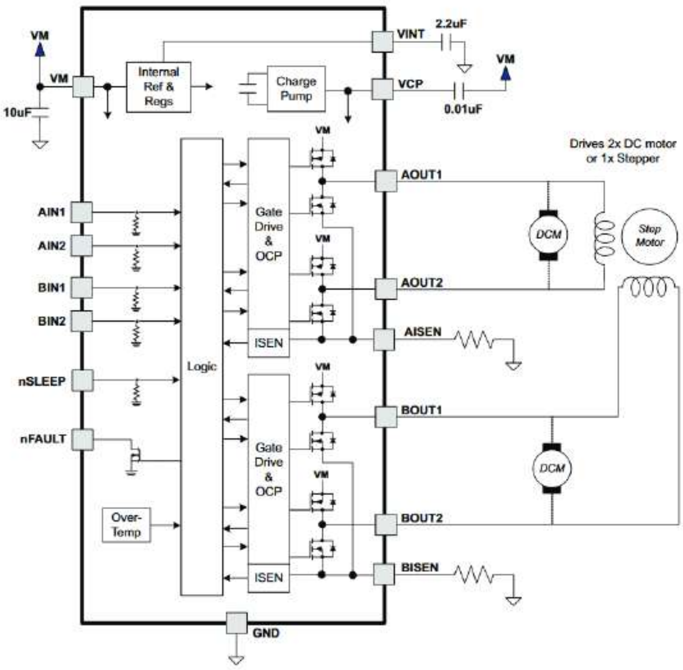


Figure 9.2: L293DNE chip

While we could make our own H bridge circuits many options are already available in practical IC form. One such option is the L293DNE which contains two full H bridges and also includes flyback diodes. This was the original IC used in design iteration 1 (SEE APPENDIX N), however after examining the datasheet we realised it would be unable to handle the initial rush of current required by the motors (up to 2A per set of three motors).

In the end we decided to use the DRV8876. This IC can handle 3.5A through its H-bridge - we will use two to drive our two sets of DC motors. The DRV8876[55] also features controllable current regulation - we will make use of the built in 'off time' regulation which is activated on an overcurrent event. This will prevent damage to the driver by overcurrent. This IC features two inputs, one PWM input for speed control and one logic input for direction.

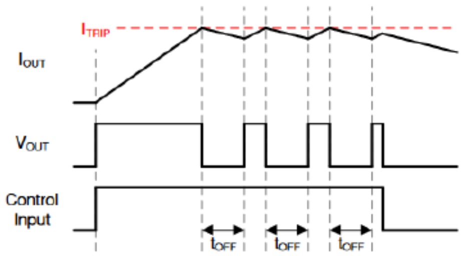


Figure 9.3: Output current regulation on the DRV8876 chip

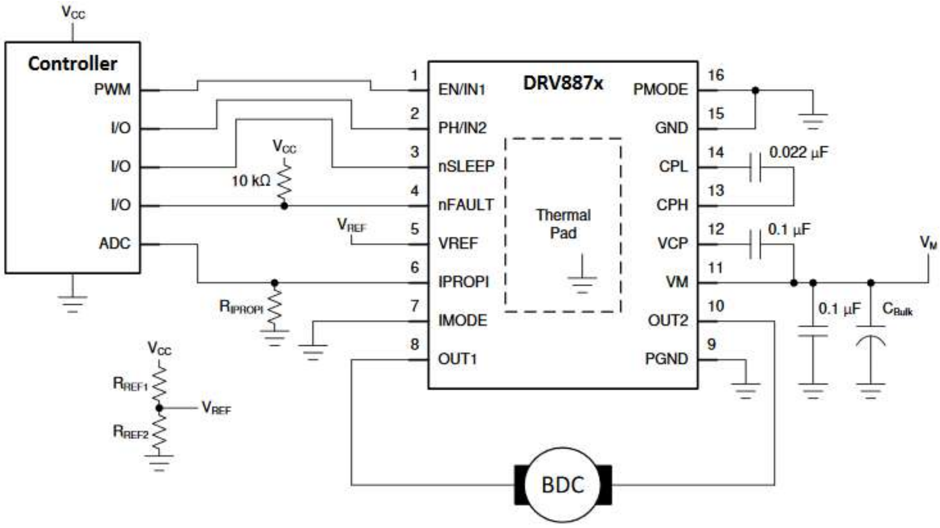


Figure 9.4: Example DRV8876 circuit

9.2.2 Power regulation: requirement B

The output voltage from the battery (4S) will vary between 16.8v and 14.4v depending on the change of each cell. We need to regulate this output to our two useful voltages, 12v (for the pi and motors) and 5v (for the logic). For both outputs we decided to use LM2596 buck regulators; this is a simple step down regulator that maintains a steady output for a wide range of input voltages. We also added an extra 5v voltage rail dedicated to powering the servos; this way noise on the logic 5v source is minimised.

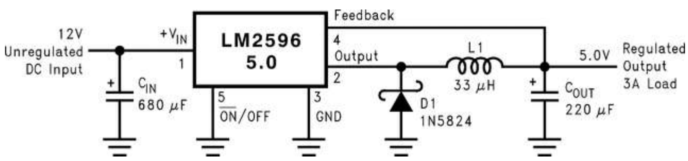


Figure 9.5: A typical application of the LM2596 (5V version)

We used the application information tables on the datasheet to choose C_{IN}, C_{OUT}, D_1 and L_1.

Component	12V and 5V
C_{IN}	UPW1V681MPD6
C_{OUT}	UPW1V331MPD6
D_1	MBRS330T3GOSTR-ND
L_1	PE-54040NL

On reflection the LM2596 was likely not the best choice as it is an old IC and has a large package. For this design simplicity took priority.

Additional things to note:

1. D1 must be placed close to the LM2596 as it requires very fast reverse recovery speeds.
2. The feedback line must be away from inductor flux.
3. CIN must be physically close to the LM2596 to smooth any input spikes.

More detailed information about picking components for DC step downs can be found in Appendix 4.

9.2.2.1 How buck converters work[56]

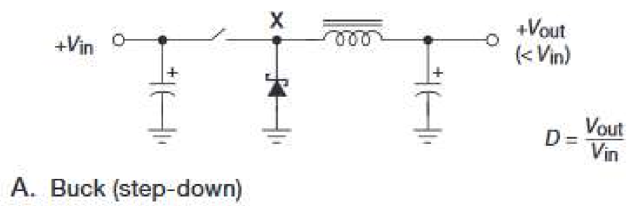


Figure 9.6: Buck converter schematic

Consider the circuit diagram above. When the switch is closed $V_{out} - V_{in}$ is applied across the inductor which causes a linearly increasing current ($\frac{dI}{dt} = \frac{V}{L}$); this current flows to the load and capacitor. When the switch is opened current continues to flow through the inductor (as inductors don't like to change the current through them quickly); the freewheeling (often schottky due to fast recovery times) diode is now in forward conduction to complete the circuit. The inductor now finds a fixed voltage ($V_{out} - V_{diode}$) across it so the current through the inductor starts to decrease at a constant rate. The output capacitor smooths the inevitable sawtooth ripple, see below.

In a real buck converter a feedback line from the output would control the pulse width.

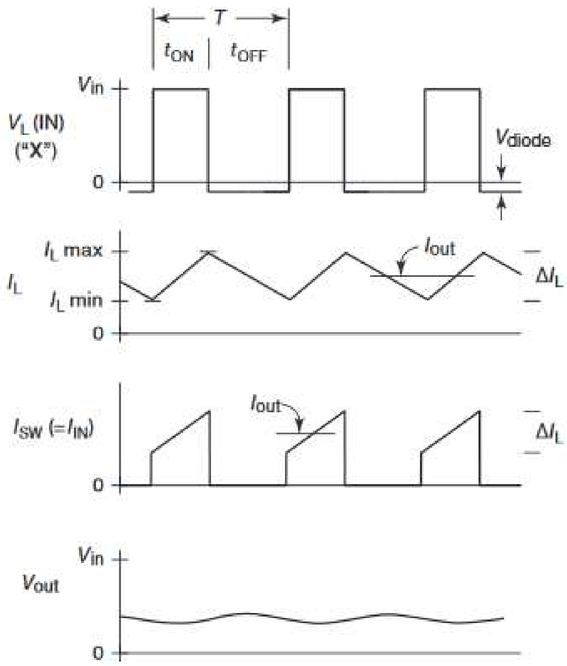


Figure 9.7: Signal smoothing by the output capacitor

The output voltage of this regulator is $(V_{out} - V_{in})t_{on} = V_{out} \times t_{off}$ as the average voltage across an inductor must be zero (otherwise its current is continually growing). This simplifies to $V_{out} = DV_{in}$ where D is the duty cycle ($D = \frac{t_{on}}{(t_{on}+t_{off})}$).

9.2.3 Servo control[57]

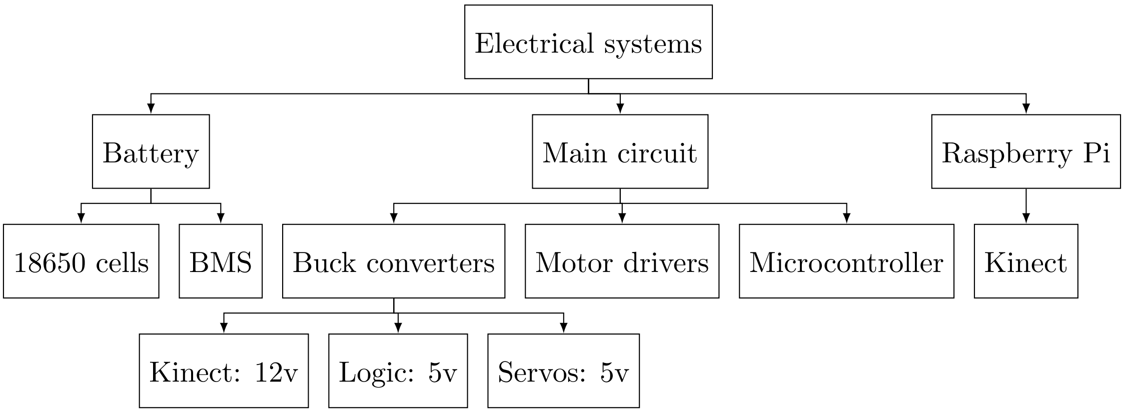
Servos contain small DC motors with a servo controller IC. Instead of simply spinning, they allow fine angle control based on their signal line. Typically servos accept a square wave signal at a set frequency: the pulse width of each pulse in this square wave determines the angle the servo controller will move the motor to. Usually a 1ms pulse width indicates -90°and a 2ms pulse indicates 90°. The fractions in between represent -90°to 90°.

9.2.4 Microcontroller: requirement C

Informed by our previous choices, the microcontroller must:

- Have 6 PWM outputs, four for servo control lines and two for the motor driver speed control.
- Have additional digital outputs.
- Have two ADCs for the metal detector.
- Have a small form factor for our limited size PCB.

We eventually chose the Arduino Nano microcontroller board (featuring the ATmega328p) for its availability and small form factor. Standard 2.54mm headers can be soldered onto the board which can then be soldered directly to a PCB.



9.3 Final electroncis design

9.3.1 Top down design diagram

Preceding the immediate design process was the developing of an accurate functional top down diagram. This allowed us to ensure that the full capability required of the rover is included in the designed circuit. Other larger flow charts can be found in Appendix 6.

9.3.2 Design of the circuitry

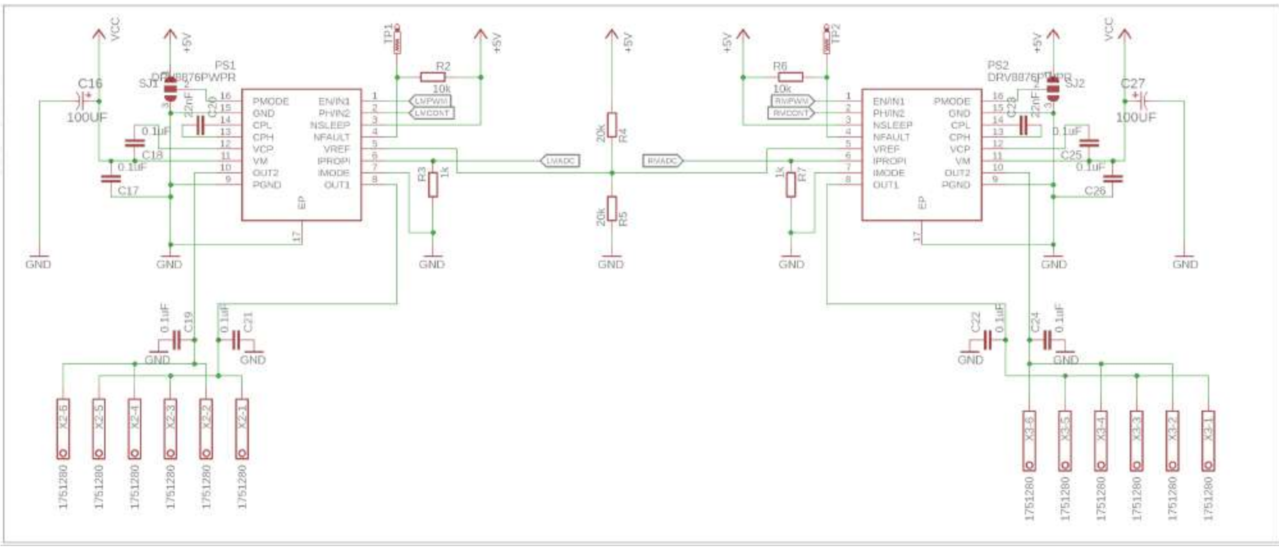


Figure 9.8: The motor driver schematics. It features two identical sections based on the DRV8876: both chips are permanently enabled and their mode of operation can be changed by soldering/desoldering the solder jumper. Both chips are referenced to Vref created by a simple voltage divider from the 5v regulated output from out power supply; this is used for various internal functions. The drivers each output to a terminal strip with space for three motors each.

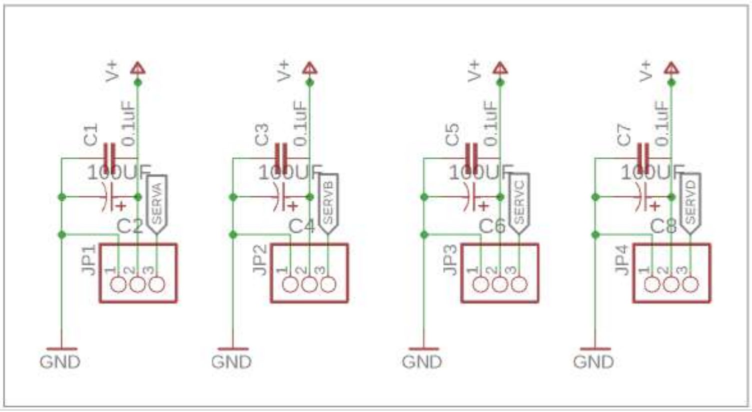


Figure 9.9: The servo outputs, these simply provide regulated 5v output to the servos with some local bulk and smoothing capacitors, along with a PWM data line direct from the microcontroller.

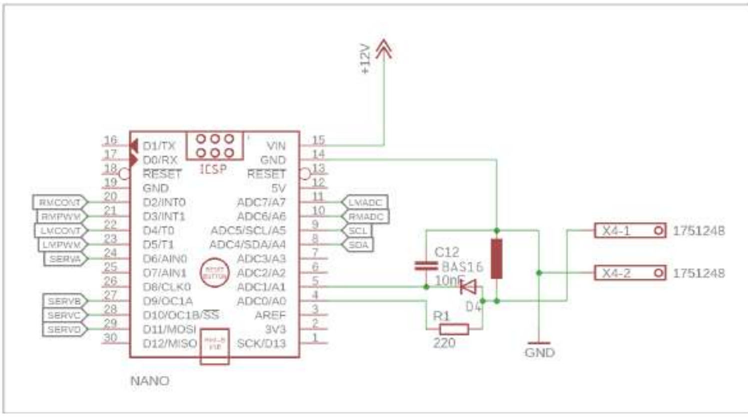


Figure 9.10: The microcontroller and metal detector schematic; the microcontroller is supplied by regulated 12v - its internal regulator steps this down to 5v. The metal detector circuit is as previously prototyped but the components have been miniaturized. The coil, represented here by an inductor symbol, is in reality connected through the terminals.

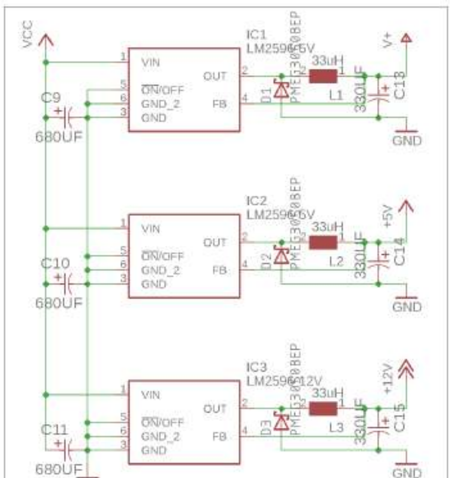


Figure 9.11: The buck power supplies. Each supply has a large bulk capacitor on its input and performs as described in how buck converters work.

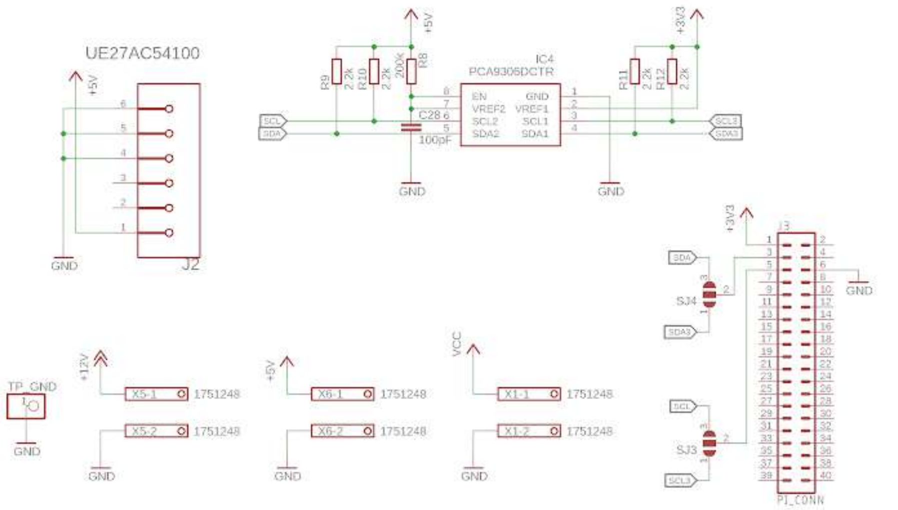


Figure 9.12: The physical output/input interfaces, including terminals for VIN, +5v and +12v. Also shown is the Pi power female USB port, the Pi GPIO connector and a GND test point for oscilloscope probes. The most complex part of this schematic segment is the PCA9306DCTR which is a logic level converter for the I2C line.

9.3.3 PCB layout

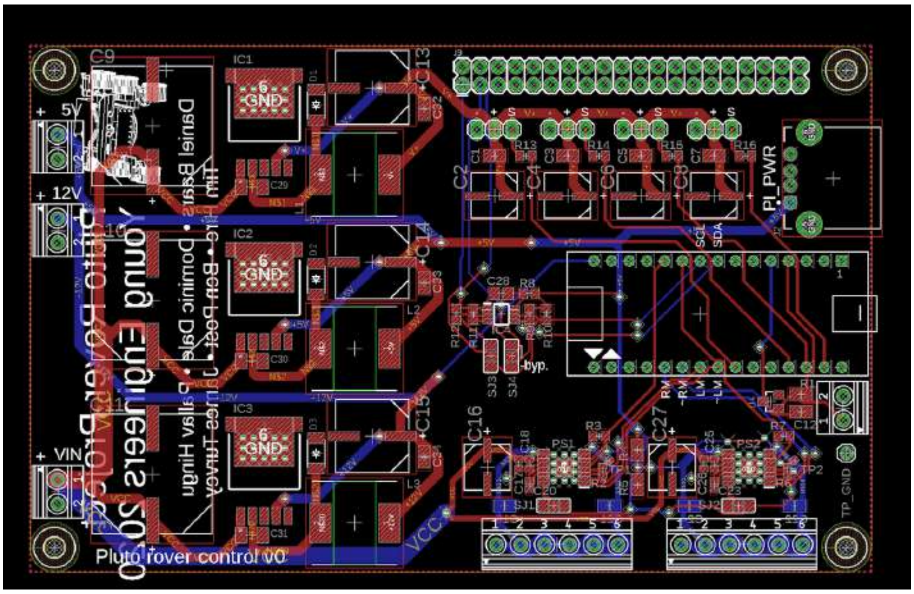
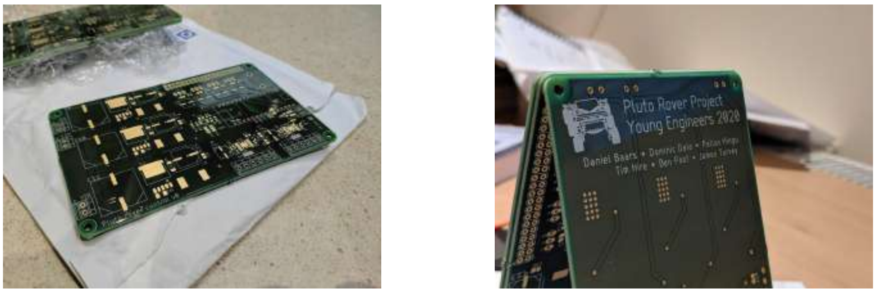


Figure 9.13: The final PCB layout. Red shows top traces, blue shows bottom traces. Both sides also included ground fills, excluded for clarity.

After the schematic had been designed we began to consider how the PCB should be laid out. Initially we had hoped the board would fit within the footprint of a Pi, but soon realised this was an unrealistic aim. We began by organising the power supply units on the left of the board, then moved on to the motor drivers. In the implementation of the motor drivers we found that a more compact package could be achieved by reducing the size of the capacitors and resistors down to '0402' (1mm × 0.5mm); this did make assembly more difficult. Working through the modules of the circuit we did occasionally have to move this around but eventually found a layout that had everything on it and was within our chassis size limitations. On feedback from an electrical engineer who specialises in power supplies, we rearranged the buck circuit to minimise the loop when the diode is in reverse conduction:

our original design can be found here.

When routing the board we used IPC-2221 standards to ensure the traces were thick enough to handle the current running through them. Both sides of the board have a ‘ground pour’; any space that is not filled with routed signals is connected to the ground of the circuit. This is useful for heat dissipation, and in the case of our buck ICs and motor drivers, multiple thermal vias are connected to this ground pour. It also means ground, a circuit many components are connected to, is accessible almost everywhere on the board.



(a) The manufactured board

(b) Thermal vias visible

Figure 9.14: Final manufactured PCB from aisler.net

9.4 Prototype power source

In order to imitate the RTG paired with lithium-ion (as concluded in 5.10.4), we decided to use a Battery Management System (BMS) in our prototype. This circuit allows for current input to the circuit in the form of a charging umbilical cord, which imitates the constant charge input from an RTG, while also allowing for current to flow to the load when required. This allows for the rover to continue to operate even as the battery is being charged, provided that the input from the charging source is greater than the load of all the components running off the battery. Likewise, if the load demands more than that provided by the charger, the cells of the battery are instead discharged.

This system also improves the lifespan of the lithium-ion cells we are using in the prototype as it ensures the cells are not overcharged, which could lead to a fire or explosion risk as the cells overheat. The circuit regulates the current and voltage inputs to the cell, thereby ensuring the battery is only ever charged to 4.2 Volts per cell. As our prototype has 4 cells, this means the whole battery is only every charged to a maximum of 16.8V.

The circuit we are using also contains other protection measures including:

- Over-discharge release detection voltage of 2.55 $\pm$ 0.08V which prevents the over-discharge of the cells which can lead to cell failure
- Overcurrent protection limit of 75 $\pm$ 5A after a 9 mS delay which prevents wires melting which could lead to fires
- Short circuit protection, with a 250 μS delay before the circuit is broken

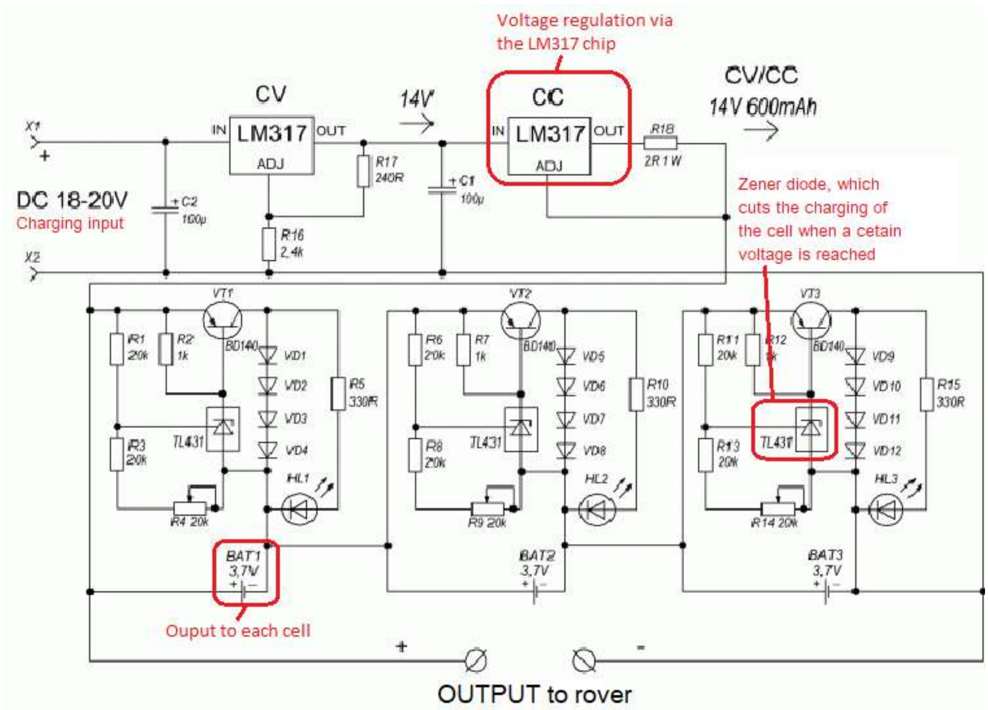


Figure 9.15: 3-cell BMS circuit with the key features marked

The main component on a BMS circuit is a Zener diode. A Zener diode only conducts electricity when a certain voltage is reached. This voltage can be adjusted by adjusting a variable resistor found on the circuit board. This mechanism is used to detect when the battery is completely charged, at which point the resistance of the Zener dramatically reduces reducing the amount of charge flowing into the battery, with the excess power lost through heat energy transfers in a resistor[58]. The output

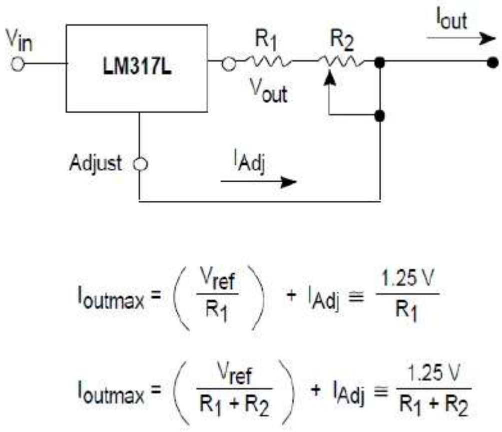


Figure 9.16: Example LM317 circuit

voltage to the load is then regulated using a linear voltage stabilizer, or a LM317 chip, to ensure the voltage stays reasonably constant despite changes to the potential difference of the battery and the charging input. The exact value of the voltage out depends on the size of the resistors in series with the LM317 chip. Out target potential difference from this BMS circuit is 14V, to allow for the voltage to subsequently be stepped down by the PCB to the required 12V and 5V outputs that power the motors, servos, Kinect and Raspberry Pi.

10 Construction

10.1 Chassis construction

10.1.1 3D printing

3D printing is an industrial process that is increasingly being used for the manufacture of products in industry because of advancements in cost efficiency and product quality. These advancements result in increased utility for producing plastic prototypes for many components. This is advantageous because it allows for the complex brackets required for the prototype design of the Pluto rover to be made quickly and relatively cheaply, while the inherent accuracy of the CAM process ensures the printed parts will fit as expected.

On the other hand, 3D printing does have some disadvantages, namely that printers that print anything other than plastic are very expensive, and are therefore not a viable option. The melting point of a printable material is usually between 200 and 260 degrees Celsius, meaning 3D printed parts are susceptible to failure if subjected to high temperatures. The larger issue is at low temperatures the plastic parts can become brittle. As a result, the plastic parts are purely to be used to construct the prototype, with the real parts being cast of machined out or a more suitable material (probably a metal). Additionally, due to the properties of the plastic the parts are liable to stress failure, especially if there are impurities in the printing process. Therefore, a post-print check of all parts is essential to ensure the parts are capable of fulfilling their required function.

10.1.1.1 Choosing 3D printer filament

Material	**Advantages**	**Disadvantages**
PLA (Polylactic acid)	- Cheap - High print quality at high speeds - Good for printing sharp corners	- Weak - Brittle
PETG (Polyethylene terephthalate)	- Smooth and glossy surface finish - Insignificant warping - Odourless while printing - Strong	- Hairs on the surface due to stringing - More expensive than other filaments
ABS (Acrylonitrile butadiene styrene)	- Strong - Very impact and wear resistant - Smooth final product - Don't need a part cooling fan	- Produces pungent smell, therefore, ventilation is required - Need an enclosure on the printer to maintain the high temperatures - High risk of warping

After considering the pros and cons listed in the table above, we chose to print our prototype using PETG filament to print the parts, because the material combines the easy-to-print properties of PLA while still creating strong ABS-like parts.

10.1.1.2 The 3D printing process

First of all, the parts need to be designed using CAD (Chapter 7). We used Autodesk Fusion 360 for this because it is a very powerful program which is free to students in educational institutions. The program allows collaborative working, helping to improve the efficiency of the design process. From

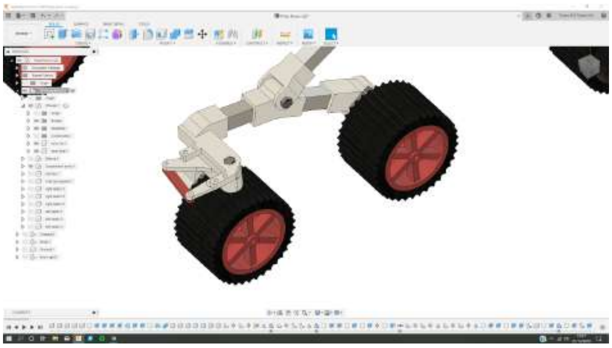


Figure 10.1: Fusion 360 CAD design tool

the CAD design, .stl files can be downloaded. This is the file type required by the slicing software which converts the design to something the 3D printer can understand. We used the Ultimaker Cura slicer because of the easy user interface and the fact that the printer settings are currently loaded into this software (as can be seen in Figure 10.2). The slicer also allowed us to change the infill of the final product (how solid/hollow the final product is) and add things such as supports (seen in light blue in Figure 10.2) to make sure the final print was the highest possible quality.

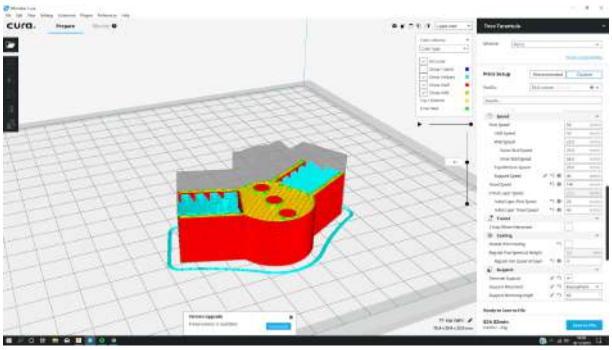


Figure 10.2: Ultimaker Cura 3D printer slicing software

The code outputted by the slicing software was then ready to be run on the printer. In the case of the printer used, this was via an online server called Octoprint which ran on a Raspberry Pi (Interface seen in Figure 10.3). This allowed for remote monitoring and control of the printer, in case something was to go wrong or there was a potential safety concern regarding the print. The printer being used primarily can be seen in Figure 10.4 (a). The printer uses the Prusa i3-style system that moves the bed forwards and backwards instead of raising the bed up and down in the Z direction (as is found in the more traditional core XY-style printers). The printer still works by extruding the plastic from the filament to form subsequent layers that add up to form a finished product. This progression can be seen in Figure 10.4 (b), which is midway through a print, allowing the design of the inside of the part to be seen.

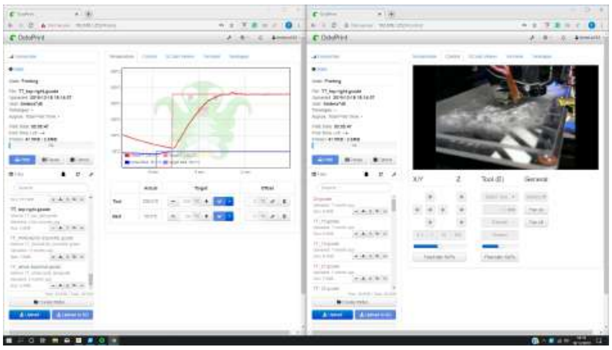
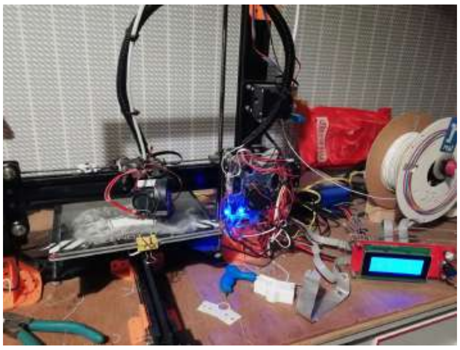


Figure 10.3: Remote 3D printer control server Octoprint, used for safety



(a) The FDM printer on which the majority of parts were made

(b) A mid-print view of how the FDM-style printer constructs parts

Figure 10.4: The printer used primarily for the printing of parts was a Tevo Tarantula, although further printing took place on a more conventional core-XY printer

10.1.1.3 Finishing of 3D printed parts

In order to ensure the parts had not been printed with defects that could compromise their strength and integrity, the parts were studied, primarily to look for layers that may not have bonded together. Should cracks be found, the part will either be reprinted or repaired using super glue depending on the severity of the defect. During the construction process, we did not have to reprint any parts due to poor layer bonding.

10.1.2 General assembly

10.1.2.1 Suspension arms of the rover

The construction process of the rover began with the 3D printing of the first of the suspension arm parts. As the 3D printed parts needed to be printed with supports, the first job in the construction process was to remove the supports and make sure the metal fitted easily into the plastic casing. This is important to reduce the stress being applied to the plastic components, to minimise the risk that the plastic will fracture when increased stress is applied. This was achieved by using metal needle files. The amount that needed to be filed from the inside of the plastic parts was reduced throughout the construction process as we refined the printing tolerances on the design files.

We then drilled through the holes designed into the 3D printed parts. In order to ensure accuracy, we use a pillar drill to ensure the drilled hole was completely vertical. This also has the benefit of reducing excess stress applied to the plastic parts during the drilling process, maximising the long-term strength of the parts. These were then bolted together as can be seen in Figure 10.5.

Figure 10.5: Drilling and bolting the plastic parts and aluminium bars together

Figure 10.6: Construction of rear suspension pivots

Part of the process of constructing the suspension arms was to make the hinge fulcrum for the rear part of the rocker-bogie suspension, as seen in Figure 10.6. The priorities when making this was to minimise the side-to-side movement in the assembly to ensure structural rigidity, a factor that becomes increasingly important when a force is being applied by the wheels when under motion. However, we also had to ensure the lateral force was not so great as to cause excess stress to the assembly, especially when the weight of the rover's chassis is applied to the hinge. We achieved satisfactory turning force by using washers that not only acted as spaces but also helped to reduce friction in the hinge system.

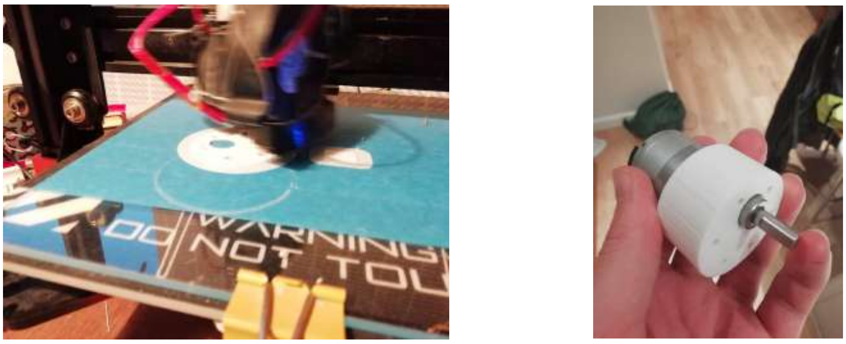
Figure 10.7: Temporary assembly of the suspension arms

During the construction process, there were parts that cracked and, on two occasions, complete failure of the 3D printed parts. In the case of cracks, super glue was used to reinforce the cracks. However, due to the design of the bolt holes being perpendicular to the 3D printer layers (where cracks are likely to be found) the cracks were not likely to grow once fixed in place.

The final finishes to the suspension arms took place at the Loughborough workshops, to take advantage of their tapping tools as seen in Figure 10.8. Tapping the 3D printed part provides sufficient strength to hold the hinge together while mimicking the ability to tap the hinge material as we would use on the machined aluminium hinge on the final rover.

Part of making the suspension arms included making the motor brackets. As the design relied on a

Figure 10.8: Tapping of the plastic hinge to imitate the final machined aluminium part



(a) Motor brackets at the start of their print *(b) Prototype of the motor casing*

Figure 10.9: Production of the motor mounts

tight fit between the motor bracket and the motor casing, a prototype case was printed to test the tolerance needed to allow an accurate fit. It also tested whether the holes for the front of the motor were accurate.Therefore there was confidence that the motor brackets that were printed would fit the motors, as seen in Figure 10.9. These were then attached to the rest of the suspension arm assembly, as seen in Figure 10.10.

Figure 10.10: Attaching the motor mounts to the rest of the suspension assembly

10.1.2.2 Chassis construction

The construction of the chassis took place in its entirety during the two-day workshop at Loughborough University. One highlight, and the most useful part of the workshop, was the CNC (computer numerical control) waterjet cutter that we used to cut the aluminium body panels of the rover as seen in Figure 10.11 and 10.12. This saved a lot of time because it allowed the 100+ rivet holes to be predrilled, saving us both marking and drilling time as well as ensuring high degrees of precision.

the designs were first exported from Fusion 360 as .dxf files, before using Autodesk AutoCAD to ensure that the 2D designs had exported correctly. The technician at Loughborough then inputted these .dxf files into the waterjet software allowing a tool path to be programmed. The parts were cut one at a time to reduce the amount of aluminium that would be wasted if something went wrong.

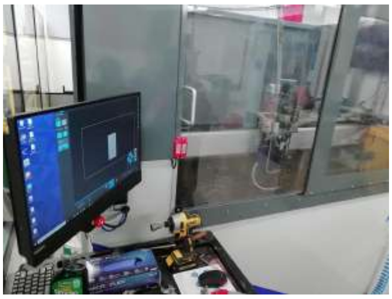


Figure 10.11: Waterjet cutter in action

Figure 10.12: The cutting takes place with the part submerged to minimise excess spray

The highly accurate parts were very useful to help with the mocking up of the chassis parts, as for example the base plate could used, as a template for making sure the aluminium bars were located in the correct positions.

Figure 10.13: Completed aluminum sheet and bar parts ready to be assembled

Figure 10.14: Chassis frame dry-fitted to the cut base plate

This relied on the aluminium bars being both square and accurately cut. To ensure this a metal band saw was used to cut the bars to roughly the correct length, before using an Engineer's Square and a scribe to carefully file the bars so they were within tolerance both in terms of their length and how square their ends were. This can be seen in Figure 10.15.

With the help of the interior 3D printed parts and the waterjet base plate acting as jigs, it was possible to clamp all of the parts into their correct position before the final cuts were made, to ensure that there were no unfortunate errors. Once the base plate was riveted to the aluminium structure, the side panels were attached individually, using the 3D printed parts to hold the 4 corner struts at the right height. The drilling and riveting can be seen in Figures 10.16 and 10.17.

Figure 10.15: Filing of aluminium bars

Usefully, the Loughborough workshop has a pneumatic rivet gun operated by the integrated compressed air pipes running around the workshop, which dramatically reduced the time it took to rivet all the side panes to the rest of the chassis.

Figure 10.16: Drilling of holes through those cut by the waterjet, using cleco pins to keep everything temporarily in place

Figure 10.17: Hand riveting the base plate

The pneumatic rivet gun was only utilised after a majority of the rivets were installed however. It would have been much more time and energy efficient to ensure we had the best tool before starting the process but miscommunication with the technicians prevented this

Figure 10.18: Constructing the central brace

Figure 10.19: Using the top plate to locate the central brace in the chassis

With the side panels riveted onto the chassis, fixing the aluminium pieces in place, the top panels were dry fit to the central chassis brace that connects to the two completed suspension arms. The holes in the top panels allowed for the marking out of where the central brace would go. The riveting process then had to be repeated to connect the brace to the rest of the chassis, securing it in place. The construction of the brace proved to be very time consuming, as the two aluminium pillars had to be perfectly vertical to ensure that when the suspension arms were attached, they would not be at an

Figure 10.20: First dry-fit of the suspension arms to the chassis

Figure 10.21: Construction output of the rover from the Loughborough workshop

angle.

At the conclusion of the Loughborough workshop the chassis was almost completely finished and the suspension arms were attached to the chassis, as seen in Figures 10.20 and 10.21.

Figure 10.22: Attaching the servo to the suspension arms and wheels

Returning to school the only thing remaining on the chassis construction schedule was the installation of the servos onto the suspension arms, and the connection of the metal detector and other electronics to the chassis. After a small amount of sanding to allow the servos to fit into their designed space, the servos bolted easily into the chassis. After printing the servo arm to connect the servo horn to the motor mount, it was found that the centre point of the servo perfectly lined up with the wheels being straight. This was a success as there was a risk that the connection linkage would be slightly too long or short for the limited servo adjustment to be able to cope with.

10.2 Metal detector construction

10.2.1 Construcing the prototype circuit at Loughborough

During the two days at Loughborough, the facilities of the electronics labs at the University were utilised to construct a working prototype of the metal detector. The aim was to make a circuit which would meet the expectations set out by the requirements.

The prototype featured a reduced coil diameter as seen in Figure 10.23, therefore, reducing the range of the detector. As a result, increasing the diameter of the coil was the main change proposed for the final detector, as it would increase the range of the detector.

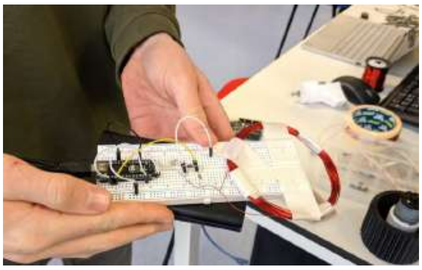


Figure 10.23: Prototype detector circuit feature a smaller coil and all components on a temporary breadboard

10.2.2 Constructing the final coil

The first step after designing the metal detector coil shroud using AutoCAD 2020 was to laser cut the base plate for the coil, producing a rigid structure which the wire could be coiled around.The inside barriers were then onto the plywood. During the gluing process between the PETG and the plywood, the adhesion was strong, allowing a reasonable amount of tension on the wire without causing failure, making the coiling process easier.

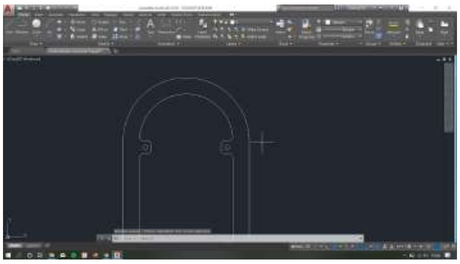


Figure 10.24: Using AutoCAD 2020 to create a .dxf file ready for laser cutting the plywood base of the coil

During the winding process, care was taken to make sure the wire did not fall out of the groove it was being wound on, otherwise the winding would fail and have to be attempted again. Therefore, to temporarily secure the wire in place during the construction process, masking tape held the wire in place while still being easy to remove later. A number of different methods to hold the wire in place permanently were considered, including glue (probably hot glue) or electricians tape. However, it was decided a more finished cover that would be 3D printed was the most suitable. This would create a neater and more resilient cover which would also not interfere with the detection process.

The 3D printed covers were attached to the plywood base plate with superglue as this had very strong adhesion between the two surfaces. Care was taken to make sure not to get any superglue anywhere it was not wanted as it could be an issue if it bonded to skin. In order to improve the aesthetics of the ring, the entire cover was spray painted black. While spray painting, extraction and used a face mark were used to prevent excess spray paint being inhaled.

10.3 Electronics planning and mounting

In order to ensure the required electronics would fit inside the chassis, we made a scale lay-plan of the inside of the rover chassis to see where each component would be situated. This allowed us to make the most of the space, so we could plan to utilise the verticle height of the chassis as well as the floor of the chassis. Furthermore, the planning process allowed us to estimate where the central brace should be located in the chassis using estimations of the moment of certain major (in terms of weight) components, such as the batteries and the Kinect as seen in Figure 10.25.

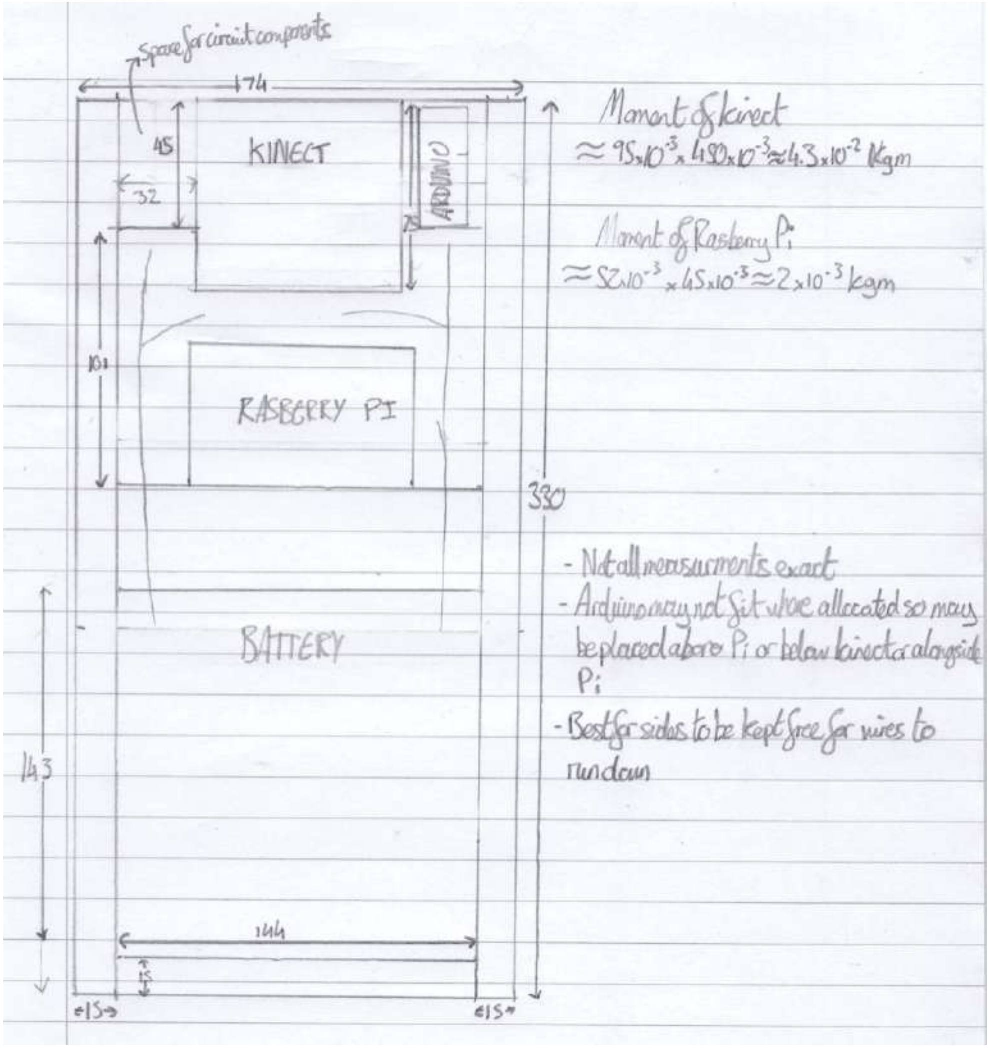


Figure 10.25: 2D lay-plan of the electronics in the chassis including some moment calculations

10.3.0.1 Making the electronics mount

When initially placing the electrical components in the chassis, we realised we had not taken into account the offset motor and servo positions in our moment calculations. Therefore, in order to minimise the resultant moment present in the rover, we decided to package the Raspberry Pi, PCB and battery in the back of the chassis.

In order to fit this in, we designed an acrylic mounting bracket to hold the PCB and Raspberry Pi. This was mounted on top of the purposefully long metal detector bolts using captive nuts. We used paper templates of the back of the rover to create a compact design which still allowed access to the wire ports in the PCB and did not prevent the wire ribbon from being able to join the two boards together.

We laser cut the acrylic for maximum accuracy, convenience and speed. As we had carefully measured the positions of all the mounting holes, the acrylic allowed for immediate mounting of the boards. However, we later had to adjust the mount to avoid the inner 3D printed structure as we had not given this enough tolerance. We also had to increase the size of the cutout at the back of the plate to allow for the charging input lead to have increased clearance.

The boards were mounted onto the acrylic using nylon standoffs, as nylon is not conductive. This reduces the chance of short circuits. The standoffs for the different boards were designed to be of

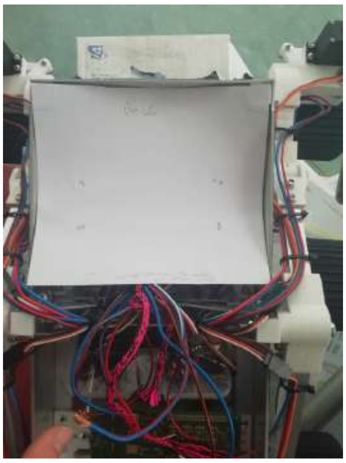


Figure 10.26: Making a template of the back area of the rover to aid the designing process

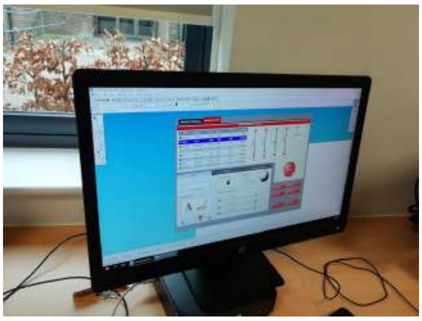


Figure 10.27: Laser cutter setup

different heights to allow for cable, mainly the Raspberry Pi power cable, to pass underneath the PCB as can be seen in Figure 10.28.

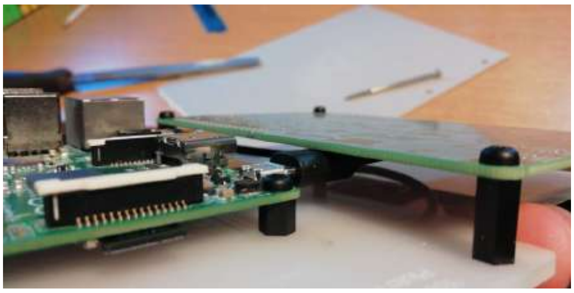


Figure 10.28: Testing the standoff heights of each of the boards, so the Pi power cable can pass under the PCB

As a result of tight packaging, all the electrical components were able to be fitted into the back half of the rover, leaving the rest of the front of the rover (which was not taken up by the Kinect) free. This could perhaps be used on the real Pluto rover to contain the RHU power generator, as this is the major component which is currently missing from our prototype. This space could also be redistributed around the rest of the chassis for insulation, which is necessary for a rover on Pluto. However, we have not included this in our prototype for risk of overheating while operating on the warmer Earth.

10.4 Electronics soldering

10.4.1 Soldering the PCB

The school soldering irons just would not do for soldering the finer pitched components found on the printed circuit board, so instead we used an adjustable temperature soldering iron which could reach temperatures upwards of 450°C and a hot air rework station.

There are two main technologies used when soldering circuit boards, through hole technology (THT) and surface mount technology (SMT). Through hole mounting is typically used on larger devices and can be identified by their long leads. They connect to the circuit board through a via (a plated hole through the board that conducts between the layers) and are soldered in place. Through hole technology is ideal where devices may undergo mechanical stresses such as a port when a device is being plugged in or pulled out.

For our circuit, keeping the size minimal was important so we opted to use surface mount technology for most of our components. Surface mount (SMD) components are soldered to a pad on the surface of the circuit board, not a hole that goes through it. One key advantage of using SMD components is that because there is no lead, they can be smaller and take up less space on the side of the board which they are located. This leads to package sizes less than a millimetre in length. Furthermore, as SMD components do not require a hole in the board, they only take up space on one side of the board; to create a connection through the board much smaller vias are used.

The main reason for SMTs growth was the ability for circuit boards to be fully assembled by machines. Once circuit boards are produced, solder paste, essentially beads of solder in a flux, is applied to all the pads where electrical connections are to be made. This is done with a stencil that has cutouts over pads. The board, now with paste applied, is then placed in a Pick and Place (PNP) machine where components fed from reels of tape are placed on the board. A camera uses reference designators along with the board layout to locate the correct pads for each part it picks. Once all of the parts are in the correct place the board is placed in a reflow oven where it is heated to a critical temperature at which the solder paste melts and bonds each terminal to its relevant pad. Flux in the solder paste prevents oxidation occurring and soldermask on the board means the solder only adheres to the exposed pads, leading to highly reliable electrical connections at extremely fine tolerances (e.g. ¡0.1mm).

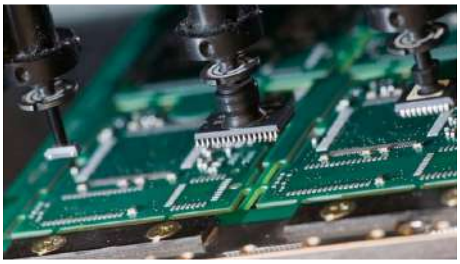
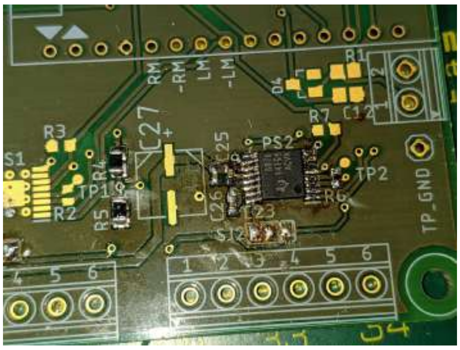


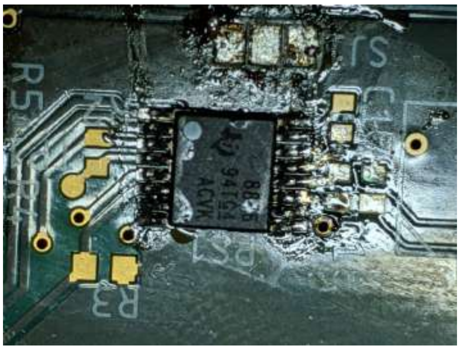
Figure 10.29: A board with solder paste applied and components being placed by a PNP machine

We did not have access to a PNP machine so instead had to hand solder the PCB. The components we picked were just about solderable without a microscope, though some magnification with use of a phone camera was employed. We started by soldering the finest pitched components, the motor drivers. First, we used a flux pen to ensure the metal pads would not oxidise during the soldering process. The motor driver presented an interesting challenge in that it had a non-visible pad on the bottom for heat dissipation; this pad is electrically connected to the ground plane. We applied some solder paste manually to this pad and flooded the board with a low heat before applying a concentrated stream of much hotter air at the driver. Soon the pad reflowed and we could move onto soldering the terminals.

At first we attempted to do this with a soldering iron by creating a small 'well' of solder on the tip of the iron and dragging it across the fluxed terminals. This did work but we soon found we had more success by manually applying solder paste to the terminals and heating them until they reflowed: as the paste was not applied by a stencil we had to experiment with volume and in some cases went back with solder wick to remove excess solder.



*(a) A fully soldered motor driver module. The smaller capacitors and resistors visible are '0402' or measure 1mm*0.5mm. The motor driver IC package has a pitch of 0.65mm*



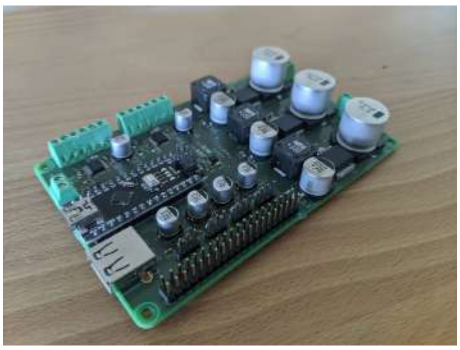
(b) A close-up of the motor driver

Figure 10.30

A similar process was executed to solder the power supplies which also have a large heat dissipation pad on the back. We first applied solder paste, ensured the pad was electrically connected then moved on to soldering the terminals.

Most of the other components went on the board with ease. The electrolytic capacitors (large cylinders) and inductors (black blocks) posed some issues due to their concealed terminals but with some hot air to ensure the hidden solder had reflowed followed by testing with a multimeter we were able to confirm they were correctly connected. Small resistors, ceramic capacitors and diodes were placed with tweezers, fixed in place by soldering one terminal, then adjusted and fully electrically connected. There were also some THT components to go on, notably the servo connectors and USB port which we chose to use THT for as they are under mechanical stress. After assembly we used 99.99% alcohol to clean off flux residue which, if left, can cause oxidation over time.

(a) The LM2596s. The far ICs are already fixed to the board by their hidden heat dissipation pads. The front IC is upside down showing this pad



(b) Finished circuit board

Figure 10.31

10.4.2 Unit testing the electronics

Testing was part of the electrical manufacturing process, with unit tests occurring throughout. Once the motor driver was soldered, we ensured it was functional by manually applying regulated 5v to its drive pin. On the first try this was not the case but after ensuring all of the terminals were electrically connected by applying a second heat with hot air, the driver worked perfectly. We also conducted unit tests on a single regulated power supply before continuing to solder the remaining supplies.

Figure 10.32: Probing the 5V output of the servo power supply. A stable DC 5v is visible on the oscilloscope

The functionality of the LM2596 can be understood better by probing the switching node, at which damped oscillations are visible as the ICs switches between forward conduction and reverse conduction to maintain a steady average voltage at the output. This is explained further in Section 8.2.2.1.

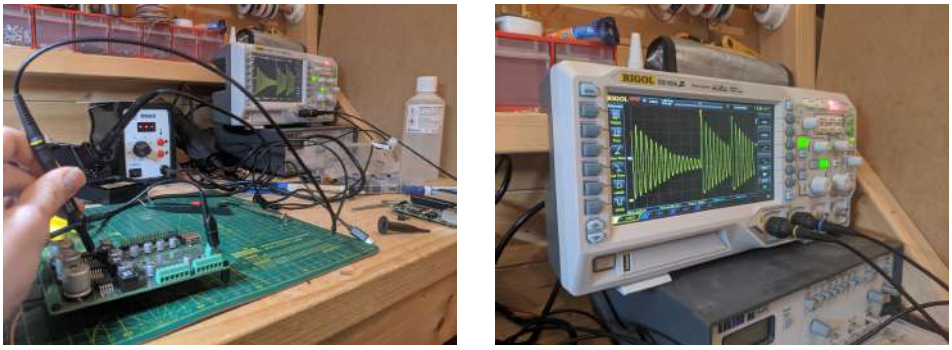
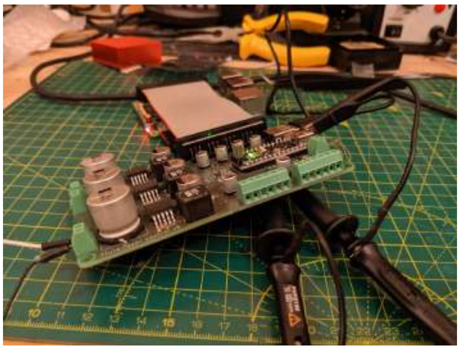


Figure 10.33: Probing the switching node of a LM2596. Damped oscillation visible

Finally, once the I2C level shifter circuit had been soldered we performed a unit test on it. We connected our PCB to the Raspberry Pi via GPIO pins and attempted to send data down the I2C line. Fortunately this worked the first time, and the Raspberry Pi's 3.3v signals were correctly being shifted to 5v signals for the Raspberry Pi.



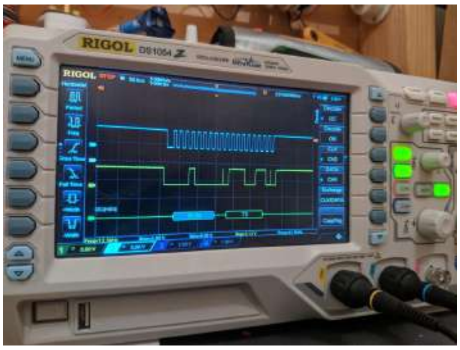


Figure 10.34: Probing the I2C line, 2 bytes of data being transmitted visible. Clock line above, data line below

Once the circuit was fully assembled we performed multiple integration tests, also ensuring the metal detector circuit was functional.

10.4.2.1 Soldering the motors and wire routing

One of the key stages of construction was connecting all of the motors and servos to the PCB. This was done through soldering positive and negative wires to the terminals on the motors and then routing them up the legs of the suspension and into the chassis for connection at a later date. This was a challenging process as there were 12 connections which needed to be made. Each connection required a different length of wire with two different colours to allow us to differentiate between the positive and negative connections.

First we modelled the connection using a wire to ascertain the length of wire needed to make the connection with some added length to account for errors. Then we tinned the end of each wire (made it into one homogenous wire using solder to connect the copper strands)(seen in Figure 10.29) and pushed them through the holes in the connectors on the motor if possible as it provided the highest chance of a successful and strong connection. If this was not possible we lay it across the face of the metal and used solder to hold it in place until more solder was applied to firmly connect it (Figure 10.30). We ensured that there was enough solder for a strong and complete connection and that all copper strands were connected. Finally, we covered the connection in heat shrink (Figure 10.31) for insulation and an additional level of support.

Figure 10.35: Tinning the ends of the stripped wires to prepare for soldering

Figure 10.36: Soldering the tinned wires onto the motor terminals

After that process was complete, being very careful not to damage the plastic supports with the soldering irons as it is a thermosoftening plastic, we then worked on routing each of the wires. They were laid against the suspension struts and attached using cable ties at strategic points to keep them neat and away from the suspension hinges as seen in Figure 10.32. The wires were then routed through the cross beam and down to the correct side of the chassis where the PCB would be mounted. It was done this way as the cross beam provides a convenient routing path and the wires could be differentiated into left and right very easily.

Figure 10.37: Shrink wrapping over the solder joint to the motor terminal, creating an insulating layer over the joint

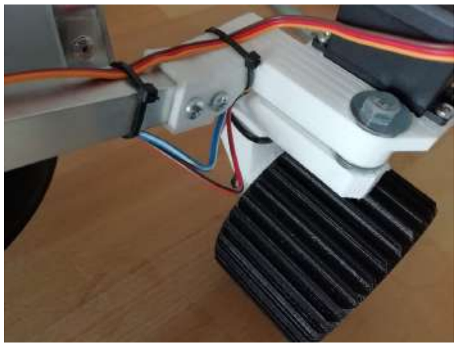


Figure 10.38: Using zip ties to attach the motor and servo cables to the frame, with care being taken to ensure there is no risk of the wires being stretched or compressed

The most challenging part of the process was working with the school soldering irons as they proved to be very underpowered and would only melt the solder if the correct side of the tip of the iron was in direct contact with it. This was annoying as it meant we had to work at awkward angles due to the fittings around the motors. This was also an issue as the solder would solidify very quickly after the heat was removed, so much of the solder had to be melted multiple times.

The heat shrink also proved tricky for some connections when the wire was attached perpendicular to the metal contact on the motor, as the wrap was not able to bend around the tight radius. Therefore, it failed to serve the purpose of completely insulating the solder joint in all connections. However, overall, this process was very successful and we are satisfied with the result as the majority of wire connections are insulated.

10.5 Systems integration

In order to increase efficiency and productivity in the construction of the rover, especially to utilise the limited time we spent at the workshops at Loughborough University, we chose to split the rover into four separate systems: the chassis, the moving electronics (motors and servos), the metal detector and the Kinect (for 3D mapping of nearby terrain). A plan for systems integration, therefore, needs to be made to marry each to the systems together to form the final prototype.

Systems integration process 1: Moving parts with chassis

Tasks:

1. Attach all physical components on the chassis (motors and servos) to ensure they have the ability to operate as designed
2. Place the Arduino in the desired location and connect all wires to the components. Manage cables using cable ties around the suspension arms
3. Calibrate servos and motors to make sure they have the correct degree of freedom and/or operate at the desired speed
4. Test the rover to make sure it is able to be controlled from the remote as required for demonstration purposes

Risks or potential problems with the integration:

- Cables will not be long enough, causing compression or stretching of the cable as the suspension components move

Systems integration process 2: Metal detector with moving parts and chassis

Tasks:

1. Attach the metal detector to the metal detector coil holder.
2. Wire the metal detector to the Arduino terminals.

Risks or potential problems with the integration:

- Made sure when holes are drilled in the underside of the rover, they do not cut any wires or damage any electronics
- Need to make sure the coil is not too far away from the ground so it cannot reliably detect metal. Could be improved by lowering the coil further towards the ground, increasing the diameter of the coil, increasing the current being applied to the coil or only detecting raised metals
- Need to calibrate the detector to make sure there is no interference with the aluminium chassis

Systems integration process 3: Kinect with metal detector and moving parts and chassis

Tasks:

1. Attach the Kinect to the stand at the front of the chassis
2. Mount the Raspberry Pi to the desired location in the chassis
3. Connect the Kinect to the battery, to ensure it receives the 12V power supply it needs to operate
4. Carry out testing of the Kinect at the speed the rover prototype will travel for demonstration purposes, to make sure the position of the Kinect on the rover is correct

Risks or potential problems with the integration:

- Kinect wire may be too long to be able to fit in the chassis along with the other components, so we may need to shorten the cable
- Make sure there is enough clearance between the Kinect and the right suspension arm when going over obstacles (as the left arm is fixed it will not be a problem). If required, the Kinect can be raised further out of the chassis.
- Re-calibrate the metal detector to make sure that there are not any problems with other electronics operating at the same time

11 Coding

11.1 Navigation

11.1.1 Resources used

During the process of designing and building the rover prototype, only a small number of electrical components were used to code on or to be coded by: a Raspberry Pi 3B 2015, Xbox Kinect V1 and a laptop.

11.1.2 Approaches

11.1.2.1 Real-Time Appearance-Based Mapping (RTAB-Map)

Introduction to RTAB-Map and Robot Operating System (ROS)

To make the Pluto rover autonomous, the first approach that we tried was to use RTAB-Map and ROS, openly source robot operating software. ROS is an operating system that can be installed on top of Linux to allow applications to communicate between each other and hardware components. It uses the principle of nodes, which hold timestamped information and can be written to by applications as well as read by other applications. This allows multiple applications and code scripts to work in sync and communicate with each other to complete different tasks. This is a necessity for autonomous navigation so multiple scripts and applications can communicate with each other, the camera and the motors simultaneously. RTAB-map is used to retrieve information from a depth sensor and RGB camera such as the Xbox Kinect and use it to generate a dot cloud to represent the relative location of objects. When the dots are concentrated, a 3D image of whatever the RGB-D camera is pointing at is generated on the computer. This is the same for both the standalone and ROS versions.

However, the standalone version can only generate a 3D map from information received from the RGB-D camera, whilst the ROS version can publish the dot cloud information to a node. This means that other scripts can read the node and detect obstacles in the dot cloud. They can then select the optimal route (see Figure 11.1), avoiding obstacles reaching the waypoint destination. ROS can also use a generated model of the robot to process and output movement operations to driver boards to make motors move. ROS is widely supported and used on many advanced robots, rovers such as Curiosity and companies such as Sony and Ubiquity Electronics.

Implementation of RTAB-Map with the Raspberry Pi and Kinect

As RTAB-Map is a pre-programmed open source software, it is difficult to implement with our specific hardware as it is difficult to completely understand how the software works. From research we have found that the software uses information from the sensors such as the Kinect, which is published to a node, which is then subscribed to by the program to receive the sensor information.

ROS kinetic, the most widely supported version of ROS with lots of resources availible, was the best option for the project. After that, Ubuntu 16.04. was found to be the best Linux distribution to run on the Raspberry Pi and work with ROS kinetic. After an image was flashed onto an SD card and the operating system (OS) was set up, the correct hardware drivers for the Kinect were downloaded so that other programs on the OS could use the Kinect as an available sensor. Freenect drivers that were well supported by Ubuntu 16.04, RTAB-Map and ROS Kinetic were chosen and used. Before installing ROS, a test was carried out with the Rasberry Pi to check that the drivers worked and that we were able to access all the sensors on the Kinect. Whilst there was lots of support online, installing

Figure 11.1: RTAB map example showing autonomous waypoints plotted on the virtual map generated from the Kinect imagery

ROS was extremely difficult as it consisted of compiling many packages manually. We completed the installation process of ROS without any outstanding errors but there was no simple way for us to test if the system actually worked. We continued, installing RTAB-Map, which was a fairly simple process as it had a clear installation guide on it s Github page.

We were able to execute the RTAB-Map program in standalone mode, in which it generated a 3D dot cloud using the information from our Kinect but did not publish this to a node. While this was operating, the rate at which the program registered the information from the sensor was extremely slow and caused the program to stop functioning as intended if the sensor was moved too fast. This is because RTAB-Map uses visual odometry, which estimates change in position over time by using data from motion sensors. As the rate of information received from the kinect was much slower than the speed of movement, the prediction algorithm failed to continue tracking the relative location of the new position, leading to termination of the program. This would be a problem for us as reliability is key for our rover. As this was a hardware limitation, due to the rate data was being fetched from the sensor, there was not much we could do to change the performance. Further testing, however, revealed the maximum speed of the rover was sufficiently low to allow the software to execute without a problem.

After confirmation the 3D map generation worked, we attempted to add navigation and movement functionality, which would require the switch from the standalone RTAB-Map to the ROS version RTAB-Map. However, the ROS version had trouble detecting the sensor. This posed a huge problem and there was little support online for this sort of issue as it is uncommon to run such a software on a Raspberry Pi. After having done a lot of research, we found that the drivers for the sensor have to be executed separately and connected to RTAB-Map using nodes. Even with the fix, the software seemed performed unreliably.

Conclusion

This method gave us proof of concept that the kinect could map the surroundings as it was very successful in making an accurate 3D map of the surroundings. However using RTAB-Map was not very successful at navigation which was our main goal and the next step after being able to detect and map the surroundings. Given our timescale, properly implementing navigation for our rover on the ROS platform was impractical and would require extensive research and learning. It would also require more processing power and other hardware not available to us.

11.1.2.2 Coding from scratch

After having tried RTAB-Map, we decided that the primary reason we were unable to implement this software was that we did not have a deep enough understanding of how the software worked. Therefore, the obvious solution was to build our own. We wanted to have a piece of tailored software that was optimal for our use and does exactly what we want it to do. The first thing we did was to identify system requirements for the software.

The system requirements were:

1. *The software must be able to detect obstacles.*
2. *The software must be able to output signals to move the rover and avoid obstacles.*
3. *The software must be able to run at adequate speed on a Raspberry Pi 3B.*
4. *The software must be able to allow remote control of the rover.*
5. *The software must be able to track the relative location of the rover.*
6. *The software must be able to interpret metal detection readings from the microcontroller.*
7. *The software must be able to store suspected locations of metal.*

We decided that we would use Processing, an implementation of Java, as the programming language. This was largely due to processing having an existing Kinect library.

After having chosen the language, we started doing research and created a system diagram. This is a method of forward computational planning that allowed us to ensure that we were able to complete all the requirements.

We developed two different applications that work together to complete the system requirements. One runs on the Raspberry Pi 3, and the other runs on another PC. Both applications communicate with each other. The application on the Raspberry Pi is not dependent on the laptop application and can run autonomously but lacks manual control in this setup.

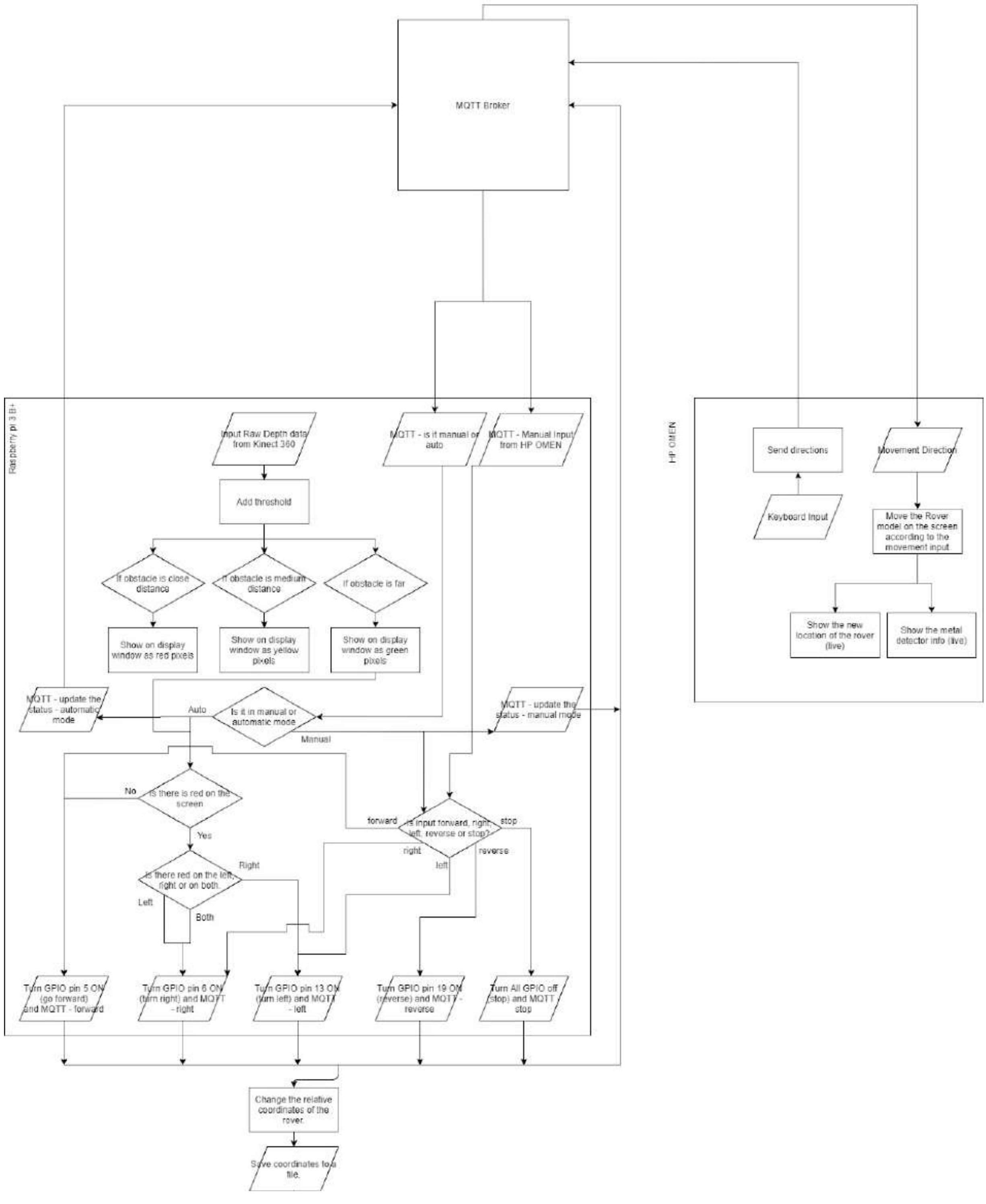


Figure 11.2: Coding flow diagram for autonomous driving system

Programming the application

Once the initial system diagram had been created, the main programming commenced. As we needed a communication medium between the laptop and the Raspberry Pi 3, we decided to use the MQTT (Message Queuing Telemetry Transport) protocol that is commonly used for IoT (Internet of Things) projects. The Raspberry Pi application was programmed first.

Raspberry Pi Program:

To solve the previous problem of data overload when using RTAB-Map, we decided to use only one of the sensors on the Kinect 360: the infrared depth imaging camera. To further optimise the system, we used a threshold to restrict the information being processed by the system. We did this by limiting the depth range from which we read information. We checked the depth of certain objects in front of the sensor. If the objects detected were:

- Close to the sensor - they appeared red.
- A safe distance from the sensor - they appeared yellow.
- Far from the sensor - they appeared green.
- Very far from the sensor and currently irrelevant - they appeared black and were ignored.

Processing is a language focused on graphics and analysis so at this stage it was fairly simple to automatically read from the depth image and flag if obstacles (in red) were present.

The use of the optimised programming language and the threshold allows the software to run smoothly on the Raspberry Pi 3. This means that the software is much more reliable and we were able to receive data from the sensor at a rate of 30 times a second. This also means that we completed the system requirement: *3) The software must be able to run at adequate speed on a Raspberry Pi 3B.*

As we have also been able to detect obstacles, we have completed the system requirement: *1) The software must be able to detect obstacles.*

While our current code could detect obstacles, we needed to know their location relative to the rover. If they are present only on the left of the screen, the autonomous navigation algorithm needs to tell the rover to turn right. If obstacles are only present on the right, the algorithm needs to tell the rover to turn left. This means the rover can avoid the obstacles by turning away from them. In a case where there are obstacles on both sides of the sensor, the sensor is hard programmed to continuously turn right until there are no more obstacles. This means that the rover will rotate on the spot until there are no obstacles in front or until it makes a 180 degree turn.

Any actions that are made by the algorithm are uploaded as string messages to a MQTT broker/server. An MQTT broker is a server that receives messages from clients and then routes the messages to the appropriate destination clients. An MQTT device is any device that uses a network connection to connect to a MQTT broker directly. The MQTT broker uses a similar 'node' system to ROS. It allows you to make a topic (which has an address) and use a device to either subscribe or publish data to it. When a device is subscribed to a topic, it receives all the data that is published by any other device to that topic. When a device publishes data to the topic, the data can be accessed by any other device that is subscribed to the same topic. This is the basic concept that is used to send data from the Raspberry Pi to the PC. As all actions are immediately uploaded to the MQTT Broker, it is easy for the computer software to know the current state of the rover.

After uploading the current movement instructions to the MQTT Broker, the Raspberry Pi 3 uses it's I2C output pins to output signals that represent the movement of the motors. The attached microcontroller uses these signals and then moves the motors accordingly; the microcontroller acts as an intermediary, allowing the Raspberry Pi 3 to instruct the motors without outputting the physical signals to the motor driver..

As the software outputs signals to move the rover away from obstacles, we have completed the system requirement: *2) The software must be able to output signals to move the rover and avoid obstacles.*

This piece of software can now recognise obstacles in front of it and can take appropriate actions to avoid those objects.

Laptop Program:

The purpose of this program is to allow the rover to be controlled remotely if needed. This program also uses the movement of the rover to calculate its relative location and record any trace of metals.

We used the MQTT server to toggle the mode of the rover from 'automatic' to 'manual'. Once the mode is set to 'manual' the instructions from the autonomous algorithm are ignored. The arrow keys on the keyboard of the laptop can be used to control the rover. The keyboard key 'm' can be used to toggle the rover movement mode.

The use of the manual mode completes the system requirement: *4) The software must be able to allow remote control of the rover.*

The rover uses a feedback loop to send the actual movement of the rover back to the laptop. This is sent just before the motors are activated to carry out a certain movement, and is therefore always an accurate representation of the movement of the rover. Using the movement signals from the rover, along with the known speed of the rover and the turning rate of the rover, we can estimate the relative location of the rover to its starting position. This is done using a vector addition in a cartesian coordinate system. When a signal is received to indicate that metal has been found, the coordinate of the rover at that instant is recorded.

Recording the location of the metal is vital to this rover's functionality and completes the system requirements: *5) The software must be able to track the relative location of the rover. 6) The software must be able to interpret metal detection readings from the microcontroller. 7) The software must be able to store suspected locations of metal.*

Difficulties

While programming an autonomous navigation application from scratch, we encountered many difficulties, the first of which was the communication between the Raspberry Pi 3 and the computer. While the applications on both devices were programmed in the same language, they had different operating systems. This was an issue as we needed to find a medium of communication that can be supported by both Ubuntu and Windows. While exploring communications, we research IoT (Internet of Things) protocols to allow us to link both devices using the internet. Our solution was the MQTT protocol which was well supported on both Windows and Ubuntu and was also extremely reliable.

Another problem that we encountered was the communication between the Arduino microcontroller (that controls the metal detector and motors directly) and the Raspberry Pi. This time, we couldn't use MQTT as the Arduino did not have Wi-Fi built-in. This meant that we needed a method of wired communication between the two devices. After doing research, we decided to use an I2C bus, allowing bi-directional communication with only two wires. While this was a possible solution, testing it and implementing it immediately was difficult as the Arduino circuit board was yet to be finished. Therefore, we decided to complete all other parts of the application first and then implement the I2C communication after the Arduino board had been made. The way we overcame the difficulty of not being able to test our solution this was by using a different Arduino board to simulate the outputs of the Metal Detector. This was the best way to test our chosen solution in the circumstances

11.2 Odometry

11.2.1 What is it?

"Odometry is the use of data from motion sensors to estimate change in position over time[59]." Odometry is used to allow robots, and in this case, the rover, to estimate their current location relative to their starting location. Localisation is essential for mobile robot application and a robot must maintain knowledge of its location over time, especially to achieve autonomous navigation.

11.2.2 Methods of Odometry

There are many methods of odometry, each with different advantages and disadvantages, as well as unique hardware requirements. Here are a few that we considered:

11.2.2.1 Wheel odometry

Wheel odometry utilises wheel encoders to count the number of revolutions of the wheels that are in contact with the ground. Using the known circumference of the wheel, the distance travelled can be calculated. Paired with the known direction of travel using recorded angle turned, the relative location of the robot from the starting location can be worked out. Unfortunately, this method suffers from position drift and inaccuracy because of wheel slippage. Inaccuracy accumulated over time can lead to significant deviation from actual relative location. "Translation and orientation errors in wheel odometry increase proportionally with the total travelled distance[60]".

Figure 11.3: Example wheel encoders from a rover.

Wheel odometry is inexpensive and simple, making it ideal for small robotics projects that do not require high levels of accuracy over long distances.

11.2.2.2 Inertial navigation system (INS)

Inertial navigation systems use hardware devices such as computers, motion sensors (accelerometers) and rotational sensors (rate gyroscopes). These work simultaneously to provide the movement of the robot, relative to a known starting position and orientation. This method works via the process of dead reckoning (DR) the position from past positions, similar to wheel odometry. DR is the process of "calculating one's current position by using a previously determined position, or fix, and advancing that position based upon known or estimated speeds over elapsed time and course[61]". While the wheel odometry methodology uses the same concept, INS is much more accurate as it uses sensors that do not require constant contact with the ground. INS also handles hills, bumps and potholes, making it much more accurate and optimal for real life solutions. However, this method has similar problems with wheel slippage to wheel odometry, resulting in the position error increasing rapidly with time.

Figure 11.4: A 1950s INS controller developed at MIT.

Global positioning system (GPS)

The Global Positioning System, GPS, is a satellite-based radio-navigation method used often to find the location of an object using satellite transmitters and mobile receivers. The system provides geolocation to a receiver when requesting using radio waves. It requires an unobstructed line of sight to four or more GPS satellites. It also has a relatively weak signal and so can be obstructed easily by natural obstacles such as mountains and buildings. The chassis of a robot can also block waves and so an antenna is usually used to allow strong signals from a satellite. GPS also provides position, navigation, and timing information free of charge to anyone who has a GPS receiver. This means that, due to its accuracy and low cost, it is an optimal option for more advanced robots on Earth or electronic systems that operate near the Earth.

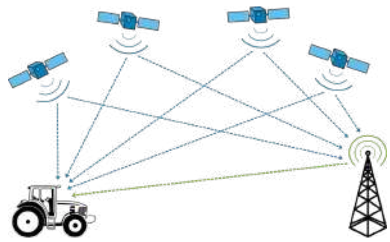


Figure 11.5: A GPS system in operation

11.2.2.3 Visual odometry (VO)

Visual Odometry (commonly abbreviated to VO) is the method of determining the location and the orientation of a robot using images from a mounted camera. VO uses dead reckoning to get the current location of the robot, and therefore requires information on the initial position and orientation. The images from a camera are analysed by an algorithm to estimate the direction and magnitude of the movement of the robot. It is used in the Mars Exploration Rovers such as Curiosity (in conjunction with other methods). Feature detection is used across in multiple images taken periodically, and their translation in the frame is used along with an accurate model of the robot to determine the exact movement of the robot. As it only requires a camera, this system is extremely useful in situations where many other sensors cannot be used. There are some problems with this method, such as loss of odometry when the camera becomes covered or feature detection fails. As this method uses DR, the location of the robot cannot be calculated after the algorithm fails once and recalibration is required. This is risky for critical applications and so this method is often used alongside other methods that are less accurate but can allow location recalculation when VO fails. Furthermore, it is a complex and expensive method so it is unsuitable for low cost applications.

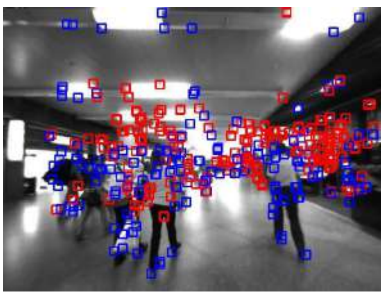


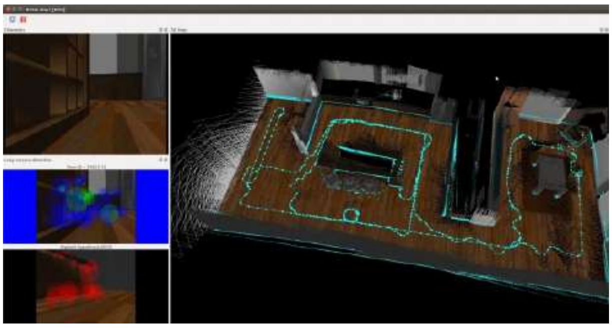
Figure 11.6: Example feature detection of an image

11.2.3 Chosen method

The method that we initially chose was to use Visual Odometry (VO). VO was built into RTAB-Map, which we were initially testing. An advantage of this was that it did not require much extra hardware as we already had a RGB camera that was built into the Kinect 360. Unfortunately, it was highly inaccurate and often failed due to the limited performance of the Raspberry Pi. It would have been extremely complex to embed a secondary method of odometry into RTAB-Map, we decided that we needed to utilise another method.

As we decided to program a software from scratch, we decided that the simplest method for us to implement in our prototype would be an Inertial Navigation System (INS). While typical INS uses specialised sensors to detect the movement and rotation of a robot, we decided to use the known speed and angular velocity of the rover when turning to easily calculate its relative location based on time moving/turning.

In reality, on Pluto, visual odometry would be used as our primary system, supplemented with inertial navigation. Depending on the scale of the mission, we maybe able to even use sun/star tracking when possible and potentially distance information from an orbiter.



11.2.4 Implementation onto the rover

To implement an Inertial Navigation System (INS) into the rover, no external hardware was needed. The system was implemented into the same program that determined the movement instruction to send to the rover. This meant that sensors to detect the movement of the rover were not required and data from the software could be used to determine the movement. A vector coordinate system was implemented, where a vector coordinate represents the relative location of the rover to the starting location. The initial position of the rover is represented using the vector coordinate (0,0,0). This position is recorded by saving it to a file along with a timestamp.

For simplicity, acceleration of the rover was ignored. Constant velocity was assumed when moving and time taken to stop and accelerate to said constant velocity was assumed to be 0. In reality, the effect of acceleration on the odometry data would be insignificant if taken into account.

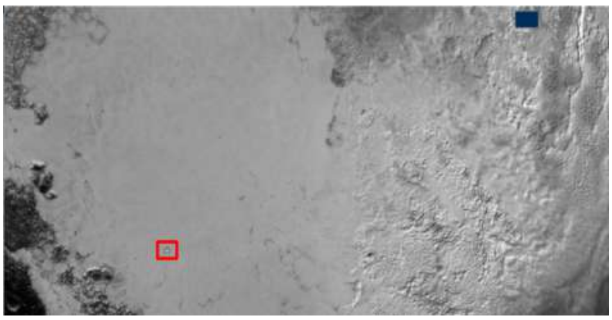


Figure 11.7: The GUI used to represent the relative location of the rover. The circle and line shows the set initial location of the rover.

11.2.5 Limitations

As the implementation uses the movement of the rover from the navigation software, it is not particularly accurate. The navigation software may represent a motion that the rover is not actually carrying out in case of skidding. This is not significant for short distances and so can be ignored but may cause issues if used for long distances. Therefore in the actual rover, we would implement rotary encoders in the wheels and also rely on other methods of odometry as mentioned above.

11.3 Metal detection

11.3.1 Integration with the rover and other code

The metal detecting has been explained in Chapter 6. The I2C connection between the Pi and Arduino allows bi-directional communication between the Raspberry Pi 3 and Arduino. This means that the Arduino can send data from the metal detector to the Raspberry Pi upon request. The metal detector is a sensor that outputs integers. The integers are multiplied by a constant and rounded, allowing the data to fit into a byte. This means that all the data can be sent across the I2C connection.

Once the Raspberry Pi receives the metal detection information requested, it performs analysis and plots the data. It also sends the data to an MQTT host, which allows the metal detector data to be monitored remotely. Integrating this communication line for the metal detector into the code was not too difficult as an I2C connection was already implemented. To preserve battery and increase efficiency, the metal detector is turned on in intervals and the data from these intervals is saved. A threshold is used to determine if the metal detector has detected metal. If the detector value deviates from the known passive reading then the location data along with the sensor data is relayed to the server. This reduces the amount of data handled by the server.

11.4 Communication between the rover and base

11.4.1 Approach

The approach that we used for communication between the rover and the 'base' or satellite was to use a centralised information hub that both the rover and base can access. To do this we used a MQTT server, allowing connected devices to write information to nodes. Other devices can then subscribe and read from these nocdes.

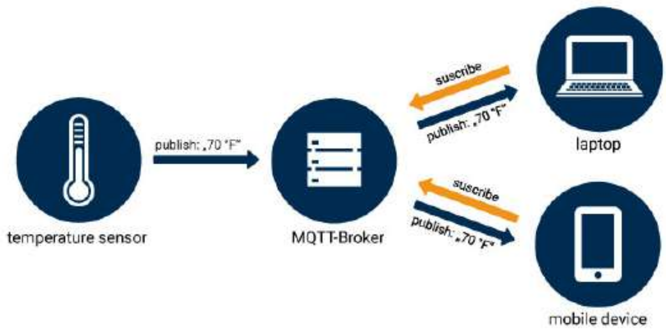


Figure 11.8: An example implementation of MQTT

There are many alternatives to this approach and there are many IoT protocols, but most are very similar and follow similar structures. The reason MQTT was our go-to protocol was because it is designed for machine - machine data transfer and as such it is easy to integrate into a custom program. Furthermore, the programming language we used, Processing, had very good support for MQTT.

The information that MQTT is used to send includes:

1. Instructions for the movement of the rover.
2. Data from the metal detector.

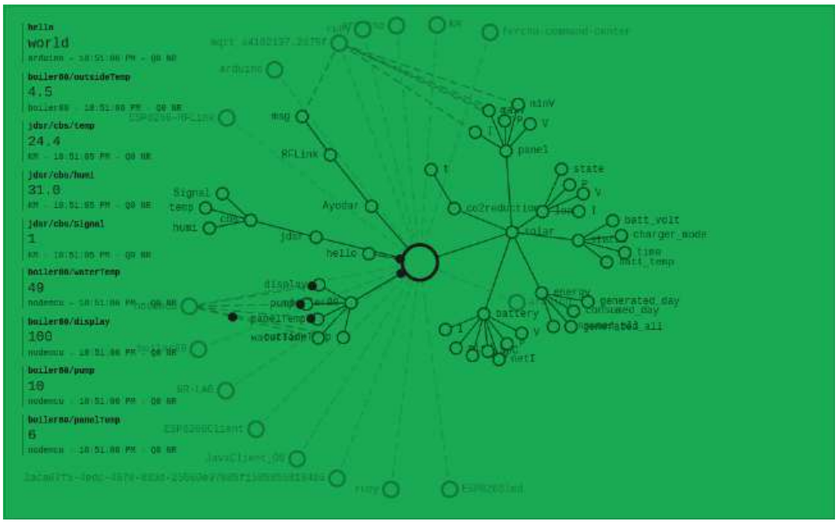


Figure 11.9: The GUI that the MQTT Broker uses to present the flow of data in and out of the server and between devices.

11.4.2 Integration with GUI

The data received from the MQTT protocol by the companion app is presented on a custom GUI. This GUI is coded from scratch and is optimised for readability.

Information about the movement of the rover is used to perform vector movement on a virtual object, which represents the relative location of the rover. This is shown on the GUI as a small oval and straight line (to represent the relative forward direction).

The data from the metal detector on the rover is also presented in a graph on the GUI. This graph shows deviation from the normal metal detection state, indicating a ferrous metal present with a positive spike or a non ferrous metal present with a negative spike. When this peaks, the current vector location and the exact strength of the signal received is recorded by the companion app onto a local file at base. This means that the information on the possible metal locations is compiled in a file for further research.

The GUI also features a toggle button that allows the rover to be switched between manual mode to automatic mode.

12 Components and Procurement

Component	Source	Quantity	Total price (£)
Structure			
Aluminium sheet	School	1	£0.00
Aluminium box section	Amazon	2	£7.58
3D printer filament	Amazon	1	£21.99
Miscellanoesous fixings	Screwfix	100	£5.00
Electronics			
Raspberry Pi Model 3B	School	1	£0.00
Arduino Nano	School	1	£0.00
18650 batteries	18650 store	(3 from school)	£4.49
18650 battery case	Amazon	1	£5.99
BMS charging circuit	Banggood	1	£2.98
Xbox Kinect V1	Ebay	1	£10.00
Motors	Banggood	6	£36.90
Servos	Banggood	4	£14.84
PCB	Aisler.net	3	£29.65 (refunded due to flaw)
Circuit components	Leonardo	40	£0.00
Metal detection			
Metal detector cable	School	0	£0.00
		Total	**£109.77**

13 Testing

13.1 Testing log

Requirement	**Test Process**	**Pass Yes/No**
1.a.i) Shall travel at least 1 metre 1.a.ii) Should travel at least 50 metres	Run the rover around a track until distance covered exceeds specified distance	Yes
1.a.iii) Shall be able to maintain a constant speed of at least 1 cms^{-1} 1.a.iv) Should be able to maintain a constant velocity of at least $5cms^{-1}$	Measure the distance covered in 100 seconds and divide it by 100 to check compliance	Yes
1.a.v) The rover shall be able to travel for a duration of at least 5 minutes without any significant systems failures 1.c.ii) The rover shall keep all components in working order after a significant distance travelled 2.b.i) The Power source shall provide enough power for all components to function effectively for at least 5 minutes	Instruct a rover to drive around an easily traversable track for the required amount of time. After which perform a systems check to ensure all components are functioning correctly and are functioning as they were before	Yes
1.b.i) The rover shall be able to traverse over flat terrain 1.b.ii) The rover shall be able to traverse over terrain with a high coefficient of friction	Instruct the rover to drive over a carpet course and assess whether it adequately maintains traction at all times (wheelspin constitutes a failure)	Yes
1.b.iii) The rover should be able to traverse over an incline of at least 20 degrees	Instruct the rover to drive over a ramp of incline 20°from a flat plane and asses whether or not in is fully situated on the ramp	Yes
1.b.iv) The rover should be able to traverse over terrain with a low coefficient of friction	Instruct the rover to drive over a course with material with low coefficient of friction and asses whether the rover is able to move continuously and does not enter a phase of uncontrolled movement	Yes
1.c.i) The rover should stay level over bumpy terrain	Attach a phone with an inclinometer to it as it travels over terrain and measure the maximum angle ensuring it does not exceed 20°as that no longer constitutes level	Yes
1.c.iii) The rover should be able to maintain contact with the terrain at all times in normal operation	In all tests ensure that at least four wheels are always on the ground	

Requirement	Test Process	Pass Yes/No
2.a.i) The rover shall contain a Raspberry Pi	Check whether the rover contains a Raspberry Pi	Yes
2.a.ii) The rover shall contain a power source	Check whether the rover contains a power source	Yes
2.a.iii) The rover shall contain a method of communication	Check whether the rover contains a transmitter and a receiver	Yes
2.a.iv) The rover shall have a method identifying metals	Check whether the rover contains a functioning metal identifier by providing it with a sample and getting a positive reading	Yes
2.a.v) The rover shall have a method of navigation	Place the rover in an unknown environment and see if it can navigate around obstacles.	Yes
2.b.ii) The Power source shall be connected to all components in the rover	Check each component receives enough power to functions after being integrated into the rover	Yes
2.b.iii) The Power source shall be safe for use in a non-controlled environment	Check to see if the power source complies with all relevant school safety protocols	Not determined
2.c.1) The rover shall be able to store or transmit the data received from the metal detection process 4.a.ii) The rover shall be able to transmit the readings from the metal detector	Have the rover drive over the metal and give a positive result and examine the data to see it is a positive result	Yes
2.c.ii) The rover should be able to report its location	Instruct the rover to cover 10 m and check whether the location data has changed	Not yet implemented
2.c.iv) The rover shall be able to regulate its speed	Instruct the rover to drive at full speed and then instruct the rover to drive at half speed and measure the speed to ensure it is travelling at half speed	Yes
3.a.i) The rover shall be strong enough to withstand the impact of inversion	Invert the rover and check if it still works	Not tested
3.a.ii) The rover shall be self supported at all times	Check to see if the rover requires external support	Yes

Requirement	Test Process	Pass Yes/No
3.a.iii) The rover shall be resistant to temperature changes	Subject the rover to the widest range of temperatures available and check if it functions at those extreme temperatures	Unable to test all ranges of temperatures, tested in range 5°-25°
3.b.i) The rover shall contain all components within the boundaries of the rover	Check to see if there are any components that are not within the body of the rover	Yes
3.b.ii) The rover shall be 220mm high	Measure the rover to check it complies	Yes
3.b.iii) The rover shall be 500mm long	Measure the rover to check it complies	Yes
3.b.iv) The rover shall be 380mm wide	Measure the rover to check it complies	Yes
4.a.i) The rover shall be able to communicate with an exterior device	Check that an exterior device receives a signal from the rover	Yes
4.b.i) The rover shall be interpretable by another system	Check whether the data sent to the external system is useable and formatted correctly	Yes
4.b.ii) The rover shall be able to communicate with the external device over a range of at least up to 50 meters	Move the rover 50 meters away from the external device and check whether the signal has been received	No - dependent on WiFi signal reaching 50m

13.2 Metal detection

The final iteration of the metal detector to be tested individually was the new larger coil married to the original circuit from the prototype. The coil is ovular in shape to make the most of the area on the underside of the rover in order to maximise range. We tried to keep the number of turns of wire which made up the coil around the same as the original prototype coil the same as, according to the inductance equation in Chapter 6, the number of coils is one of the factors which affects the total inductance of the coil. The testing process also gave us the opportunity to calibrate the Arduino code to the new larger coil, both in terms of refresh rate and detection output threshold (used to calibrate out any background interference), thereby increasing the detection range and reliability.

Using a plate of 4mm thick steel, we tested the coil and estimated the accurate range of the detector to be about 50mm. This was a large improvement over the first prototype coil which had a range of roughly 20mm. However, we could not increase the range further without increasing the current flowing through the board, which had the associated flaw of creating large back-currents that could potentially short circuit causing harm to both users and other electronics.

(a) Using a ruler to estimate the reliable range of the detector based from audio outputs from the buzzer on the circuit

(b) Testing the auto-calibration of the detector with an aluminium plate on top of the coil

Figure 13.1

We also conducted tests to see whether the presence of aluminium in close proximity to the coil would pose a problem. As discussed in Chapter 6, we did not think aluminium would pose much of a problem because it is relatively non-magnetic allowing the interference by this to be easily accounted for in the Arduino code. As the code searches for changes in the decay time of the current in the coil, the coil can easily be calibrated to take into account the interference of the aluminium with readings. As a result, tests concluded that having a sheet of aluminium placed directly on top of the coil had no noticeable effect on the range of the metal detector.

These tests were repeated once the metal detector had been installed on the rover and integrated into the PCB.

13.3 Movement capabilities

The testing process proved that the rover had the ability to meet the movement demands in terms of distance. The gearing of the motors allow for high levels of torque, allowing the rover to climb up slopes and obstacles, was tested to be sufficient to allow for a maximum speed on more than 5 cms-1 as per the requirement. After the movement tests, there were no issues associated with the mechanical components of the rover. However, further testing would still be required to see how the rover handles longer periods and distances of operation.

(a) Testing the rover over an 8cm vertical climb.

(b) Testing the maximum traversable incline.

Figure 13.2

The rover successfully handled rough terrain, which one test using an 8cm vertical block as the test terrain which was handled perfectly by the rover. This test also proved that in most cases all 6 wheels remained in contact with the ground at all time. However, due to a design issue, the middle wheels on each side lacked the ability to lift use over very large obstacles. To test driving on a surface with a high-coefficient of friction we used carpet and grass, while for a low-coefficient of friction we used wood chippings and a smooth plastic floor. The rover traversed all of these terrains sufficiently.

13.4 Functional requirements

The rover contains key elements which were determined it was necessary for it to have during the production of requirements for the rover. The rover contains a Raspberry Pi, a power source which is connected to all components in the rover and a transmitter and a receiver to provide for the requirements of communication and processing.

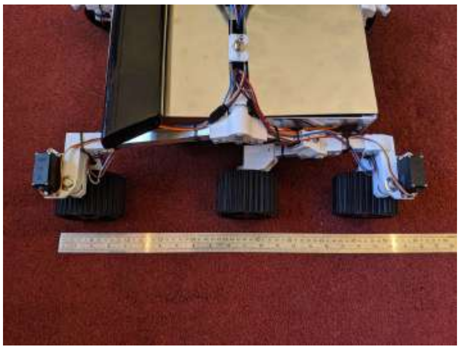
Figure 13.3: Raspberry Pi visible, power source below.

These requirements were fulfilled in the designing and building of the rover and we carried out tests on the necessary components throughout the project, especially when integrating them into the rover. As we had completed most of the tests beforehand, the final testing stage was simply a formality for the functional requirements.

13.5 Form/structure requirements

The key aspect that needed testing in the form/structure section was that the rover was physically capable of withstanding the demands asked of it. For the rover to be able to function on Pluto, first it has to be taken to Pluto. Therefore, the size requirements were extremely important to test, as if we were unable to fit our relatively simple systems in the scaled-down body of the rover it is unlikely a larger rover would be able to contain the much more sophisticated systems of the final design. These tests are extremely quick and risk-free as we set up constraints in designing the rover which ensures these tests will be successful.

The much more risky tests are temperature resistance and structural integrity. These tests are critical as the key challenge of Pluto as the mission destination is the temperature; the rover has to be able to withstand the extreme cold and unknown nature of the surface. The inversion test mimics an accident where the rover is hit in transit or rolls over while traversing the surface. It is important that the rover still has a possibility to continue the mission after such an event so this must be tested for. Furthermore, the test ensures that all components are mounted well so that there is a lower risk of damage during takeoff and landing of the rover when external forces are the greatest. The rover passed all of these tests and there were no issues.



(a) Measuring the final dimensions of the rover.

(b) Testing the structural integrity of the rover body by manual inversion.

Figure 13.4

13.6 Communication requirements

The method used to test the ability of the rover to communicate successfully with the computer was tested before implementation by monitoring inputs and outputs to detect if any errors were visible. Inputs from the rover's sensors were mapped with desired outputs from the MQTT client on the companion software, and then these were tested. For every tested input, the desired output was compared with the actual outputs and any changes were noted down. Once the bugs were found, they were resolved and the program was altered to optimise it for the transfer of data in this scenario. In this way, the communication of the rover was tested before it was implemented permanently in the software.

13.7 Evaluation of the testing process

Our testing process was continuous throughout the project. Therefore, filling out the testing log at the end was just the final check in a much longer process. The testing process sufficiently tested the majority of requirements that we were able to do with the equipment available to us. In order to further test the rover to ensure success when on Pluto, we would need to carry out longer tests to ensure components do not begin to wear excessively. We would also need to test at temperatures closer to those found on Pluto to ensure all components still operate at very low temperatures. This could especially link to the testing of thermal regulation via insulation and radioactive heat sources. We were also not able to carry out testing to destruction but this would be necessary for a real mission to Pluto to fully test the limitations of the rover.

14 Trips

14.1 Our workshop visit to Loughborough University

Our group visited Loughborough University's Engineering department on the 13^{th} and 14^{th} of January 2020. The department is spread across many buildings that provided good facilities for us to construct our prototype and left nothing to be desired by way of the equipment on offer.

Our team split up into two groups of three students. This way, one group was able to focus on the construction of the actual rover chassis and body, while the other group could focus on the electronic side of the rover which included not only the software important for operating the Xbox Kinect, but also constructing the metal detector. Through this, we were able to split the group's resources and time efficiently, with different members of the group electing to work on the part of the project that was their specialism.

The group that worked on electronics benefited by being in the electrical engineering area of the Wolfson School of Mechanical, Electrical and Manufacturing Engineering. This gave them good access to specialised assistance from staff who worked at the university, meaning that there was always assistance if something went wrong. Further to this, the group had access to specialist electronic equipment which meant that they were able to test what they were producing as they went, allowing them to find any issues with the designs and have a greater chance of fixing them since there were staff and equipment on hand to help them. The staff were also able to discuss any ways of improving designs with the group and this allowed them to improve their work, be this improving the layout of the metal detector on the circuit board or increasing the efficiency and reducing the space required by the code for the Xbox Kinect.

The group that worked on the structural parts of the rover were fortunate to be in the university's STEM Labs. These labs included a large scale workshop with lots of machinery allowing for a far greater variety of machining techniques than are available in most school's design and technology department. This opportunity to use highly efficient and modern equipment allowed us to machine pieces for our rover's design very quickly, and allowed us to focus on the construction of the shapes of the chassis and body of the rover. What was impressive about the university's workshop was the sheer breadth and variety of tools on offer. These ranged all the way from simple equipment appropriate for manually machining wood and metal, all the way up to high precision computer-based machining systems which cut metal to a high level of accuracy. As a result, we made impressive progress with the construction of the chassis and body of the rover over the course of the two days. Again, in this workshop there were many mature students and technicians who could help us use the equipment and find tools. They also helped us work more efficiently and they suggested better manufacturing and material working methods where they saw fit. We were also fortunate in that one of our team's mentors was also in the workshop, as he understood our project in greater depth and could, therefore, help us to a greater extent.

The short amount of time we had in the workshop was beneficial, as it gave us a better understanding of real-world time constraints. To this end, we had to use a detailed plan to ensure that as little time as possible was wasted. This taught us valuable skills in micro-scale project planning, and meant that there was a great emphasis on devising a chronological and reasonable process of steps to follow in order to make our work as productive as possible in the laboratories.

In addition to all this, a real-world appreciation for some aspects of engineering was learned. Not only was the importance of safety reiterated to us over the course of the two days, resulting in us always being conscious of our actions in this respect, we also learned a small amount more about what studying for engineering is like at university level, as we gained an appreciation of the facilities available to us by way of laboratories and workshops.

However, by far the most important thing we learned was the true nature of making a project. This included the different parts of planning and execution, including contingency planning, as well as thinking about the steps and chronology we had to follow throughout the manufacturing processes in order to complete the project within the desired timeframe.

14.2 Our Site Visit to Leonardo UK in Luton

Our group visited one of the eight UK sites of our sponsor, Leonardo, on the 4^{th} of February 2020. This site of the company is home to specialists in electronic warfare, especially the use of the electromagnetic spectrum in warfare such as in radar technology.

In our visit to the site, we were first given a talk on the type of work that goes on at that specific site and the general activities of the company as a whole. This gave us a better understanding of the company's line of work and its specialisms, which helped us to see how our project linked with Leonardo.

Next, we were given a tour of the buildings, which helped us to learn about past and present activities of Leonardo and see employees at work. We visited the anechoic chambers (which absorb electromagnetic radiation) and were given a talk on the workings of the research labs there. We also learnt about some of the company's current projects. As all the large projects are collaborative in nature, with both companies within and outside of the UK, we gained a better understanding of how engineering projects are conducted in a commercial setting and the challenges this involves.

In the afternoon, we were given help with writing a professional looking specification, requirements and testing lists as these had been areas that we'd been struggling with. We were also able to get input from members of staff about different parts of our project, especially the xbox kinect and metal detector. The ability to discuss the specific and technical areas of our project with those who are experts, as well as having access to a greater range of specialist equipment was greatly beneficial to the project as a whole.

In conclusion, our visit was not only valuable because of the help we got with our project, but also because it gave us an understanding of the workings of, and working in, an engineering firm in the modern day. The whole group would like to thank Leonardo, especially our mentors Daniel and Anthony, for their help with this visit.

15 Challenges we faced

In the design phase of constructing the rover, we struggled to decide on a correct design for the structure of the rover, this is because this issue was tied into the question of how to integrate the metal detector with the rover. As a group, we became worried about what effect the magnetic field induced by the metal detector would have on the electronics which we initially decided would be above the metal detector. This led to trying to find a design solution to be able to incorporate the metal detector. However, we eventually decided to use a pulse inductance metal detector. Through the use of this metal detector type, we were able to return to the original and optimal design of a central box that stored all of our electronic equipment.

Another challenge we faced was incorporating the hardware used for the transmission of information, detecting metals and carrying out commands, as well as the space needed for the Xbox Kinect, the batteries and the wires. We found it difficult to put every component into the space we had within our rover, and it took a while to fit everything into our rover, as we had to consider the balance of weight throughout the rover, however, we ultimately decided on the layout and included some custom made parts in order to fit everything together.

Deciding on the extent to which the rover would be able to drive itself was dependent on how difficult it was to develop the code we needed to be able to get the rover to control its own movement. Eventually, we were able to put in place a system to get the rover to move from place to place, with us telling it where to go and then getting the rover to carry out the commands. Furthermore, the rover was able to use a tailor-made algorithm to detect obstacles and avoid them, allowing it to drive by itself. These are currently the optimal ways of controlling the rover, however, it may be that this system becomes increasingly developed in the future meaning the rover will have the ability to be completely autonomously controlled.

During our project, the coronavirus outbreak occurred, which meant that our school shut two weeks before Easter. This limited the amount of time we had to put finishing touches on the rover and carry out tests at school. It also meant that we were not able to see our mentors for three weeks before Easter, made the testing process more difficult and made it likely that we will not be able to attend the EDT graduation ceremony at the end of our project.

In the design of the rover, we used plastic brackets in order to hold different parts of the rover together. These brackets where particularly brittle and some of them snapped when the strain of being screwed into the box section of the rover chassis was placed on them. Some of these plastic pieces snapped when attached to chassis, meaning they needed to be manufactured again.

It would never be possible to build the rover to the same tolerance that the computer aided design software allowed us to achieve, meaning some aspects of the construction such as building the bracket running across the middle of the rover was difficult. We also discovered during construction that some processes were too difficult to carry out in real life, meaning that we had to adapt the design, these setbacks also slowed down the construction of the rover.

16 Adaptations for the actual rover

16.1 Changes we would make

Category	**What have we done**	**Changes with an unlimited budget**
Sensing	In order to sense our environment we have used an Xbox Kinect. This is because this method is cheaper, was preconstructed and yet still provided our rover with enough information in order to be able to navigate.	For the final rover, we would use a whole suite of specialised cameras that are adapted for the Pluto environment which would give us a large amount of information about moving around Pluto.
Energy systems	In our prototype we used a combination of batteries and a transformer module as this was easy to convert to our optimum voltage needs and was cheap. It provided enough energy for our rover.	For the final rover, we would use a Radioisotope Thermoelectric Generator which would provide as much energy as we would need no matter what we were using on the rover and would also provide a source of heat which would reduce damage to components in the rover.
Metal detection	In our prototype we used a pulse induction system in order to detect metals. This allows us to detect metals without being expensive to construct and demonstrating metals being detected.	For the final rover, we would likely use a spectrometer, and/or ground penetrating radar, which would mean that we would be able to go further down into Pluto's crust in order to be able to better detect metals.
Communication between the rover and operators	In our prototype, our rover communicates with a laptop using a Raspberry Pi 3B, this is an effective way of allowing the rover to communicate with laptop and is effective for manual control. Since the distances between the rover and the laptop in the prototype stage are so small, we do not require anything more sophisticated for communication.	For the final rover, our rover would use an antenna to transmit radio or microwaves to a ground station on Pluto which would then communicate them via the NASA deep space communication network. This network is advantageous as it will allow the rover to communicate with the Earth along a standard path, reducing the amount of infrastructure that is required for the receipt of communications.
Materials used in the rover chassis	In our prototype, we used aluminium sheets and tubing which are structurally strong and thus reduces the need for structural rigging. This increases space for internal components.	For the final rover, we would still be using aluminium sheeting, but maybe also titanium, as these are both strong materials and allow for greater space for internal components. However, we would also use Computer Numerical Control machining in order to make more precise cuts and make exact components.

Category	What have we done	Changes with an unlimited budget
Materials used for the wheels	In our prototype we have used plastic (PETg) for the wheels which are of appropriate strength in order to support the weight of the vehicle. They are also designed to have enough friction with the ground in order to be able to move.	For the final rover, we would use a metal mesh wheel. This would still provide enough friction to meet our requirements but would also be collapsible, meaning they could fit into a smaller space when the rover is being transported.
Motors used for the rover	The motors we used in our prototype were DC 12V 520 Gear Box Electric Motor 12rpm Speed Reduction Brushed Motors. The main reason for this was in order to stay on budget.	For the final rover, we would use brushless motors as they have a life cycle far longer than what is required for the lifetime of the rover. Brushless motors were used on the MERs, so they have been proven to work in a planet exploration application.
Circuit boards used	In our prototype, we used an Arduino in Conjunction to a Raspberry Pi 3B, which met the processing needs of our project. We also used a computer for location and manual steering, representing what would happen in the actual design.	In the real thing, we would use circuit boards specially designed to deal with the extreme cold of Pluto. Furthermore, we would need to increase the processing power, providing us with enough computing power to deal with the data from the metal detector and the input from the multiple sensors on the rover.
Size	Our rover is approximately 35cm wide by around 50cm long which is large enough to fit in all the equipment that is required to be in the rover.	For the final rover, our rover would be bigger allowing for more advanced powering, communication, metal detecting and sensing equipment to fit into the chassis.
Temperature control	Our rover prototype operates in a tolerable environment for the electronics, and therefore it is not necessary to have any temperature control mechanism in order to keep the temperature at a level that is both stable and tolerable for the electronics.	For the final rover, the temperature of the rover would be controlled using insulation in order to reduce the amount of energy lost in maintaining the temperature of the rover. The source of heat would from the Radioisotope Thermoelectric Generator.

Category	What have we done	Changes with an unlimited budget
Wiring	The rover features individual positive and negative wires which are cable tied as a group to the outside of the suspension arms. They then enter the chassis through holes in the top of the chassis.	In order to make the wiring more organised, we would use heat shrink to group both the positive and negative wires coming out of each motor. These could then be grouped with the rest of the wires travelling up the same arm, creating an organised wiring loom. This would have the benefit of allowing more insulation to be present, preventing the copper inside from cooling to a temperature where it becomes brittle at the cold temperatures. Insulation could further be improved by routing the wires through the inside of the suspension arms. This would also give them more protection to the physical environment, helping to make the rover more reliable.

16.2 Any future design developments

In order to reduce the size of the rover for transportation, methods of compacting the rover should be explored, an idea also found on the NASA Sojourner rover (mentioned in Appendix 3) which collapsed to almost flat so it would take up less space in the rocket module.

One way of implementing this might be by integrating lead screws and stepper motors to each side of the rocker-bogie suspension arms and adding bearings in the top bracket to allow the two main arms to move closer and further away from each other to change the height of the rover above the ground. Other options could include hydraulics or pneumatics, however, these cannot be used in the extremely cold and airless environment of Pluto as the pressure difference inside and out of the pneumatic system would be very high. While adding bearings to the top bracket of the suspension setup is easy on the

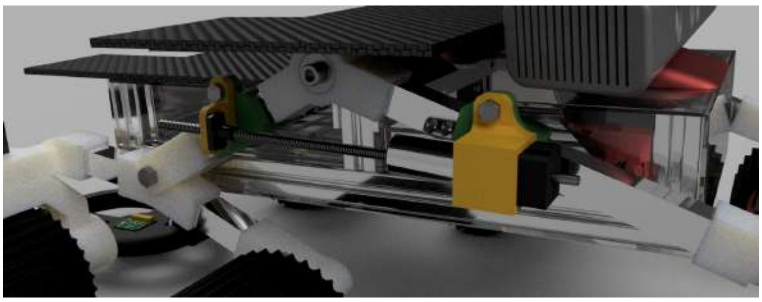


Figure 16.1: Render of an early-stage rover design with integrated stepper motors to allow the arms to collapse for transport

right side of the rover (as the whole suspension rotates around the chassis), it is more difficult to accomplish on the left side as the chassis needs to be held horizontal to the ground by the two main branches of the suspension setup.

One potential idea to achieve this is by using a solenoid valve to engage and disengage a castellated nut, that will allow the left side's suspension to be locked in place once the ride height has been changed. However, using this method creates a weakness in the design, as while the ride height is being changed and the castellated nut is disengaged, the chassis will have a free axis of rotation which cannot happen. Therefore, the ramp setup used to allow the rover to exit the lander module would have to be designed to make sure the rover could be locked in place before exploration begins.

Unfortunately, we were unable to build this into our prototype because of the increased cost required to implement a system that is strong enough to withstand the rigours of use.

17 Prototype evaluation

17.1 Things we would change

- Unfortunately, when designing the system in CAD, the exact model on the servo we used was not taken into account. As a result there was not enough clearance under the servo. In order to solve this problem, we rotated the linkage attachment point which gave us the clearance for the linkage to miss the extended servo horn and still be able to rotate the wheel 45°in both directions.
- There was not enough clearance above the wheels to a allow a nyloc nut to be used, forcing us to use a normal nut with Loctite to stop the wheel pivot loosening every time the wheel is turned. However, this solution is very effective.
- The suspension brackets need to be made larger and, therefore, stronger, as we broke two steering brackets. This is because the load on the bracket is perpendicular to the 3D printed layers. We could improve this in the future by increasing the size of the part to increase the area of layer bonding or change the design of the part to allow the layers to be in the same direction of the primary load, reducing the chance of part failure. However, this is not a major issue because for the real Rover, all the suspension parts will be made from machined aluminium, which is stronger and does not have a weakness along any of its axis.
- The back hinge on the suspension arm does not have enough space to freely rotate the middle wheels upwards. This could be changed by increasing the length of the hinge arms allowing the back arm to have greater freedom of rotation. This would improve the ability of the rover to traverse rough terrain.
- The pivots on the drivetrain arms could be improved to reduce the amount of movement in the system. This is especially prevalent on the back two pivots. This movement could be reduced by incorporating bearings into the design of the pivots, as the metal bearings are less likely to get worn away from use (unlike the plastic we are currently using) and have a much smaller degree of freedom away from the axis of rotation.
- For another prototype, we need to take more care in the design of some of the 3D printed brackets, especially the 4 corner steering brackets which are attached to the suspension arms. Do to weaknesses along the layer lines of the printed brackets, we snapped two during the construction process. Another option would be to make these brackets out of another material. This could be out of machined aluminium as mentioned earlier.
- We would also have devised original designs for the rover as a whole earlier. We tended to take the project one step at a time instead of as a whole (e.g. design exterior of rover without thinking of the interior), so with a more comprehensive original plan, systems integration would have been easier. Whilst this didn't become a big problem, it was a big risk factor for our project.

17.2 Progress evaluation

Progress point 1 - November 24th

Planned progress - compile requirements list, complete initial Gantt chart, complete initial research needed for the Project e.g. about metal detection, plan original design ideas, research parts to order

Actual progress - Draft requirements completed, Gantt chart plan completed, original design completed and checked with group, some parts ordered and others researched

Progress evaluation - At this point, we are ahead of schedule. We have made better progress than expected in design - as it is now a complete design for the rover (bar later iterations). We have also compiled a large research section, which means that we have made more progress with the report than expected. However, we have not yet planned the insides of the rover or procured the electronic components such as batteries needed for the rover.

Progress point 2 - January 13th (Loughborough workshop)

Planned progress from last point - Complete final design, 3d print all necessary parts, cut out aluminium, begin to assemble chassis, initial research into using Kinect sensor, build original metal detector circuit, all parts ordered

Actual progress- Final design completed, all parts 3d printed (with many 3d printed parts integrated), aluminium cut out, chassis assembled, metal detector circuit built, initial use of Kinect successful (mapping using RTAB Map), most parts procured (still need PCB, batteries), suspension built and integrated

Progress evaluation- We are ahead of schedule as we've completed nearly all of the structural building of the rover at Loughborough. Before this, we have 3d printed most of the necessary parts and assembled the suspension. The only structural additions that we need is the metal detector and the permanent integration of the "arms" of the rover. The metal detector has been proved in concept and we can now move onto winding a bigger metal detector coil. The Kinect has proved that it can map its surroundings and therefore, we can try to get it to sense objects around it and then, ideally, develop autonomous driving.

Progress point 3 - February 10th

Planned progress from last point - order all parts, build and integrate suspension, finish exterior of rover (apart from metal detector), find method to establish a link between the rover and external computer, begin compiling report, all electronic components tested separately, use Kinect to be able to detect objects

Actual progress - batteries procured (pcb still outstanding), exterior of rover completed (apart from metal detector), method of linking Pi to Computer found, report compiling begun, all electronic components tested separately, Kinect now able to detect objects (autonomous driving capabilities)

Progress evaluation- We are currently on track for our project. The main progress has been electronic component testing and development of object detection with the Kinect sensor. We have also found software that would give us autonomous driving capabilities. We have also made significant progress with the report. Our biggest risk is our integration of all components. We will have to do this quickly or risk losing time to iterate.

Progress point 4 - March 17th

Planned progress from last point - building section complete, build final metal detector, be able to transmit data from rover, rover can now move, majority of systems integrated, electronic integration plan completed, majority of first draft of report completed, link software to Kinect to be able to move rover around obstacles

Actual progress - Our building has been completed bar the small tweaks needed to integrate systems, final metal detector attached to rover (but not yet linked to batteries), interior of rover designed but not yet completed - batteries not yet linked to electronic components, motors and servos cables attached but not yet linked to batteries - rover can't move, many sub-systems now physically attached to rover, electronic circuits tested together outside of the rover but not yet integrated into the rover, electronic integration and interior design planned, report stands at about 100 pages with few sections still to write, Kinect can now detect objects and change motor inputs to move around them.

Progress evaluation- We are still on track. Our building work all but finished. Our biggest remaining tasks are to integrate electronic circuits into the rover, finish the interior of the rover and complete testing the rover. We are ahead of progress on the report, which has few sections still to complete. The biggest task for the report is proof reading and ensuring that our finished report is concise. We have achieved our goal of the Kinect being able to prevent the rover crashing - this now has to be integrated

Progress point 5 - April 21st (end of project)

Planned progress from last point - All requirements to be fulfilled, detailed report compiled, time and thought taken over presentation of our project

Actual progress - We managed to finish the project, however, due to the Coronavirus outbreak there is no final presentation day at this time like we accounted for. Our testing log shows that we were able to carry out the neccessary tests. The rover was able to pass all the tests and therefore all the requirments for the project.

Progress evaluation- Due to this, the following changes had to be taken in the final stages of completing the rover: smaller group integrating electronics (led by Dom), face to face weekly meetings with the mentors were replaced with group discussions on Whatsapp chat and video calls; the report also became the priority for the people who couldn't physically work on the rover. You can read more about this in our "Challenges we faced" chapter.

18 Professional Standards

The number one rule is safety. In order to make sure that the whole team got the most out of the project, we ensured we had standards in place to make sure the team would stay safe while ensuring the end result would be of the desired, and required, quality.

18.1 General

When considering the health and safety aspects, we need to split the primary areas of risk into three different categories: the construction workshop at Loughborough; the electronics workshop at Loughborough; and finally any other risks, primarily when working on the project at school.

Risk assessment table:

Risk	**Likelihood**	**Severity**	**Mitigation**
Sharp filings from metal files	Low	Medium	Wear goggles and make sure everybody knows where the nearest First Aid box is
Cutting with a metal hack saw	Medium	High	Make sure everybody undergoes tuition on the correct use of the tool
Getting caught in machinery	Low	High	Having loose clothing (e.g. ties) tucked in and using a lab coat when operating machinery
Burns from using 3D printers	Low	Medium	Make sure to keep hands away from the hot end and bed
Inhaling solder or flux flames	High	High	Use a fume extractor when soldering
Soldering burns	High	Medium	Make sure to turn the soldering iron off when not in use and make sure all electronics are sufficiently held in place before beginning soldering
Small electric shocks	Medium	Medium	Make sure to insulate all wires, make sure to ground all electronics and make sure to switch off all electronics when tinkering with the circuits
Dropping heavy tools onto feet	Medium	Medium	Be sure to wear steel toe-capped boots while working with heavy machinery (as used in the workshops in Loughborough)

18.2 Chassis Construction

The most noticeable aspect of manufacturing quality standards is emulated by the quality of the final rover chassis. As the rover was completely designed in CAD modelling prior to construction beginning, we had access to precise measurements in the orders of thousandths of millimetres of precision. However, even this is beyond the CAM machines we used, such as the 3D printers, therefore, a long way from the precision of the hand-cut components. Therefore, we agreed on tolerances of $\pm$ 0.3mm for all hand-cut components on the rover, predominantly the aluminium bars for constructing the chassis. In order to achieve this precision, we used digital callipers with precision to hundredths of millimetres.

18.3 Report

As a team, we chose to take on the challenge of producing the report using latex, the automatic typesetting program used to create professional-quality scientific reports and technical documentation amongst other uses. This allows us to create a report that is consistently high-quality.

One choice we made to produce a quality report was the decision to Havard-style referencing, with a bibliography at the end of the report with a number of referenced materials.

19 Reflections

19.1 Dominic Dale

For me, this project has been thoroughly enjoyable and has allowed me to apply knowledge I already had but also learn a huge amount. For our group, the project seemed clear enough once we had a CAD model and electrical schematics, but the most beneficial experiences came from the mistakes we made and worked as a group to resolve. As the electrical hardware lead, my main focus was the design and wiring of the multiple electrical systems featured in our rover. The engineering mentors' focus on systems was extremely useful in the initial decomposition and sub sectioning of the task and because of this, I came at the electrics with a modules based approach.

The key challenge with the rover electrics was the core circuit design. As a group we concluded the functional requirements of the circuit and I then proceeded to design the schematic from scratch, from choosing suitable components to picking communication protocols. Choosing components was one of the hardest processes for me, as I would find a suitable component and read through the datasheet only to find a better alternative and have to swap out the whole layout. The buck converter design was also particularly difficult, but research into the characteristics of inductors and the principles of buck converter operation helped me improve the quality of the design to achieve a better regulated output. A key skill I built upon in this phase was how to effectively analyse against a specification; in this case placing datasheets of components side by side with our functional requirements to determine suitability. Would the chosen IC deliver enough current to drive our motors at start? Is there enough bulk capacitance at the servos to prevent damage in case of a voltage spike? Does the diode in the buck converter have a fast enough recovery time to ensure our output is stable? These were all questions I had to ask, and they led to the rejection of many potential components.

For me, one of the most enjoyable processes in this project was the assembly of the printed circuit board. In the past I have done some soldering, but nothing close to the level of precision required for the fine pitch components used on our PCB; it was a huge relief when the whole board was assembled and it all worked together as intended! With the skills I have acquired I am now reasonably confident at SMT soldering. I also learned a huge amount about how PCBs are manufactured, their makeup, and how PCBs are assembled automatically in industry from pick and place machines to automatic reflow soldering ovens.

Not only have I built upon my electrical engineering skills, this project has exposed me to other areas of the engineering sciences I never would have otherwise had the opportunity to explore. Beforehand I had very little interest in mechanical engineering, but seeing how the rover suspension system functions and helping review the servo steering system has boosted curiosity in the discipline. The mentor's speciality in systems engineering was also the source of many key skills I applied throughout the project.

19.2 Pallav Hingu

This project has taught me many different useful skills and helped me further understand the process involved in software engineering, which I hope to pursue at a higher level.

This project was extremely interesting for me as it was one with extensive possibilities. There were many challenges along the journey but finding creative solutions amplified the experience. Being head of coding, I was tasked with making the software that would drive the rover, manually as well as autonomously using some sort of intelligence.

Initially, my approach was to adapt and use an existing solution, but this was much more difficult that I thought. The programs that were already made were optimised for other applications, making them less efficient for our project. The main initial approach that I used was to employ ROS and use an application called RTAB-Map, but that was optimised for more advanced machines. This meant that it needed a lot more adjusting to run on the limited hardware that we had access to. I spent a lot of time studying its existing code and attempting to make it navigate the rover autonomously. This became harder when I wasn't able to fully test the application as the electronics were not yet completed. I overcame this by adding other sensors onto the Raspberry pi to test the output. Most of the time, a voltmeter or an LED was used, but when we were testing the program's ability to map the surroundings, we used a RC car that was moved with another controller. While these tests were successful, I was not able to send outputs from RTAB-Map to move the motors. This means that the program worked successfully to an extent, but did not have enough hardware available to actually move the rover. Another problem was that the program became more and more complex at this stage and it really stretched my abilities to adapt the application further so that it could be used for our primary application. As this led to researching and reading through many more PhD thesis documents, it became too much to process. After thorough research and advice from our mentors, I believe that this approach would be "overkill" for the Raspberry Pi and so I decided that it was time for another approach.

My secondary approach was to code an application from scratch that had the ability to detect objects using our sensor and send outputs to the other components accordingly to move around them. I would need to do much more research to be able to program such an application so I decided to use a spiral development approach. The spiral model is a software development model used in industry where development is started with modest goals which are eventually expanded outwards in ever-wider spirals called rounds. This meant that we could begin creating a program with some goals that were realistic and some that were very ambitious. A professional approach like this allowed me to experience a realistic programmer's approach. At the beginning, our goals were to have a program that could remotely move the rover and perform low level obstacle detection, moving the rover one way every time an obstacle was detected.

I saw building this program as the perfect opportunity to learn a new programming language that was optimised for low hardware performance, for our available sensors and for our specific application. I learnt a new programming language, processing 3, which proved to be extremely useful. There were many difficulties as the program had different syntax and used a completely unfamiliar interface, but nevertheless, I created our first iteration that ran on the Raspberry Pi 3 and detected obstacles. One problem that we had was that the sensors gave too much information to the program and it took a very long time for the program to process that information. This created lag, which we would like to reduce. So, to do this, I created a second iteration by adding a threshold and cutting down the input data before processing it. There was a significant drop in lag after doing this, meaning that it was a successful round in the spiral model. There were also other problems, including the fact that there was no immediately obvious way of remotely sending information to the application on the Raspberry Pi that accounted for the large distance that the signals needed to travel. So, I researched Internet of Things protocols that were used for networking many devices, and I came across MQTT, which allows real time data to be sent from one device to another reliably. I immediately set to applying this to our program and was successfully able to send data forwards and backwards from my computer and the application on the Raspberry Pi. This allowed me to control the movement of the rover manually.

While we had met our base requirements with our program, we decided that we wanted the rover to have a smart algorithm that would allow it to move around obstacles in the smartest way possible. Keeping in mind our limited resources, I designed a tailored algorithm from scratch that detected if the obstacle was on the left or on the right of our sensor. This allowed the program to move around the obstacle in the optimal way. Using the previously used IoT protocol, MQTT, I was also able to use the movement of the rover to calculate the relative location of the rover and display it on a computer using a companion app and also present data from other sensors. The integration of different systems caused minor problems with receiving the information from the metal detector but that was eventually solved by using common I2C connection. This was a huge achievement and we had already spiraled very far from our initial modest goals and so we decided it was time to end the spiral and put the program into application. While testing the program with the completed rover, we established a bug where the program detected objects on the side of the rover as on the front and attempted to avoid them. To solve this problem, we created one last iteration in which more information from the sensor was ignored, meaning that objects on the side of the rover that were not actually obstacles were ignored.

After simulating a professional application development environment and having gone through the spiral development model, I have learnt invaluable skills including: effectively and successfully planning an approach to solve a specific problem, conducting required research, designing and programming a software, testing, finding bugs, and repeating iterations of the program to solve new errors or adapt the application further. From this project, I have also experienced the real life struggle of software developers when deciding if they should end the spiral and complete application or to keep using resources to spiral on. I have learnt that there are many problems when creating an application, more than the ones that are visible on the surface, that require creative and unique solutions to create modern and effective solutions, which has made me even more fascinated in software engineering and more eager to face the future problems ahead of me. But something that I would like to do differently would be to use a modular of functional programming approach to make programming and system testing much easier. But as this program did not have an extremely long source code, it was not a huge problem.

19.3 Daniel Baars

During this project, I have built upon many soft and technical skills used in the engineering process. Personally, I have learnt huge amounts about construction, design and problem solving. In our weekly meetings, I offered many different solutions that our group discussed to overcome design issues. Making contributions to a discussion and evaluating them as a solution has helped me to develop a critical thinking and forced me to consider how a certain parts of a design will interact with other members. One example is my contribution to our discussions on the rover's navigation, a subject for which I brought about a range of system solutions. The first of these was using incremental steps in order to navigate around a deposit of metals and then identifying the area covered and sending this back to Earth. Another was a solution for the navigation of the rover in the final model. In a design of how the systems would interact, I analysed in a broader sense how the different sections of the rover would have to interact in order to get it to move. This allowed me to develop my skills of making flow diagrams, and thinking holistically in order to bring about a design solution for the real thing which was in many ways similar to the final prototype.

I partook in the construction of our rover and this enabled me to further develop my practical making skills. The requirements of the work we undertook during this time were more difficult than in GCSE product design. The wider set of techniques available and the greater number of tools that I used meant that I was able to learn about machining of pieces and get hands-on experience of manufacturing a prototype. Accuracy within given tolerances was critical to this design so I had to become more familiar with the use of specialist equipment such as vernier calipers for measuring lengths. The greater number of techniques we used to design the rover also exposed me to fixing methods such as pop-riveting. This greater variety has given me an understanding of how design problems can be solved through different methods of manufacture. In the workshop setting, I also learnt about correct safety procedures and also how to concisely communicate with technical assistants in order to indicate my intentions. This meant outlining my aims properly and discussing possible manufacturing methods. I was faced with challenges at many points during the manufacturing process and I had to think quickly about the optimal solution to these problems and discuss this with my peers. Time for construction was limited since we had only two days at Loughborough, so the costs and benefits of different options had to be weighed up quickly in order to choose the best way forward.

This project also gave me the opportunity to carry out research into technical subjects that I would not have normally explored. This helped me better understand the methods we were going to use for both the real design or our own prototype and allowed me to form a base of reason, on which my design recommendations were based. I also was involved in research about the climatic conditions and terrain Pluto so I was heavily involved in the development of the specification for the rover forcing me to think holistically about the project at all times.

During this project, I learnt lots about engineering and design from the process and steps we followed to complete our project. These include working on written documents such as research, a report, and a specification. All these documents were a learning curve for me and they allowed me to discuss our project in detail while maintaining readability. The need to communicate well and the importance of teamwork led to development of my soft skills: I have never partaken in a group project that lasted this long and required such effective team management. I have also learnt more about the formalities and conventions of an engineering project, the importance of specification writing, client requirements analyses and how to deal with a brief from a customer. Doing this in a group was a beneficial introduction to this process and the mentors helped educate us on these conventions.

To conclude, this project has given me an improved understanding of engineering, construction and a project-based work atmosphere, and has heightened my interest in the field going forward. I have gained invaluable soft skills that I will be able to employ right away to improve my ability in collaborative work and projects.

19.4 Tim Hire

It is amazing how much we have achieved in our Young Engineers project over the last term and a half. From a vast array of initial ideas, some crazy and wacky, we have produced a prototype that effectively meets the majority of demands of our client, Leonardo. Our mentors, with their expertise in systems engineering, were pivotal to us to taming our ideas and restricting our scope thereby enabling us to develop well-crafted project requirements. It was this detailed planning, incorporated into the Gantt chart, that was leagues above anything I have ever done before. This planning process certainly proved useful and gave our team the opportunity to split into carefully coordinated and managed subteams, to maximise efficiency and productivity.

My main role in the project was designing the rover in CAD. This project gave me the opportunity to explore new and exciting CAD functions in the Fusion 360 software, most notably the stress testing on the servo linkages that can be found in Appendix 6. Using computer modelling to influence design ideas is something that I am very interested in, but have not previously utilised.

The EES scheme gave the whole group a number of opportunities, most notably the two-day workshop at Loughborough University. The facilities in the engineering department were far superior to anything I have experienced before. My highlight was the use of the waterjet cutter; it was amazing to see the panel designs produced from aluminium. Perhaps the best part of the project for me was the construction process, as we worked efficiently as a team solving problems that we had not anticipated. It was these problems, caused by overlooking small details, that taught us the most, as every aspect of every part must be adequately considered during the design process to ensure smooth construction and operation. For example, the lower hinge on each suspension arm does not have enough clearance to allow the middle wheel to lift over bumpy terrain, an issue which we added to our evaluation.

I have also been heavily involved with the writing of the report using LaTeX. This process has helped me understand the stringent process of crafting a good report, recording both the process as well as the challenges of the project, supported by accurate referencing. Learning LaTeX inturn has inspired me to begin a Python coding course.

However, the most important and influential outcome of this project is a newly developed interest in electrical engineering. Before I started this Young Engineers project, my electrical engineering experience had not stretched beyond the wiring of my kit 3D printer. This has changed as I have followed Dom's design and production journey of the PCB as well as the construction and testing of the metal detector. While I still do not understand everything, I would love to know more about this area. This is perhaps one of the largest reasons why I now want to study General Engineering at University. This project will, therefore, hold me in good stead for the future.

19.5 Ben Post

I have thoroughly enjoyed working on this project and I feel that I have grown so much in my understanding of engineering. The design process was far more complex than I first thought. Whereas I believed that we would stick very closely to existing designs of rovers, we discussed and even chose (temporarily or permanently) some very interesting ideas - the metal detector extending around the sides of the chassis being a personal favorite (Chapter 6). This out of the box thinking was thoroughly enjoyable and I found that I became better at critically evaluating these ideas as the project progressed - always returning to the aim and requirements of the project to decide whether we had really made a ground-breaking innovation. I was very interested by how engineers make decisions and our group evaluated many decisions such as choosing the project and components analytically, as demonstrated by the project choice decision matrix(Appendix 1).

As Team Leader, my main task was to keep the project on track in terms of our time-scale and budget. Our team was very motivated and always completed the tasks set on time, so time management was not an issue. Team cooperation was also excellent as everyone seemed to enjoy working together. Everyone understood the importance of collaboration on the project and was open to feedback from other members of the group. However, control of the budget proved harder than it first seemed as we ordered from many different suppliers at different times. It also wasn't overly clear what our final budget was throughout the project over confusion about if the school and Leonardo had pledged £100 each or combined. We placed multiple orders because we decided against coming up with a complete plan for the rover straight away and instead built our approach on adaptability - focusing on building sections separately and gradually tweaking our integration plan. For example, we decided to have the option of putting the metal detector behind the rover if the electronics and aluminium body prevented it from working when placed underneath. Whilst this plan was useful for a first project where there were so many unknowns as something could easily be changed due to unforeseen circumstances, I would, in the future, endeavor to plan the project as a whole before construction began. Ultimately, I believe that a complete design for the whole rover and a full list of parts would have made the project easier, and more structured as well as making the budget far easier to control.

I also had a very diverse role in the project, carrying out many different tasks. I started off by researching metal detectors and other remote ways of detecting metals and other objects, which naturally led to being on the team that made the first iteration of the metal detector at the Loughborough Workshop. After this, I also helped in further design, production and procurement (particularly the batteries) tasks as well as playing a part in writing up the report. This wide range of tasks was very beneficial as it enabled me to experience many different engineering disciplines. I really enjoyed the mechanical side of the project but was also intrigued by the electrical engineering, particularly the circuit board designed by Dom. I was surprised to learn the interconnectivity between all these different disciplines and I love that to complete an engineering task, you have to look at it in terms of all its parts (mechanical, electrical, structural etc.). I had originally thought that we were nearly finished after the body of the rover and the circuit boards had been assembled so it was an important learning that systems integration is as important a task as any.

I feel that the main learning from the project is collaboration. We worked very well together as a team but I believe that we could have collaborated more on certain issues, such as the design. Our best creative problem solving came when working as a group, such as on our later design changes, so I believe that a larger team working on the original design would have helped the overall project.

I feel that this project has opened my eyes to the many varied disciplines of engineering and I am motivated to learn more about electronic engineering after following Dom's design of electronic hardware and coding after seeing the ease at which Pallav manipulated it. This project has also made me view a possible degree and career as an engineer with excitement as I loved the continuous problem solving that this project entailed.

19.6 James Turvey

This project has really helped me to appreciate what it is to be an engineer. At the beginning of the project I came in naively thinking that the main part of the project would be constructing something interesting and while I was not entirely wrong I have now come to appreciate the amount of detail and rigour in completing a project. One of the key areas that opened my eyes to this was in writing the requirements for the project as my first draft was barely usable and had to be rewritten many times until the mentors produced a very large booklet on requirements engineering for me to use. I had no idea of the intricacies of report writing in order to produce a document that was acceptable for the client and my main take away from this project is that while it is important to produce an end result it is infinitely more important to make sure it is the end result that the customer will be happy with.

The project has also helped my abilities in construction and manufacturing as during the time at Loughborough I was on the construction team. I learned just how important tolerances are in making the production process easier as well as how important it is to plan the manufacturing process as a few fittings were inaccessible to install. Furthermore it is important to lay out minimum, expected and extra completion milestones so that there is always something necessary to complete and there are strict guidelines on what needs to be done. Furthermore the project has improved my technical skills as I only had limited experience working with electronics and metals. I hope to continue to learn more about hardware as I already have software experience and as this project had multiple aspects I did not understand I hope to be able to contribute more to that side of a similar project later on in my career.

Appendixes

Appendix 1: Project Brief

	Young Engineers project options decision matrix						
Criteria	Weighting (1-6)	Fox detector		Pluto rover		UAV hanger	
		Rating	Total	Rating	Total	Rating	Total
Feasibility	3	6	18	4	12	5	15
Complexity	4	2	8	4	16	3	12
Utilisation of skills	5	3	15	5	25	3	15
Project scope	5	2	10	6	30	3	15
Group interest	6	2	12	5	30	3	18
Time scale	3	4	12	2	6	4	12
EES Project Cost	3	4	12	1	3	4	12
Research potential	2	2	4	5	10	3	6
	Total		91		132		105

Decision matrix about choosing the project

Pluto Rover

NASA have shown their interest in allowing Leonardo to work on a prototype for their next mission to Pluto. After the success of New Horizons (which Leonardo contributed to), NASA have begun to plan a mission which will involve sending an unmanned rover to explore the surface of the planet (much like the ones already on Mars). Data analysis from the New Horizons fly-by shows that large deposits of metal, possibly iron, may be present in the Pluto's crust, but NASA do not know for sure.

The task is to create a working prototype which should be capable of:

- ✓ Actively searching Pluto's surface, being able to scale the icy terrain
- ✓ Detecting the presence of metal in the crust

NASA

Rover brief given to us by our client, Leonardo

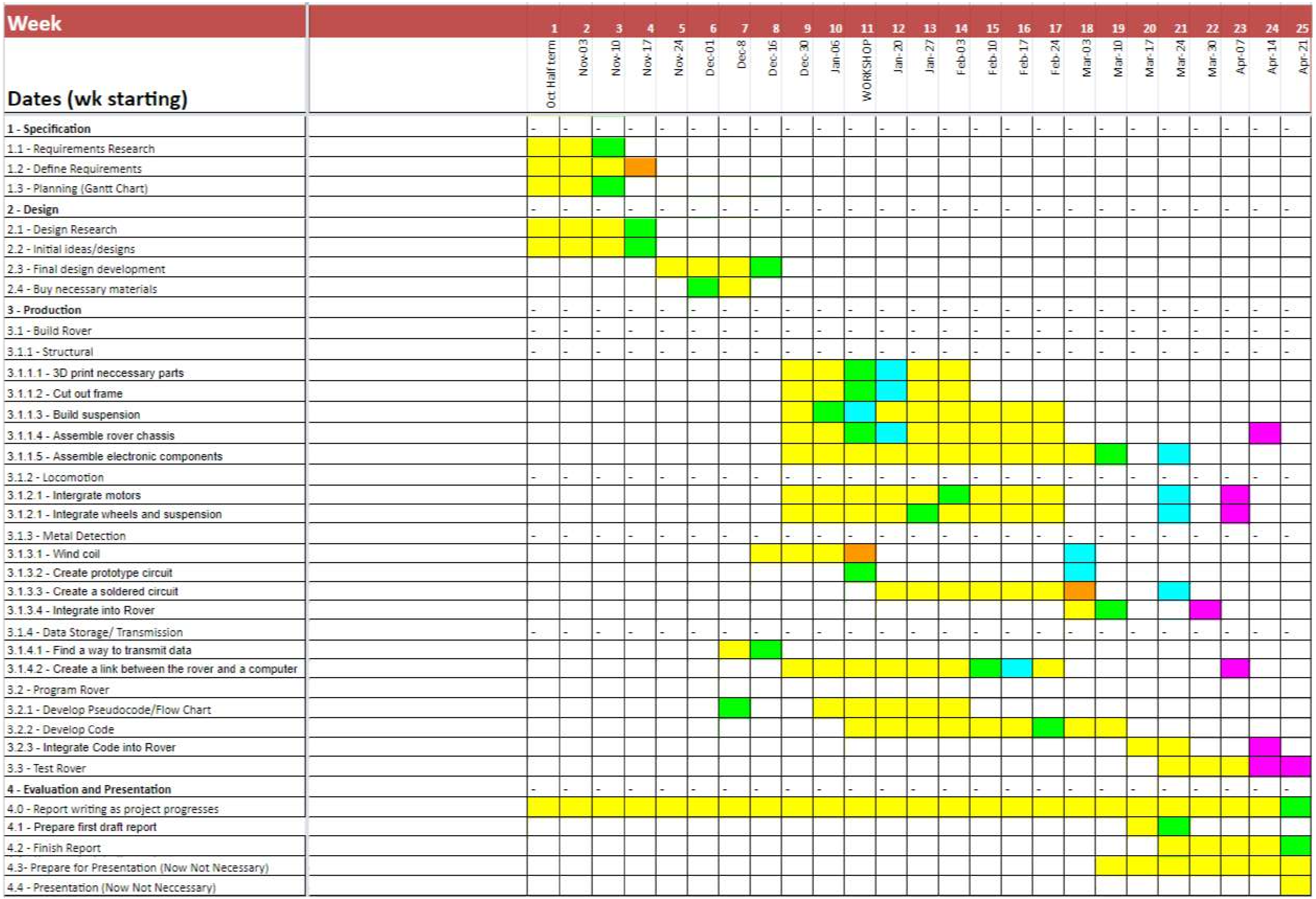
Young Engineers stakeholder importance matrix			
Criteria	Influence/power (1-5)	Interest (1-5)	Engagement strategy
Leonardo (client)	5	5	Manage closely
Us as a team	3	5	Keep them satisfied
School	2	4	Keep them informed
NASA	4	3	Keep them satisfied
Manufacturers	3	1	Monitor
Materials suppliers	1	1	Monitor

Shareholder matrix detailing the importance of different factors in the production of requirements

Appendix 2: Gantt Chart

GANTT KEY (where applicable):
Completed on schedule / early
Completed late
Planned
Integrated
Completed test

Gantt chart key



Gantt chart used for time management of the project

Appendix 3: Additional celestial rover information

Lunar rovers

The surface of the Moon is characterised by the layer of regolith on top of the solid basalt underneath. Due to the Moon not having an atmosphere, it had nothing to protect itself from Small Solar System Objects crashing into its surface, creating the heavily cratered surface (especially on the far side of the Moon) and resulting in lots of loose rock being scattered on the surface. This creates a number of problems for lunar rovers, as they need to be able to avoid rocks and craters that are too large to just drive through, as well as being able to cope with the poor traction caused by the loose rock underfoot.

Lunar rovers also have to comprehend the difficulties associated with the lunar day length of 29.5 days (or one Earth month). While lunar rovers receive direct sunlight for about 14 days and can, therefore, rely on solar panels for an energy source, the equally long about 14 day night creates other issues, namely the frigid temperatures of -150°C which has a high risk of damaging the onboard batteries (due to the rapid discharge of current during cold temperatures) or freezing any moving parts (such as motors). At the other end of the spectrum, during the lunar day, the temperature can reach as hot as 100°C when in direct sunlight because of the absence of an atmosphere.

The Apollo rovers used a standard four-wheel design much like a beach buggy because the rover was being driven by an astronaut and could, therefore, be easily controlled to avoid and large obstacles or areas where there may be lots of loose rocks causing especially poor traction.

However, unmanned lunar rovers have the added dimension of not being able to always rely on human intervention if they are about to crash into an obstacle or enter and area with reduced traction, due to the 2.4-2.7 seconds that it takes for data to travel to the Moon and back.

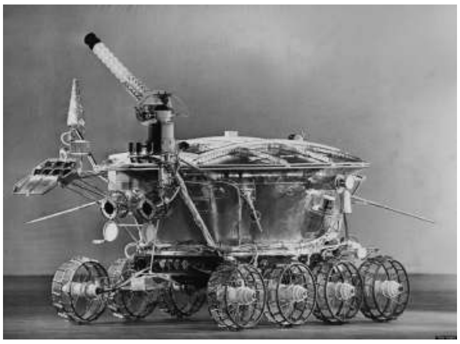


Figure 19.1: The picture above is an image of the Russian rover that was the first to go to the Moon

The Lunokhod 1[62] was the first roving remote-controlled rover to land on another celestial body, having landed on the Sea of Rains on the Moon in November 1970 (while still in the Luna 17 rocket). The rover was controlled via images from the two navigation cameras from mission control back in the USSR, with the drivers compensating for the lag time in the images showing how the rover had just moved. The rover was powered by solar panels to allow for a long life-span of the mission, with a polonium-210 radioisotope heater onboard to provide thermal energy to prevent the batteries from completely discharging during the long lunar night. In order to address the traction problem caused by the abundance of loose rock, the Lunokhod 1 rover was driven by 8 individually powered wheels (which would allow the rover to continue should one motor break). Each pair of wheels were joined together by leaf springs in order to reduce moving parts, and the steering of the vehicle was achieved by adjusting the speed of the motors on each side of the rover. The rover also featured a system that would stop the rover if the rover was tilting at an angle that risked it rolling over. The rover had dimensions of 4.42m x 2.15m x 1.92m allowing it to have enough space for the large electronics equipment of the day. The rover used a free-rolling 9th wheel sticking out of the underside of the rover to allow for an accurate distance travelled to calculated, therefore aiding finding the location of the rover when looked for with a telescope.

This was followed by the second Lunokhod 2 rover, which had a mission aim of collecting images of the lunar surface, work out the distance between the Earth and the Moon using lasers, observe solar X-rays, measure local magnetic-fields, study the soil mechanics of the lunar material, and to look at the ambient light on the Moon to see whether long-term manned observations on the Moon (where there is no atmosphere to distort observations) may be possible. The second rover was much smaller than the first, having dimensions of 1.7m x 1.6m x 1.35m, but featured the same individually-driven 8-wheel design steered with tank steering. The rover had two speeds of 1kmh-1 and 2kmh-1, as the slow speed helped to improve the longevity of the rover and gave more reaction times if the rover was about to crash as the rover was controlled by scientists on Earth using the images coming from the rover. The rover was immensely successful, travelling 39km over its lifetime, a mark only currently surpassed by Curiosity. A lack of funding caused the Lunokhod programme to be cut short after the 3rd rover had been built and therefore never saw action in space.

Since the launch of Lunokhod 2 in 1973, there were no new lunar rovers until the Chinese Chang'e 3 mission's Yutu rover which landed in 2013. The project demonstrated China's ability to perform a soft-touchdown on the Moon and is hoped to be the first rover to investigate the structure of the lunar crust down to a depth of 30m (using ground-penetrating radar), as well as using an Alpha Particle X-Ray Spectrometer to analyse the chemical makeup of any samples collected. The lander uses a Radioisotope Heater Unit (RHU)(provides about 1 watt of thermal energy caused by the decay of a few grams of plutonium-238) in order to keep all the components warm enough during the 14 day lunar night, as well as solar panels to recharge the batteries during the lunar day. In order to prevent the rover from crashing into obstacles, three pairs of cameras were positioned on different parts of the rovers to allow for image distancing by triangulation to build up a 3D model of the terrain in front of the rover. The rover features a 6-wheel design with 4 wheel steering to allow for rapid manoeuvring and has dimensions of 1.5m long, 1m wide and 1m high. The rover also utilises the rocker-bogie suspension setup developed by NASA in 1988 for its Sojourner Mars rover, which minimises moving parts.

Figure 19.2: China's Chang'e 3 mission rover showing-off its high centre-of-gravity design, which has the advantage of allowing the large solar panels to fold down against the side of the rover when traveling

The Chang'e 4 mission carried the second generation Chinese rover, Yutu 2, onto the surface to the Moon to further investigate the structure of the Moon, by examining a large crater which is thought to have exposed the upper layers of the mantle because of the huge impact. The crater that is being studied (the mission is still ongoing) is located on the far side of the moon, which makes communication with the rover from Earth difficult. The Chang'e 4 mission, therefore, uses a relay satellite positioned at Langrangian point 2 in the Earth-Moon system, allowing for data from the far side of the Moon to be received using microwaves. The rover has a very similar design to the previous Yutu rover (having been built as a backup to the first rover) and therefore features the same RHU and Solar panel setup to power the six wheels, same steering system, same suspension setup and same dimensions.

Mars rovers

The Soviets were the first superpower to try and put a rover on Mars as part of their Mars Programme. The Mars 2 and 3 rovers were identical in design, as the landing of Mars 2's lander was not successful resulting in the destruction of the rover inside. Similarly, the Mars 3 rover, although becoming the first spacecraft to successfully make a soft landing on Mars, failed 20 seconds after the landing. The rover remained attached to the lander via a 15m umbilical cord for power and moved around (propulsion source unknown) on two skis. Due to the large communications lag, the rover was self-driven, with two bars at the front of the rover to detect if it had collided with an object. The Soviets once again tried to put a rover on Mars (in conjunction with NASA), which featured 6 wheels which utilising tank-style steering. Each of the three axles had the ability to revolve around the centre chassis, ensuring that all 6 of the wheels remained in contact with the ground at all times.

The first successful rover to operate on Mars was the NASA Sojourner rover which landed in 1997. The rover was powered by a single non-rechargeable battery and solar panels, which therefore restricted the operating capabilities of the rover to the day when the battery was drained. Unlike the Moon, Mars has a lot shorter day and night (almost exactly the same as an Earth day) which therefore reduces the importance of keeping the robot warm during the night as there is less time for the batteries to be drained (the main concern associated with extremely cold temperatures). The rover featured a 6-wheel design on a brand new rocker-bogie suspension that minimised the moving parts required in the suspension setup while still ensuring all 6 wheels were in contact with the ground at all times, maximising traction on the tricky Mars surface. The rover was very small in size, with 130mm wheel diameter, but the 4-wheel steering setup allows for good manoeuvrability to avoid obstacles. The height of the rover was also adjustable to allow for the rover to become more compact for traveling in the lander, which can be seen in the photo below. Furthermore, the 0.4m/min top speed allowed for the onboard autonomous driving system to easily have enough time to identify and then avoid obstacles.

One of the main aims of this mission was to test out the autonomous driving technology, as well as to test driving on unknown terrain. As per the majority of celestial rovers, the main power sources come from the solar panels which are powered during the martian day, which an insulated body (including using special high and low emissivity paints) and three 1W RHUs made sure the temperature remained warm enough that the electronics would not be damaged during Mars' night. The mission used a relay system of sending data from the rover to the lander for later transmission to Earth. The main instrument on the rover was an Alpha Proton X-Ray Spectrometer that allowed the elemental composition of rocks to be determined.

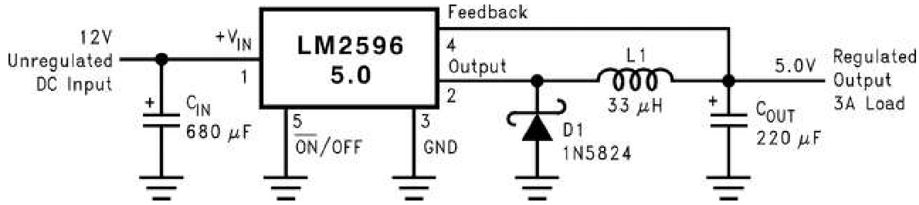
Figure 19.3: NASA's Soujourner rover in compact storage position to minimise space on the flight to Mars

The Beagle 2 was a British Mars Lander deployed by the ESA to look for signs of previous life on Mars. The lander was not a rover as such, given that it was designed to operate from the same location that it touched down in, but had some important instruments onboard to allow for the study of the nearby Mars surface. The lander featured a robotic arm with a microscope attached to it, allowing for detailed images of nearby rocks to be taken. Samples could also be taken to be looked at by the onboard mass spectrometer and gas chromatograph to look at the chemical makeup of the nearby rock.

Appendix 4: Picking components for DC step downs [63]

This section has been included to evidence how we selected components for the entire circuit. We only evidenced this section as a demonstration, in reality chosen parts changed multiple times based on availability and many other factors so it would be impractical to evidence the entire circuit.

'ESR' is equivalent series resistance; real capacitors are not ideal but can be approximated as an ideal capacitor in series with a resistor. For our application, it is important this resistance is low.



Example circuit shown above (ANSI symbols)

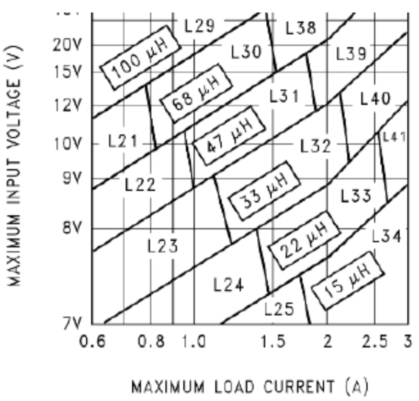
D_1 requirements:

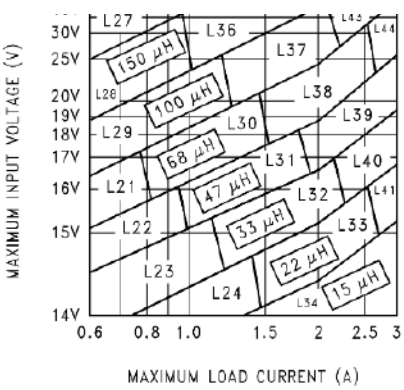
- Current rating at least 1.3x maximum load (3A)
- Fast Recovery $\leq 500ns$
- Reverse voltage rating at least 1.25x max input (16.8V)

For both the 5v and 12v converter the PMEG3050BEP is a suitable diode.

L_1 requirements:

- Inductor selection graphs for both 5v and 12v converter models in continuous operation.
- Maximum input voltage: 16.8v (4S charged li-ion)
- Maximum load current: 3A



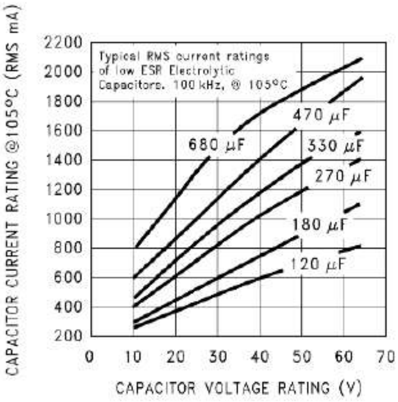


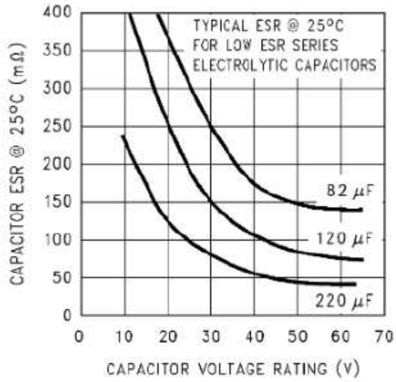
Because we plan to have two regulators, ideally we use torroid or E-core inductors rather than bobbin, rod or stick core. The former have closed magnetic structures meaning they are less likely to interfere with each other (or the feedback line). The current rating must be above the maximum load current (3A).

For both 12v and 5v converters, a $33\mu H$ inductor is suitable, rated for at least 3A. We chose the 7447709330 which is rated for 4.2A.

C_{IN} requirements:

- Low ESR aluminum electrolytic (solid tantalum capacitors can be used but require extra precautions).
- RMS current rating must be at least $\frac{1}{2}$ DC load current (3A).





Due to both current rating increasing and ESR decreasing as the voltage rating increases, we will use capacitors rated for significantly higher voltages than ever present

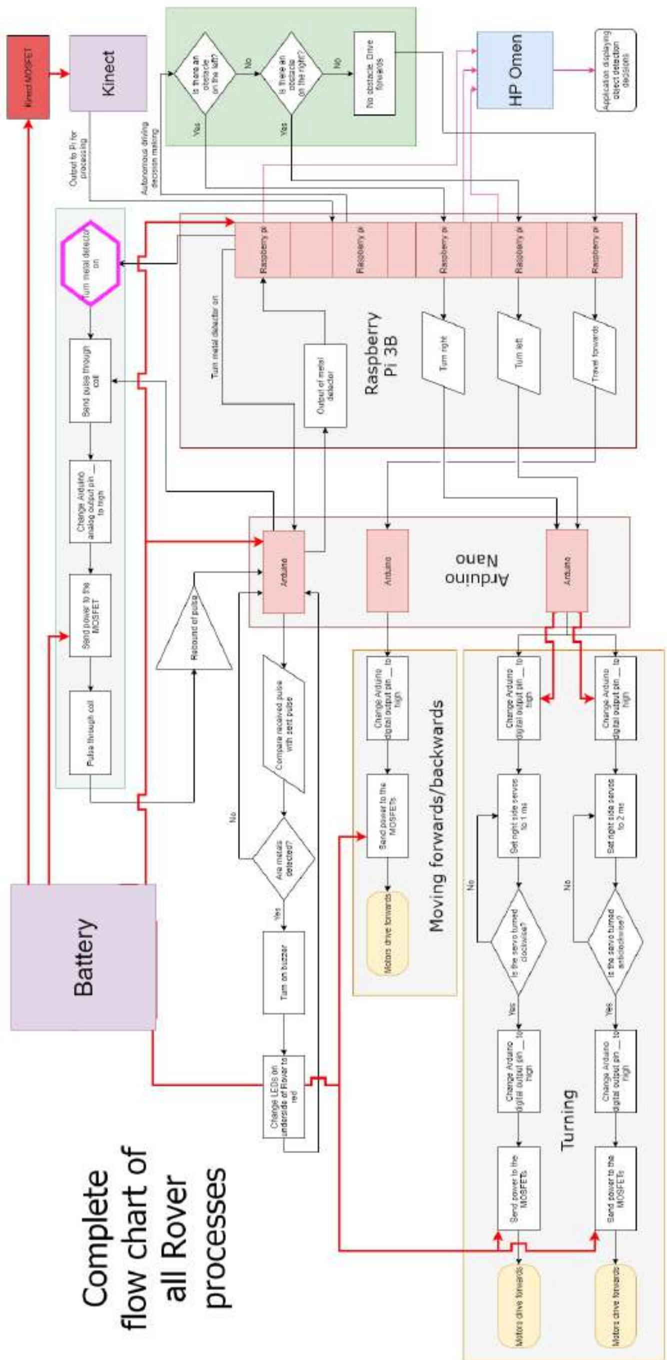
- Voltage rating must be at least 1.5 times greater than the maximum input voltage for an aluminium electrolytic (16.8V).

For both 12v and 5v converters, a $680\mu F$, 35V electrolytic capacitor with low impedance will be suitable (this should have a high enough RMS current rating) - EEVFK1H681M

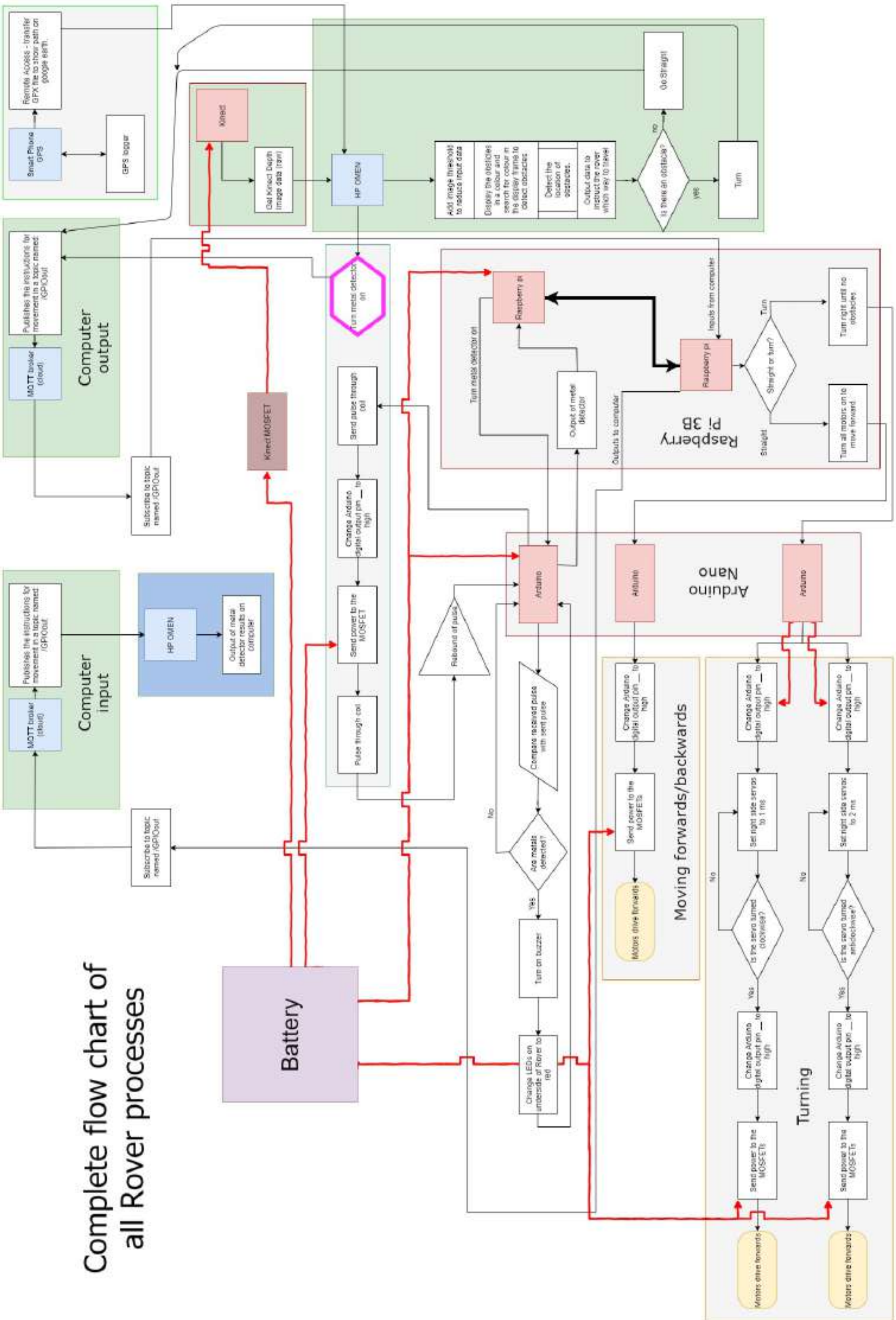
C_{OUT} **requirements:**

- Low ESR, determined by maximum allowable ripple voltage of 1%-2% of output.
- As recommended by the datasheet of IC, suitable for both 5V and 12V converters a $330\mu F$ 35V electrolytic capacitor - EEEFK1V331P. ESR is $80m\Omega$.

Appendix 5: Technical Drawings



Final functional flow diagram of the rover, using the Raspberry Pi for all the processing in the rover



Initial rover flow chart before all the Kinect processing was able to be run independently on the Raspberry Pi

Appendix 6: Servo linkage static stress analysis

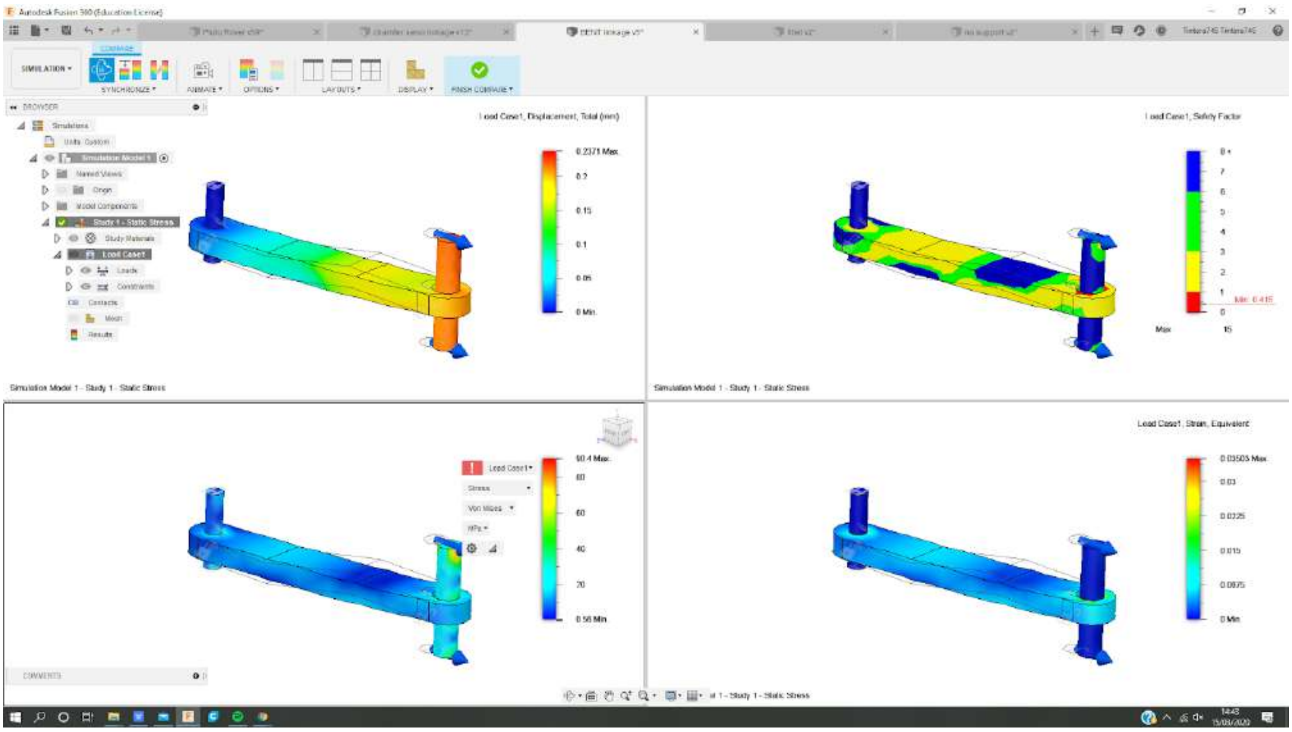
Fusion 360 static stress analysis on the four servo linkage designs (Colour from Figure 8.2 in chapter 8):

- Red $\implies$ bent linkage
- Green $\implies$ countersunk linear linkage with no support
- Yellow $\implies$ countersunk linear linkage with chamfer (45°) support
- White $\implies$ countersunk linear linkage with fillet (constant radius) support

Each stress analysis image shows 4 simulations when 200N of force is applied to the right pin in the positive x direction:

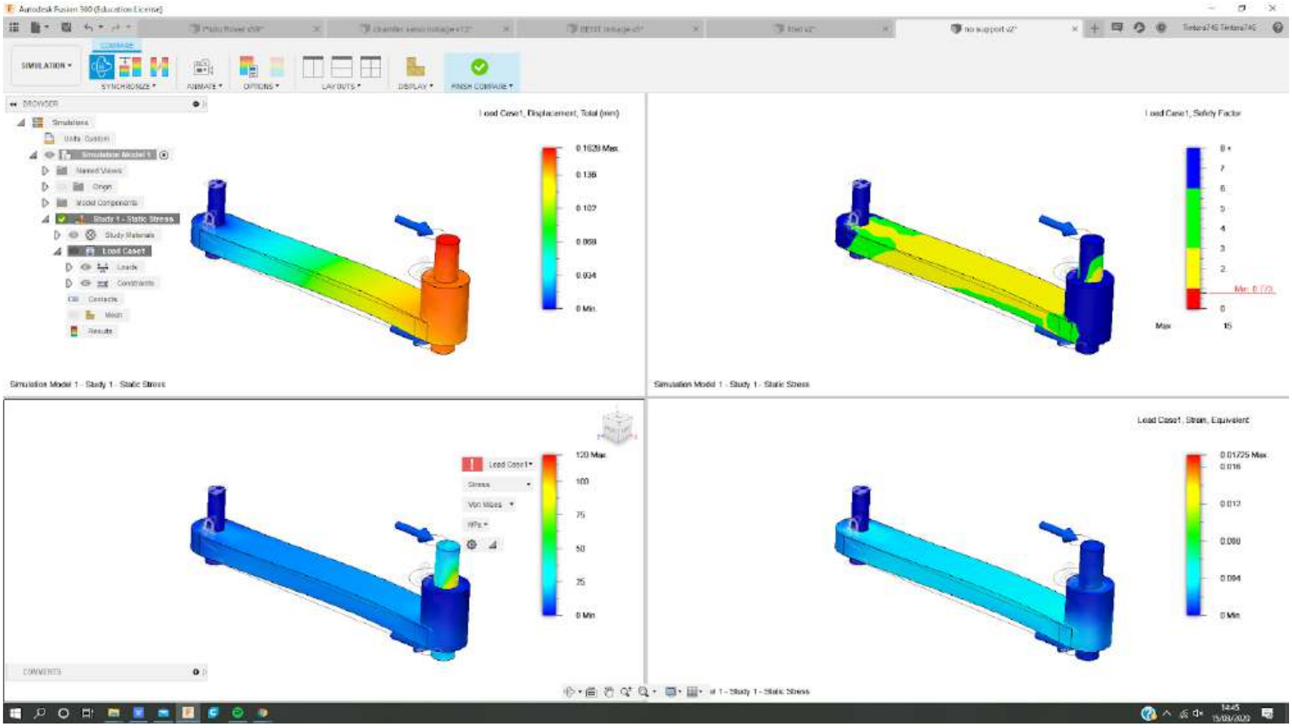
- Top left $\implies$ displacement (mm)
- Top right $\implies$ safety factor (0-15, where low scores are likely to fail)
- Bottom left $\implies$ stress (Nm^{-1})
- Bottom right $\implies$ strain (unitless, representing the percentage by which the original length of the linkage changes when force is applied)

The large force applied (200N) to the linkage is more than is expected to be applied to the linkages. However, as the value is closer to the breaking point of the linkages, the best design can be ascertained more easily. The majority of this decision comes from comparing the safety factor of each of the designs, as this acts as a numerical representation of how the design performs across all of the simulated areas. This value can be seen plotted on the scale of the top right simulation output.

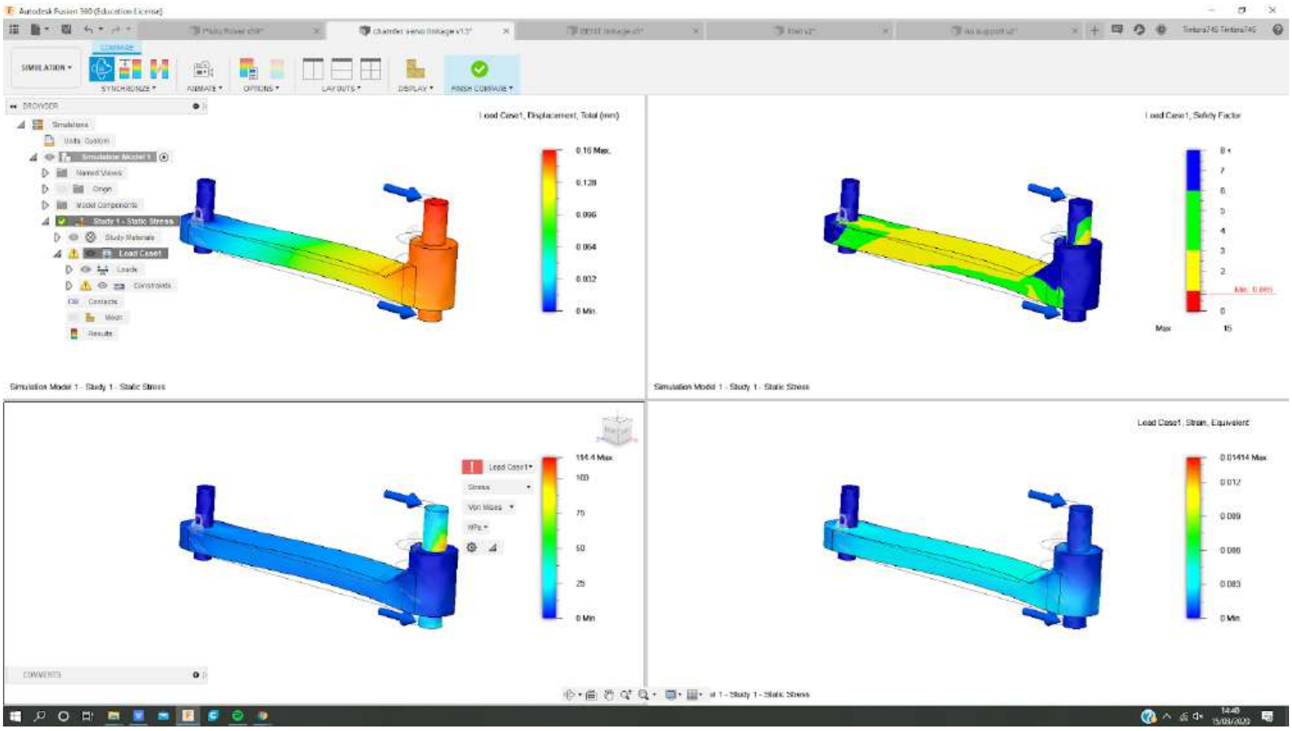


Bent servo linkage design (red) static stress analysis

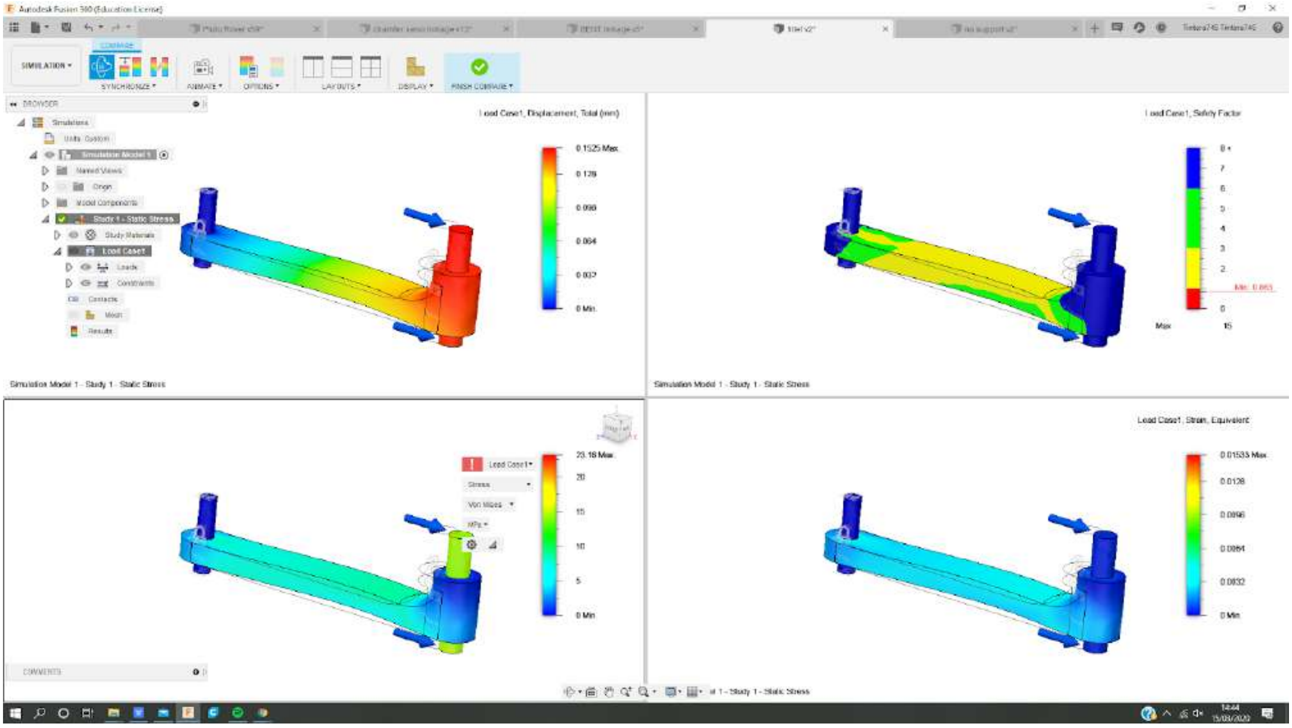
The test was carried out in a controlled environment, with all forces and contacts being applied at the same place for each test. For example, the same material was used for all the tests (ABS, as this was the closest material to the PETG we are using) and the rod to which the force was applied to was the same length. In the case of the simulations, the two rods at each end simulate the bolts which would connect to the rest of the linkage, attaching it to the servo and the rest of the steering system.



No support countersunk servo linkage design (green) static stress analysis



Chamfer support countersunk servo linkage design (yellow) static stress analysis



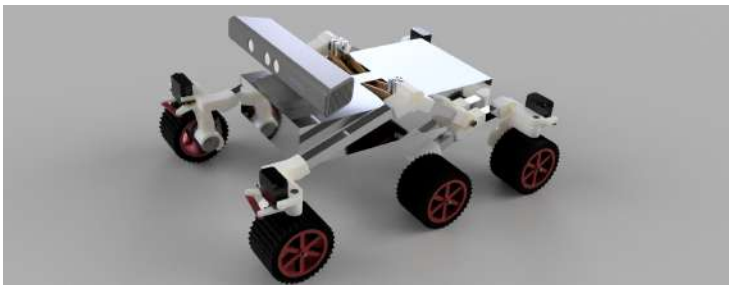
Fillet support servo linkage design (white) static stress analysis

The stress analysis concluded that, although all the designs performed similarly, the chamfer support design was the strongest with a safety factor of 0.865 compared to 0.863 of the fillet support, 0.772 of no support and 0.415 of the bent linkage.

Appendix 7: CAD design process

Initial rover structural design using $20 \times 20mm$ *extruded aluminium and wooden laser-cut cross brace*

Early-stage render including two solar panels



Full render with old wheel design

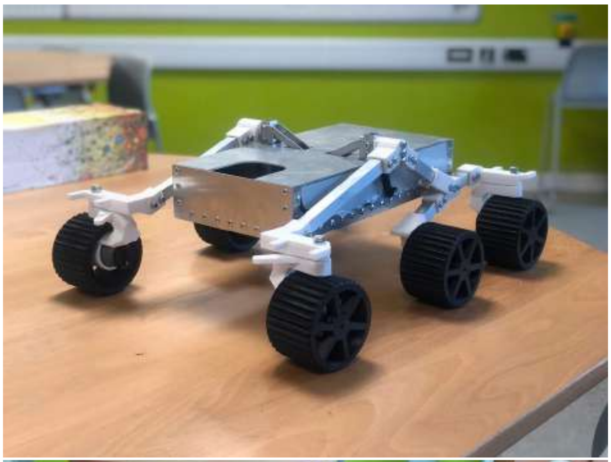
Sub frame of the rover

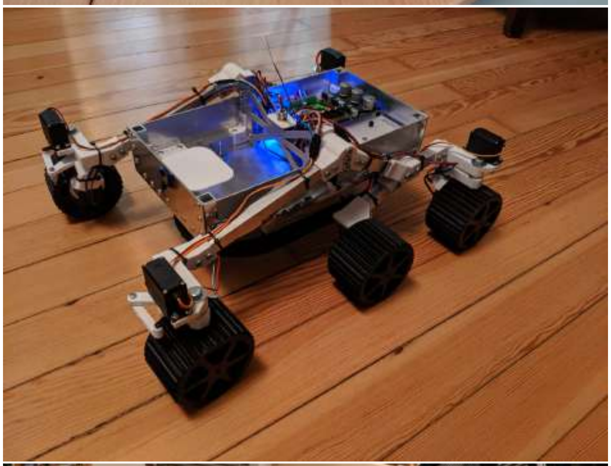
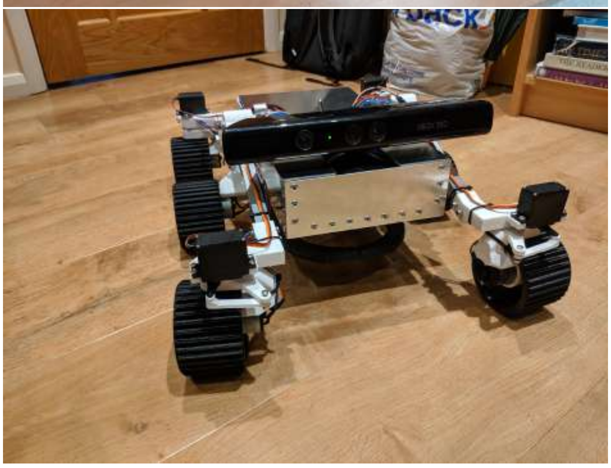
Appendix 8: Testing Gallery

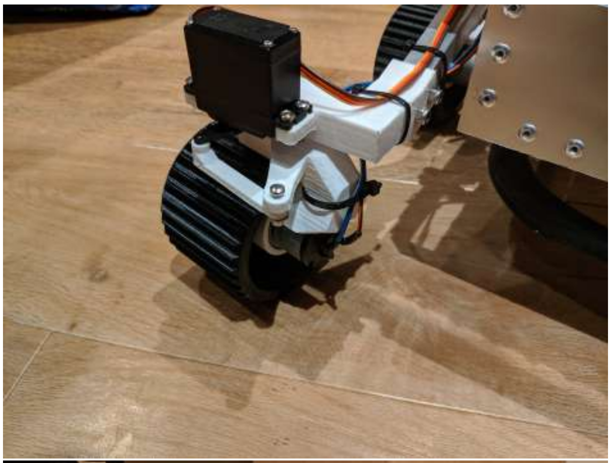


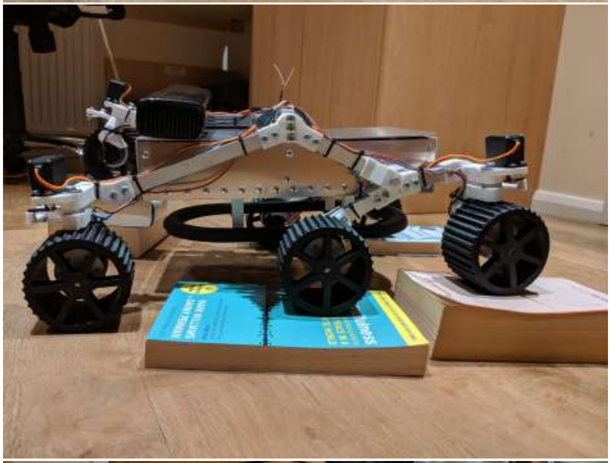
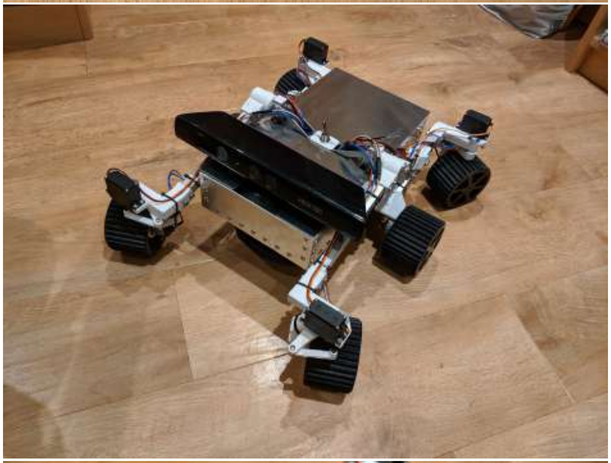
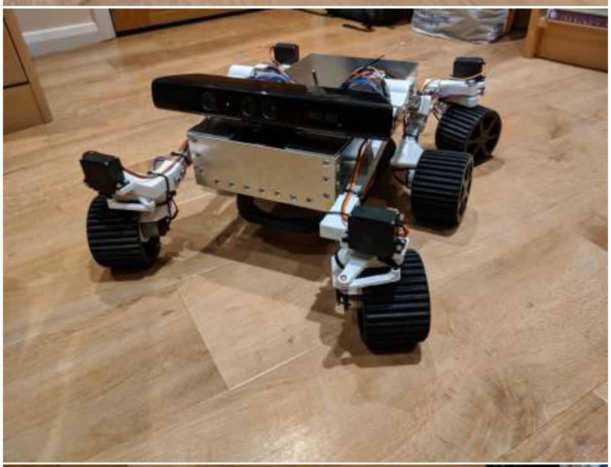
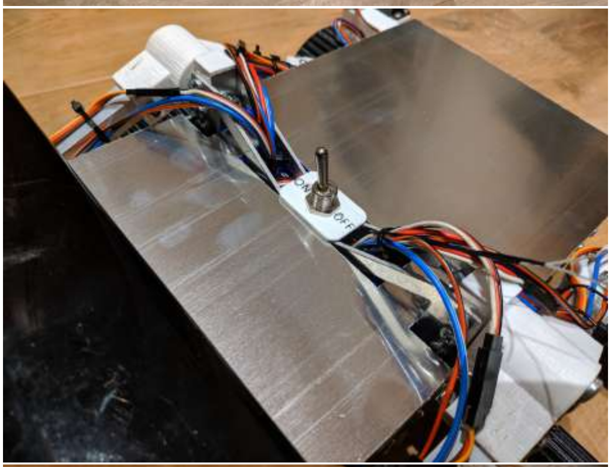
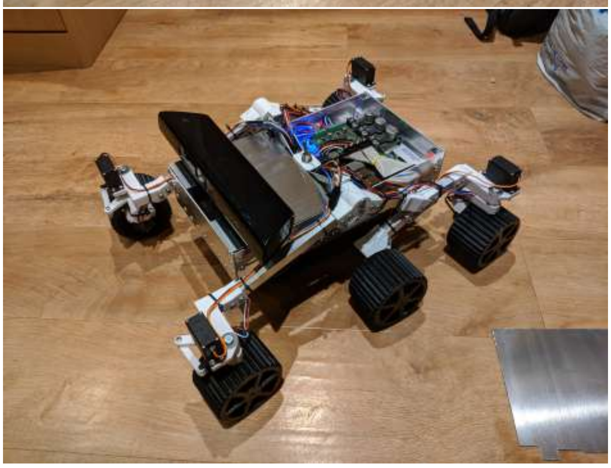
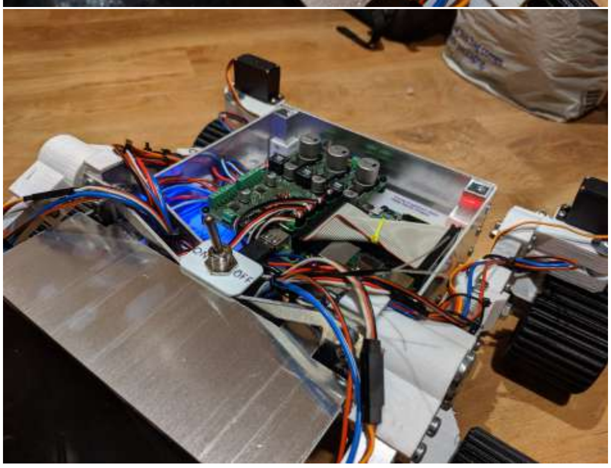


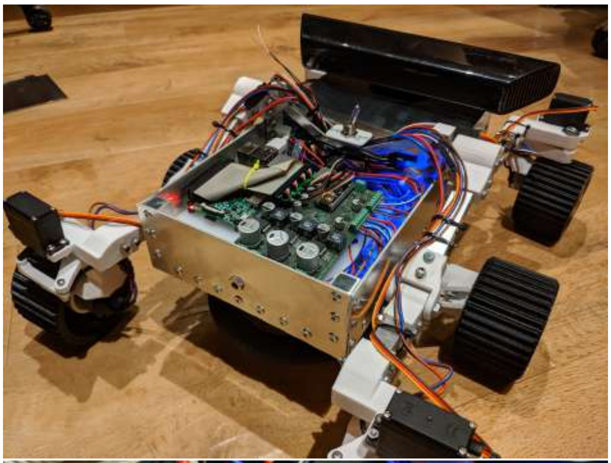
Appendix 9: Gallery

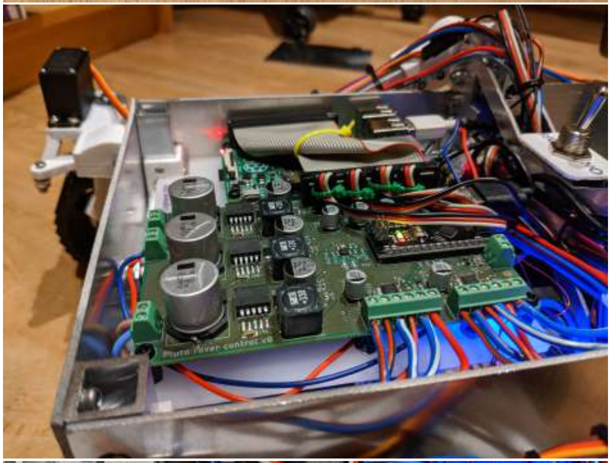


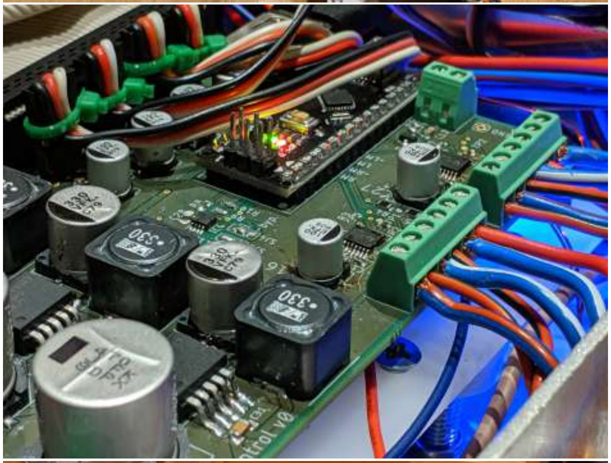




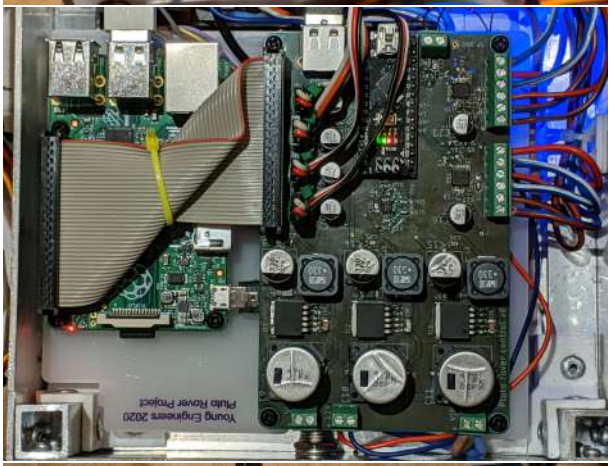







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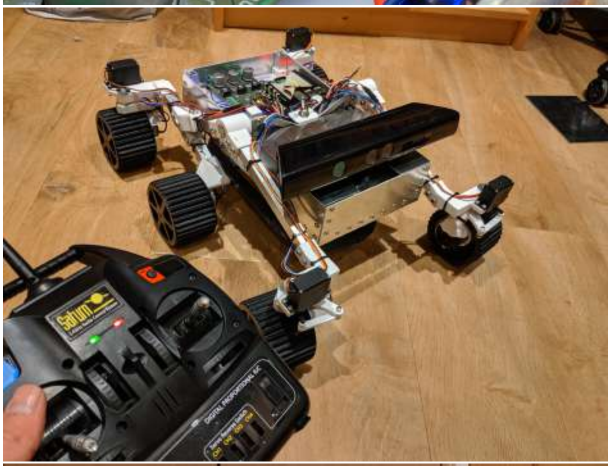

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