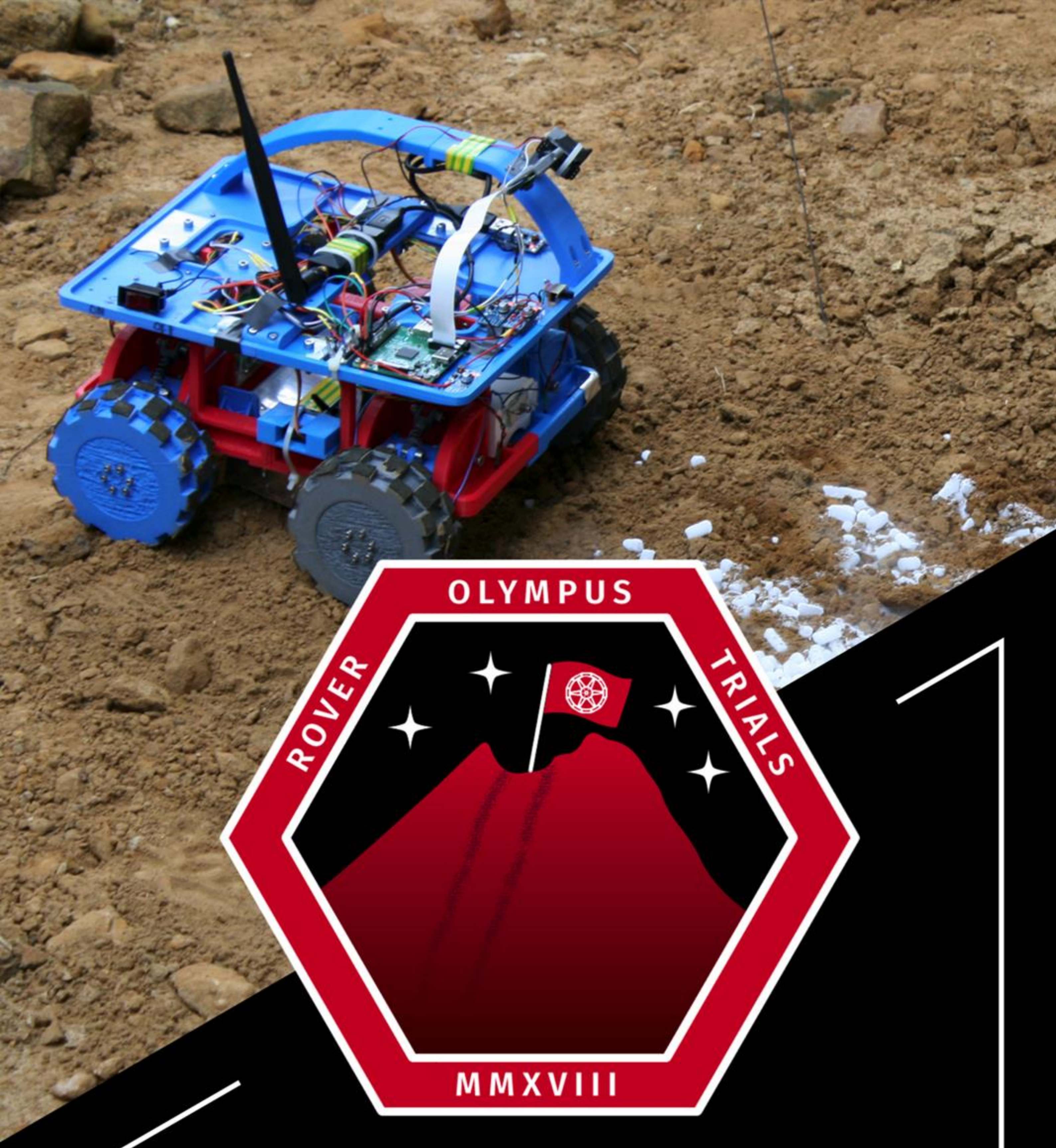


ROVER OLYMPUS TRIALS

MMXVIII

# Oxfonauts
University of Oxford

2018 – 2019

Team Name: Oxfonauts
University: University of Oxford
Submission Date: 17/03/2019

# Olympus Rover Trials CDR

Oxfonauts

2019

## CONTENTS

Issued by: Matthew Budd and Project Team
University: University of Oxford

# 1 INTRODUCTION

We are a team of Engineering and Computer Science undergraduates from the University of Oxford, working towards a successful run in the Olympus Rover Trials challenge. Our team is supported by the Oxford University Rocketry Society. This CDR document summarises all design work performed on the rover, as well as the status of the autonomous functionality.

## 1.1 Mission Statement

Our team aims to deliver effective autonomous capabilities on a Mars rover platform, combining space-proven designs with advances in ground-based robotic technologies.

# 2 PROJECT MANAGEMENT

## 2.1 Assigned Roles & Team Roster

| Name | Roles | Year/Course | Contact Details |
|---|---|---|---|
| Matthew Budd | Project management and systems engineering | Engineering Science Y3 | matthew.budd@pmb.ox.ac.uk |
| Benjamin Bernhard | Electronics Engineering and Kinematics Design / Analysis | Engineering Science Y3 | benjamin.bernhard@new.ox.ac.uk |
| Daryl Koo | Autonomous Systems Engineering and Architecture | Engineering Science Y3 | daryl.koo@lmh.ox.ac.uk |
| Yi Fong Mah | Electronics Engineering and Manual Control System Design | Engineering Science Y1 | yifong.mah@hmc.ox.ac.uk |
| Ollie Matthews | Electronics Engineering and Kinematics Design / Analysis | Engineering Science Y3 | oliver.matthews2@univ.ox.ac.uk |
| Maximilien Tirard | Autonomous Systems Engineering and Architecture | Maths and Computer Science Y1 | maximilien.tirard@lmh.ox.ac.uk |
| Teodor Totev | Autonomous Systems and Communications Engineering | Engineering Science Y3 | teodor.totev@stcatz.ox.ac.uk |
| Manoj Abhishetty | Body, Suspension System and Drive Train Engineering | Engineering Science Y2 | manoj.abhishetty@oriel.ox.ac.uk |
| William Dolke | Body, Suspension System and Drive Train Engineering | Engineering Science Y2 | william.dolke@magd.ox.ac.uk |
| Joanna Heymann | Canister Pickup/Storage Mechanical Design Engineering | Engineering Science Y2 | joanna.heymann@new.ox.ac.uk |
| Jared Maritz | Body, Suspension System and Drive Train Engineering | Engineering Science Y3 | jared.maritz@stcatz.ox.ac.uk |
| Amelia Standing | Canister Pickup/Storage Mechanical Design Engineering | Engineering Science Y1 | amelia.standing@st-annes.ox.ac.uk |
| Yifeng Wei | Body, Suspension System and Drive Train Engineering | Engineering Science Y2 | yifeng.wei@pmb.ox.ac.uk |

*Table 1: Assigned Roles & Team Roster.*

## 2.2 Project documentation and management systems

- ➔ Work Package progress is tracked by weekly meetings for the Mechanical and Electronics/Software sub-teams, and instant message communication via Slack.
- ➔ Version control for software and electronics is achieved with a Git repository on GitHub.
- ➔ Version control for mechanical parts is achieved with a shared OneDrive with file version history. Important project documents are also version controlled in this folder.
- ➔ Kit tracking and spending tracking is achieved with an access-controlled online spreadsheet. The spending tracking spreadsheet is reviewed by the OURS Treasurer.

## 2.3 Technical Work Breakdown Structure

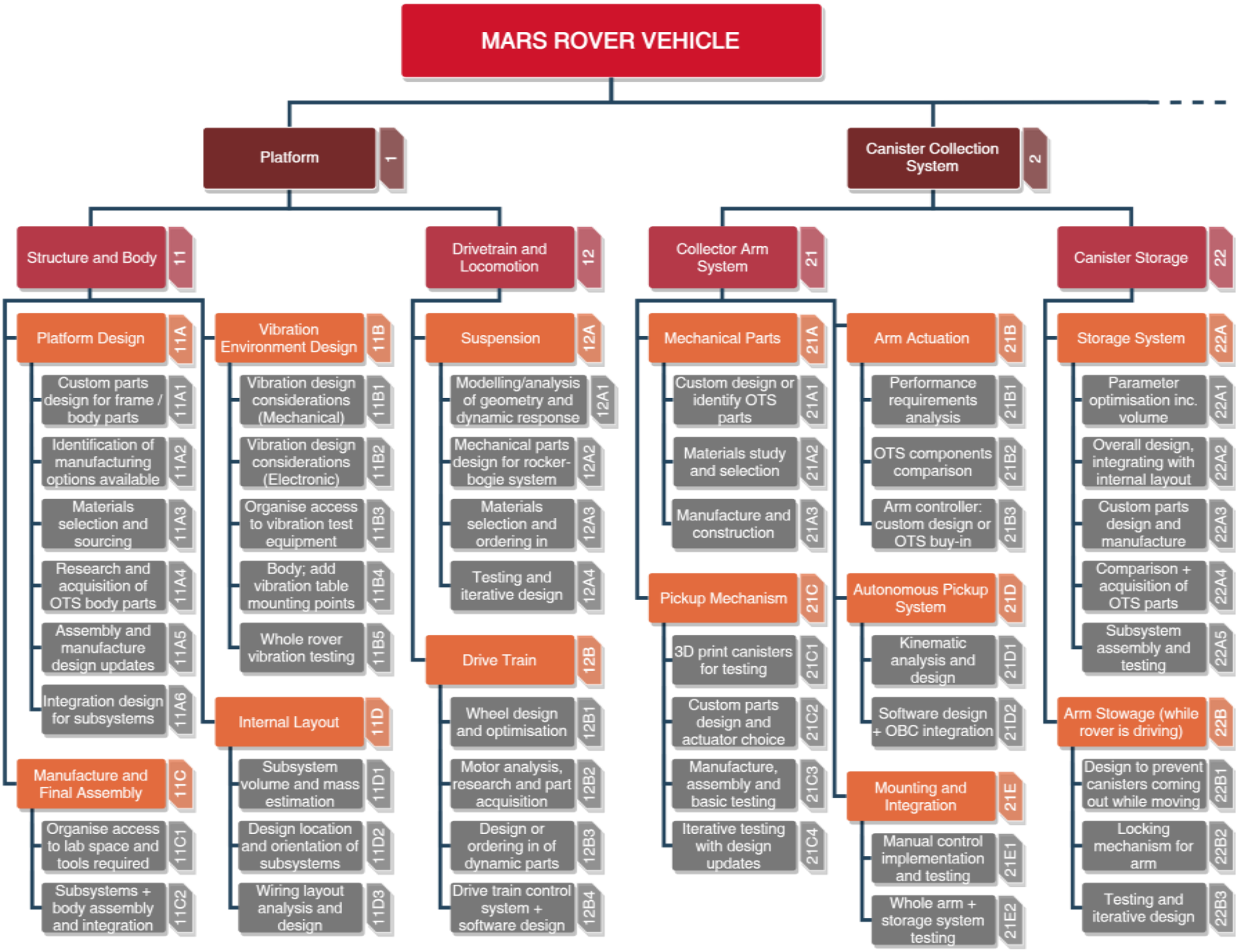


*Figure 1: LHS of Work Breakdown Structure, with Task Identification Numbers.*

## 2.4 Work Package Allocations

| Initials | Assigned Tasks | | | | | | **bold** = responsibility for Work Package | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MB | **11A2** | 11A6 | **11B3** | **11C1** | **12B2** | **21C1** | **31A1** | **31A2** | **33B2** | **41A1** | **41A2** | **41B1** |
| BB | 12B4 | **21B1** | **21B2** | **21B3** | **21D1** | **21D2** | **21E1** | 32C4 | **41B2** | 41B4 | | |
| DK | 31A3 | **31A4** | **31A5** | 32C2 | 32C3 | **32C4** | | | | | | |
| YFM | 31A3 | 31A6 | **31B1** | 31B2 | **32C1** | 32C4 | **33C1** | **33C2** | 41B4 | | | |
| OM | **11D3** | **12B4** | 21D1 | 21D2 | 31A3 | **31B2** | 32C4 | **33B1** | 33B2 | 33C1 | **41B3** | 41B4 |
| MT | 31A3 | 31A4 | 31A5 | **32C2** | **32C3** | 32C4 | **33A1** | **33A2** | **41A3** | **41A4** | | |
| TT | **31A3** | 31A4 | **31A6** | **32A1** | **32A2** | **32B1** | **32B2** | 32C4 | **33A3** | | | |
| MA | 11A1 | **11B1** | **11B2** | **11B5** | **12A3** | 21C4 | 22A5 | 22B3 | | | | |
| WD | 11A1 | 11B1 | **11B4** | 11C2 | **11D1** | **11D2** | **12A1** | **12A2** | **12A4** | 22A5 | | |
| JH | 11C2 | 11B5 | 11D1 | **21A1** | **21A2** | **21A3** | 21C3 | 21E1 | **21E2** | **22A2** | **22B1** | **22B3** |
| JM | **11A1** | **11A4** | **11A5** | **11A6** | 11C2 | 11D1 | **12B1** | **12B3** | 22A5 | 22B3 | | |
| AS | 11C2 | 11D1 | 21A3 | **21C2** | **21C3** | **21C4** | 21E2 | 22A2 | **22A3** | **22A4** | **22B2** | 22B3 |
| YW | 11A1 | **11A3** | 11C2 | 11D1 | 11D3 | 12B2 | 12B4 | **22A1** | **22A5** | 22B3 | | |

*Table 2: Work Package allocations as of submission date.*

## Technical Work Breakdown Structure - Continued

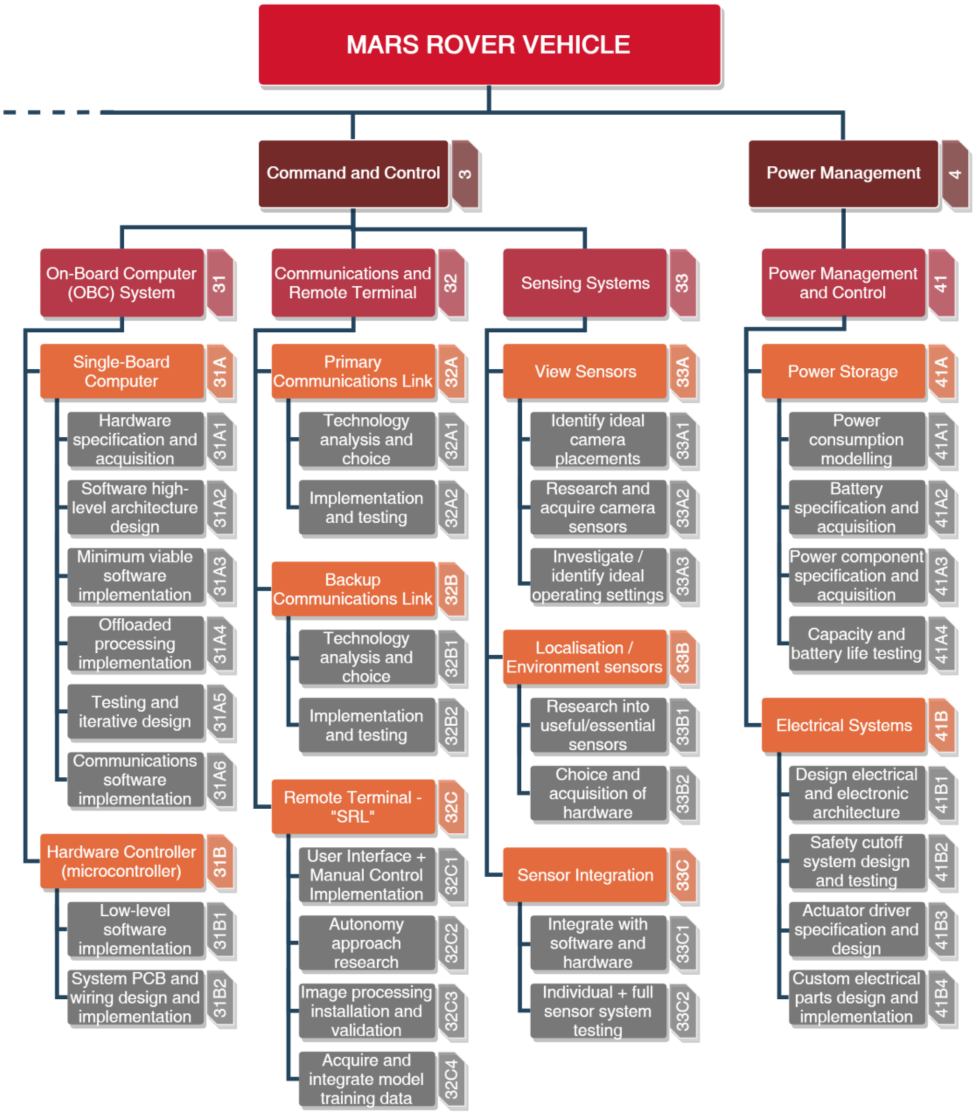
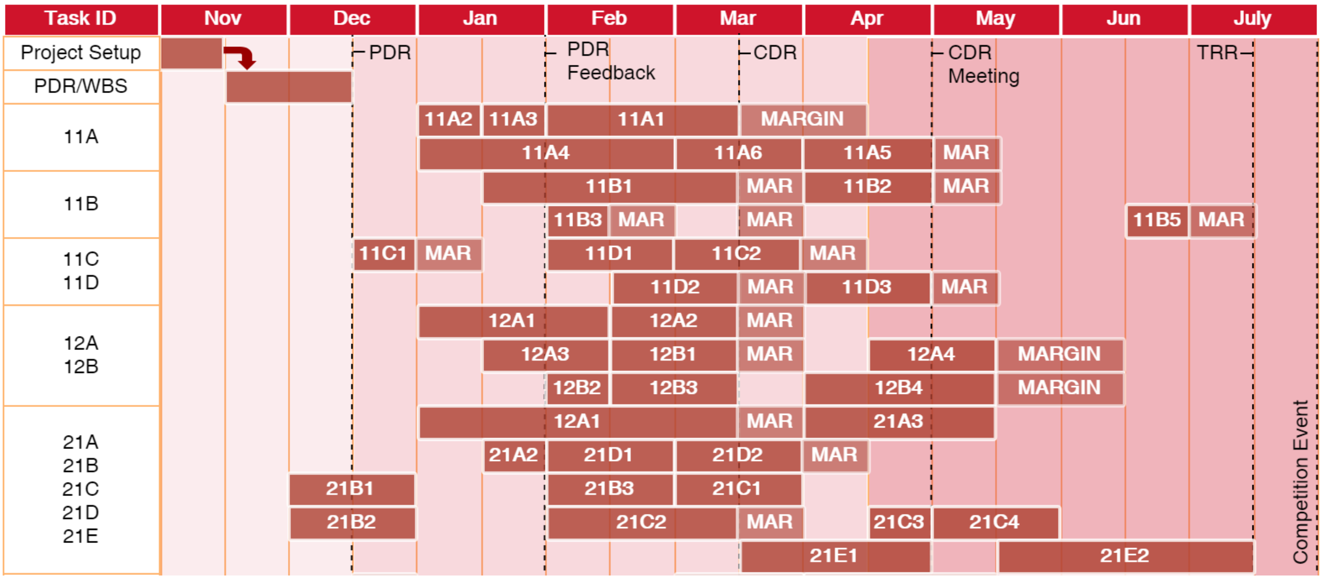


*Figure 2: RHS of Work Breakdown Structure, with Task Identification Numbers.*

## 2.5 Schedule



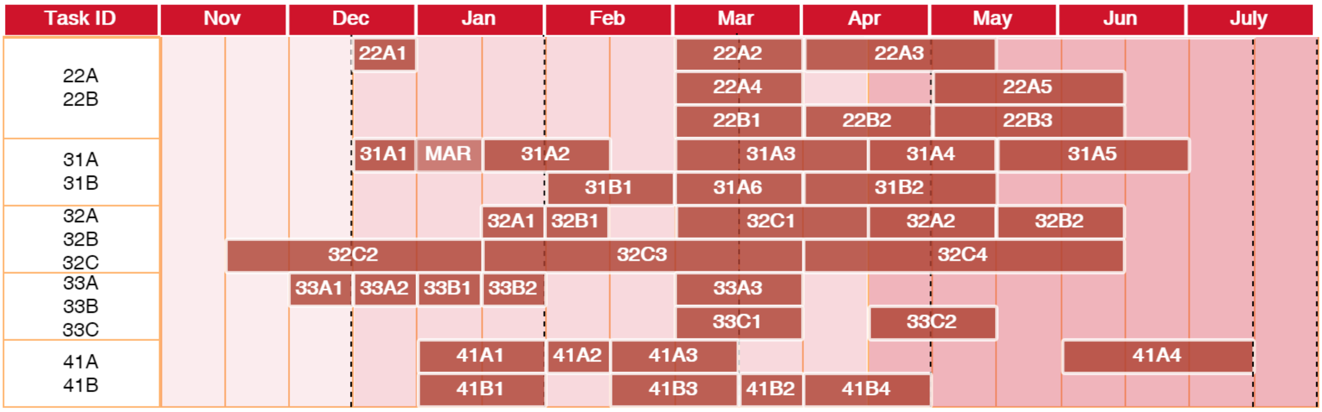


*Figure 3: Project Schedule.*

## 2.6 Test Plan

**Derived high-level requirements from PDR:**

A) System should be operational in a wide variety of conditions.

B) System should take less than 10 seconds to collect 1 canister.

C) Autonomous canister collection - rover should be capable of autonomously collecting canisters when driven to the correct position manually.

D) Power - should be capable of powering the rover for at least 30 minutes and 40 metres travelled.

[R] are from the Rules & Requirements document [1]. Technical requirements are found using the Group IDs.

| ID | Relevant Group IDs | Relevant Requirements | Test Description |
|---|---|---|---|
| T1 | 11A, 11C, 11D | [1.1 Mass]<br>[1.2 Volume] | **Mass and Volume compliance test:** Measure the mass and volume of the rover or rover subsystem and confirm that it matches the mass/volume budget for that part, within the margin. If not, identify the issue and update budgets if necessary. |
| T2 | 11A, 12A, 12B, 21A, 21C, 21E | [1.5 Static Stability] | **Static stability test:** test the static stability of the rover, with and without the collection arm deployed, on a range of inclines up to 30°. Rover should be capable of staying upright at these angles. |
| T3 | 11A, 11B, 12A, 12B, 22B, 31-, 32-, 41A, 41B | [2.1 Atmosphere]<br>[2.2 Surface]<br>[2.3 Travel distance]<br>A) | **Traversability and battery life test:** test drive the rover for a distance of at least 40 metres. The following surface types should be tested both on level ground and at a 30° incline: grass, dry gravel/sand, wet gravel/sand, and rocky (with larger rocks ~6-8cm diameter. Rover should be capable of traversing these surfaces successfully, taking less than 20 minutes to travel 40m. For this test to be representative, rover should have a full load of canisters stored. If possible, run this test with a variety of wheel designs. |
| T4 | 11A, 11B, 11C | [1.3 Vibration Environment]<br>[1.4 Vibration Test Attachment Mechanism] | **Vibration test:** Rover should be tested on a vibration testbed with the vibration specifications in Rules & Requirements [1] Table 10 and 11, and a vibration plate compatible with the rover vibration attachment points. Rover should operate correctly after the vibration test with only minor damage. |
| T5 | 41A, 41B | [4.1 Live Voltage]<br>[4.2 Battery]<br>[4.3 Kill Switch] | **Safety systems test:** test the effectiveness of the software kill switch and manual rover kill switch at different points in the rover operation process. |
| T6 | 31A, 31B, 32C, 33A, 33B, 33C, 21-, 22- | [4.4 Declaration of Autonomy]<br>C) | **Automated pickup system test:** Measure average time taken and reliability for autonomous canister collection and storage system to collect and store 40 3D printed canisters. Compare this with the requirement, and the equivalent time with manual operation. |
| T7 | All | [3.1 Primary Communication] | **Individual subsystem-level tests:**<br>➔ Reliability/throughput of primary communications link tested at |

| | | | |
|---|---|---|---|
| | | [3.2 Backup Communication]<br>[3.3 Legality]<br>[3.4 Equipment Placement]<br>[3.5 Line of sight and sensing]<br>[4.4 Declaration of Autonomy]<br>A), B), C) | <20m range, and with simulated interference from other devices.<br>➔ Reliability/throughput of secondary communications link tested at <20m range, and with cable tension simulated.<br>➔ Autonomous canister recognition should be tested with a range of test images with differing lighting, canister location/orientation, occlusion, ground conditions, gradient, etc.<br>➔ HWC and SBC should have built-in self-test mode which tests all connected sensors and actuator drivers. This test should pass.<br>➔ Test basic (manual) operation of canister collection mechanism.<br>➔ Actuator tests: test power draw at different torque requirements and compare with figures in power budget.<br>➔ Test repeatability of robot arm kinematic positioning, and ensure this is high enough for autonomous functionality to work.<br>➔ Test collection system ranging sensor reliability/accuracy with different surfaces and differing ambient lighting conditions. |
| T8 | All | All | **Full system test:** Test the whole rover platform with all competition functionality enabled, in a mock-up of the competition format. This test should identify any issues caused by interaction between subsystems. Also, test with an intermittent communications link. |

*Table 3: Test Plan.*

## 2.7 Project Risks and Management

*LL = Likelihood, SV = Severity.*

| Risk | Type | LL | SV | Mitigation |
|---|---|---|---|---|
| Risk of project team members dropping out or falling behind due to high course workload. | Project | H | M | ➔ Ensure at least 2 team members familiar with each work package for redundancy.<br>➔ Keep track of team members' workload, and reassign more team members to important work packages if needed. |
| Risk of long lead times for certain components delaying the project. | Project | M | H | ➔ Order additional spares for long lead-time and high importance components.<br>➔ Identify alternative parts / suppliers to reduce risk. |
| Risk of difficulty getting access to department resources e.g. vibration testing equipment. | Project | L | M | ➔ Contact relevant faculty members well in advance so that alternative arrangements can be made if necessary.<br>➔ Identify alternative ways to get access to resources – for example, through other university departments. |
| Risk of breakage or loss of key parts or equipment. | Project | M | L | ➔ Order/manufacture spares for all parts practical, especially parts known to break often. Spares with a software component should be pre-programmed and tested.<br>➔ Track high-importance/value parts with tracking list (**2.2**).<br>➔ Ensure spares are available both after vibration test (where breakages are expected) and for the competition day. |
| Risk of underestimation of difficulty or time requirement for implementing autonomy functions. | Technical | H | L | ➔ Start work on autonomous aspects at earliest opportunity, before main platform is built.<br>➔ Each autonomous component to have a manual control counterpart implemented, which can be smoothly switched to during operation. |
| Risk of interface issues when integrating subsystems. | Technical | M | M | ➔ Define and use version control systems.<br>➔ Identify areas where interfaces need to be defined as early as possible, and discuss between sub-teams. |
| Safety considerations for rover operation must be taken into account. | Safety | L | L | ➔ Autonomous operation can cause unpredictable behaviour, and the rover must be made safe with a remote software kill switch and a hardware kill switch. |

*Table 4: Project Risks and Risk Management table.*

## 2.8 Budget

| Sub-System | Component | Quantity | | Cost | | | Bought-In? | Lead time (days) |
|---|---|---|---|---|---|---|---|---|
| | | Req. | Spares | Unit | Shipping | Total | | |
| Control Electronics | Raspberry Pi 3B+ | 1 | 0 | £34.07 | £0.00 | £34.07 | Y | 2 |
| | RasPi Camera V2 | 1 | 0 | £25.79 | £0.00 | £25.79 | Y | 2 |
| | Arduino Nano | 1 | 0 | £3.80 | £0.00 | £3.80 | Y | 2 |
| | USB Wifi w/ antenna | 1 | 0 | £10.00 | £0.00 | £12.00 | N | 3 |
| | Vl53L1X Ranger | 1 | 0 | £12.87 | £0.00 | £12.87 | Y | 2 |
| | Test arm platform | 1 | 0 | £27.85 | £0.00 | £27.85 | Y | 20-40 |
| Training | Training Dataset Material | 1 | 0 | £25.00 | £0.00 | £25.00 | N | 7 |
| Power Electronics | 5V (Logic) Regulator | 1 | 0 | £10.00 | £0.00 | £10.00 | N | 3 |
| | 6V (Actuation) Regulator | 1 | 1 | £2.56 | £4.39 | £9.51 | N | 20-40 |
| | Dual Motor Controller | 3 | 1 | £10.99 | £2.00 | £43.96 | N | 3 |
| | Battery - Li Ion | 1 | 0 | £30.00 | £0.00 | £30.00 | N | 20-40 |
| Wheel Assembly | DC Motor + Gearbox | 6 | 2 | £12.00 | £0.00 | £96.00 | N | 20-40 |
| | 6710-2RS bearing | 6 | 2 | £2.75 | £3.70 | £25.70 | N | 20-40 |
| Drivetrain | 3D printed parts | 1 | 1 | £0.00 | £0.00 | £0.00 | N | 14 |
| | Rods and joint fixings | 1 | 0 | £25.00 | £0.00 | £25.00 | N | 20-40 |
| | Differential gears + fixings | 1 | 0 | £25.00 | £0.00 | £25.00 | N | 7 |
| Canister Collection | RC Servo, standard size | 4 | 0 | £14.00 | £0.00 | £56.00 | N | 5 |
| | 3D printed joints/brackets | 1 | 0 | £0.00 | £0.00 | £0.00 | N | 14 |
| | Servo brackets | 4 | 0 | £3.00 | £0.00 | £12.00 | N | 20-40 |
| Body Assembly | General electronics parts | 1 | 0 | £30.00 | £0.00 | £40.00 | N | 2 |
| | Wiring (power + data) | 1 | 0 | £25.00 | £0.00 | £25.00 | N | 2 |
| | Fasteners/bolts etc. | 1 | 0 | £20.00 | £0.00 | £20.00 | N | 2 |
| | Body Bulk Material | 1 | 0 | £0.00 | £0.00 | £0.00 | N | 14 |

Funding sources (in order of usage):

| | |
|---|---|
| **Engineering Department EUIF:** | £250.00 |
| **UKSEDS matched funding:** | £250.00 |
| **Oxford University Rocketry Society:** | £200.00 |
| **Total:** | £700.00 |

Budget Estimate:

| | |
|---|---|
| **Total spent to date:** | £79.44 |
| **Total left to spend:** | £480.11 |
| **Total:** | £559.55 |

*Table 5: Budget Breakdown and Spending Forecast.*

Engineering Undergraduate Innovation Fund (EUIF) funding is provided by the Oxford Department of Engineering Science. This budget assumes that 3D printing will be provided for no cost by the Engineering Science department – this is not yet confirmed. There is margin in the budget which can be used for printing costs if this is not the case.

**20-40 days lead time:** AliExpress.com – datasheets are examined and parts are only purchased from reputable suppliers, taking into account the long lead times expected.

**14 days lead time:** Parts from the department which take time to order and prepare. Some department-sourced parts may take much less time than this if they are readily available.

**5 days lead time:** Proto-PIC, and most general UK sites that ship by standard post.

**2-3 days lead time:** RS Components, Farnell, Cool Components, Amazon UK.

# 3 ROVER DESIGN

## 3.1 Design Overview

The rover mechanical design consists of a 6-wheeled, rocker-bogie suspension system with a differential gearbox between the two rocker-bogie sides to keep the body level. The body contains an electronics compartment, battery compartment, pickup arm (which folds flat across the top of the rover body), and a canister storage area which is also used to store and protect the pickup claw on the end of the pickup arm.

## 3.2 Mass Budget

| N | Subsystem | Component | Individual Mass (kg) | DMM (%) | Group Mass (kg) |
|---|---|---|---|---|---|
| 1 | Electronics | VL53L1X Rangefinder | 0.001 | 5 | 0.001 |
| 1 | Electronics | Raspberry Pi 3B+ | 0.05 | 5 | 0.053 |
| 1 | Electronics | Raspberry Pi Camera V2 | 0.02 | 5 | 0.021 |
| 1 | Electronics | TeleOp Camera - USB | 0.025 | 5 | 0.026 |
| 1 | Electronics | Arduino Nano + Wiring estimate | 0.047 | 5 | 0.055 |
| 1 | Electronics | USB WiFi Network Card | 0.04 | 5 | 0.042 |
| 3 | Electronics | Dual motor controller | 0.005 | 5 | 0.016 |
| 1 | Power Elec | 12V/6V/5V regulators | 0.08 | 5 | 0.084 |
| 1 | Power Elec | Battery | 0.5 | 5 | 0.525 |
| 6 | Drivetrain | Wheel Assembly | 0.15 | 20 | 1.080 |
| 6 | Drivetrain | DC Gearmotor | 0.17 | 5 | 1.071 |
| 1 | Suspension | Differential Assembly | 0.1102 | 20 | 0.132 |
| 2 | Suspension | Rocker-bogie 1 side | 0.091 | 20 | 0.218 |
| 4 | Pickup Arm | Arm servo | 0.055 | 5 | 0.231 |
| 1 | Pickup Arm | Arm assembly | 0.108 | 20 | 0.130 |
| 1 | Pickup Arm | Claw assembly (mechanical) | 0.0735 | 20 | 0.088 |
| 1 | Body | Whole body assembly | 0.8 | 20 | 0.960 |
| | | | | **SUM** | 4.733 |
| | | | System Mass Margin | **SMM (%)** | 5 |
| | | | Total w/ margins: | **TOTAL** | 4.970 |

*Table 6: Mass Budget.*

The Mass Budget and Power Budget margin philosophy are defined in reference [4]. Namely:

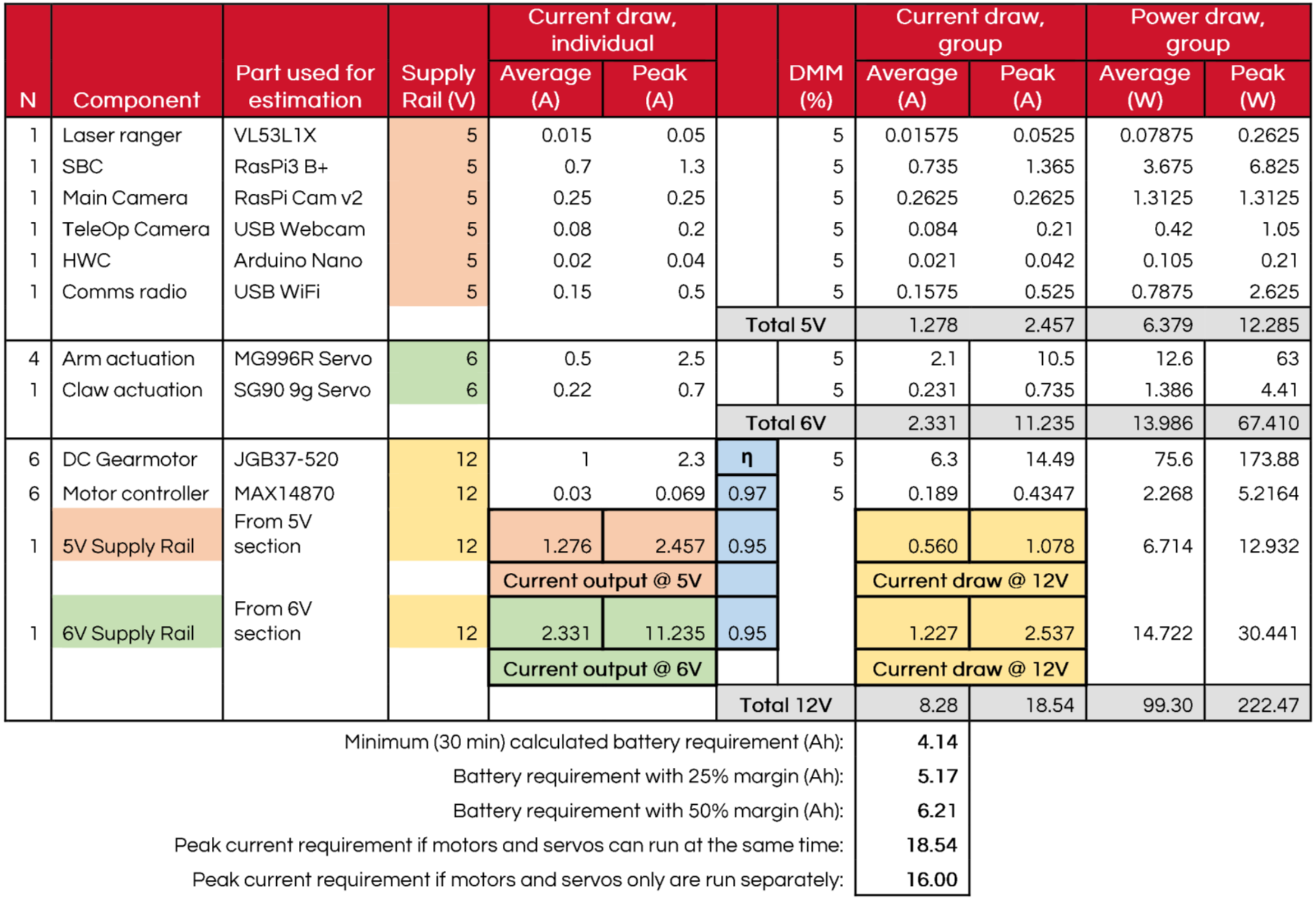
- ➔ Custom design parts/assemblies have a Design Maturity Margin of 20%.
- ➔ Off-the-shelf parts with minor modifications have a Design Maturity Margin of 10%.
- ➔ Off-the-shelf parts used without modification have a Design Maturity Margin of 5%.
- ➔ The whole system is subject to a System Mass Margin of 5% on top of other margins.

## 3.3 Volume Budget

The volume budget is managed through the whole-rover SolidWorks model, with a 5% volume margin on the bounding volume for the rover body. This leads to outer bounding volume dimensions (in mm) of 380L x 300W x 250H, giving a nominal volume of 0.285$m^3$ – a 5% volume margin from the 0.3$m^3$ limit. The current rover design fits within this bounding limit. Estimating the volume for each individual part / subsystem is not considered necessary.

## 3.4 Power Budget

All figures are sourced from the relevant datasheets (or calculations based on the datasheet in the case of the MAX14870). Motor group current (peak) assumes all motors stalled.



| N | Component | Part used for estimation | Supply Rail (V) | Current draw, individual | | | DMM (%) | Current draw, group | | Power draw, group | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Average (A) | Peak (A) | | | Average (A) | Peak (A) | Average (W) | Peak (W) |
| 1 | Laser ranger | VL53L1X | 5 | 0.015 | 0.05 | | 5 | 0.01575 | 0.0525 | 0.07875 | 0.2625 |
| 1 | SBC | RasPi3 B+ | 5 | 0.7 | 1.3 | | 5 | 0.735 | 1.365 | 3.675 | 6.825 |
| 1 | Main Camera | RasPi Cam v2 | 5 | 0.25 | 0.25 | | 5 | 0.2625 | 0.2625 | 1.3125 | 1.3125 |
| 1 | TeleOp Camera | USB Webcam | 5 | 0.08 | 0.2 | | 5 | 0.084 | 0.21 | 0.42 | 1.05 |
| 1 | HWC | Arduino Nano | 5 | 0.02 | 0.04 | | 5 | 0.021 | 0.042 | 0.105 | 0.21 |
| 1 | Comms radio | USB WiFi | 5 | 0.15 | 0.5 | | 5 | 0.1575 | 0.525 | 0.7875 | 2.625 |
| | | | | | | Total 5V | | 1.278 | 2.457 | 6.379 | 12.285 |
| 4 | Arm actuation | MG996R Servo | 6 | 0.5 | 2.5 | | 5 | 2.1 | 10.5 | 12.6 | 63 |
| 1 | Claw actuation | SG90 9g Servo | 6 | 0.22 | 0.7 | | 5 | 0.231 | 0.735 | 1.386 | 4.41 |
| | | | | | | Total 6V | | 2.331 | 11.235 | 13.986 | 67.410 |
| 6 | DC Gearmotor | JGB37-520 | 12 | 1 | 2.3 | η | 5 | 6.3 | 14.49 | 75.6 | 173.88 |
| 6 | Motor controller | MAX14870 | 12 | 0.03 | 0.069 | 0.97 | 5 | 0.189 | 0.4347 | 2.268 | 5.2164 |
| 1 | 5V Supply Rail | From 5V section | 12 | 1.276 | 2.457 | 0.95 | | 0.560 | 1.078 | 6.714 | 12.932 |
| | | | | Current output @ 5V | | | | Current draw @ 12V | | | |
| 1 | 6V Supply Rail | From 6V section | 12 | 2.331 | 11.235 | 0.95 | | 1.227 | 2.537 | 14.722 | 30.441 |
| | | | | Current output @ 6V | | | | Current draw @ 12V | | | |
| | | | | | | Total 12V | | 8.28 | 18.54 | 99.30 | 222.47 |

| | |
|---|---|
| Minimum (30 min) calculated battery requirement (Ah): | 4.14 |
| Battery requirement with 25% margin (Ah): | 5.17 |
| Battery requirement with 50% margin (Ah): | 6.21 |
| Peak current requirement if motors and servos can run at the same time: | 18.54 |
| Peak current requirement if motors and servos only are run separately: | 16.00 |

*Table 7: Power Budget.*

# 3.5 Mechanical Design

## 3.5.1 Technical Requirements

| Requirement | Description | Achieved? |
|---|---|---|
| M.1 | The rover suspension system should be capable successfully traversing the terrain defined in requirement of The rover should have sufficient body ground clearance to pass over the smallest rocks present, and should be navigated around larger rocks. | Y |
| M.2 | On 30° inclined, obstruction-free ground, the rover drivetrain should be capable of achieving a rover top speed of at least 0.3ms$^{-1}$. On this surface it should also be capable of accelerating to the top speed within 2 seconds. | Y |
| M.3 | The rover design should incorporate a separate compartment for the battery which allows the battery to be externally accessible. | Y |
| M.4 | The rover design should incorporate a pickup arm that can position the end of the arm 8cm above the ground within a semi-circular range of at least 25cm, centred on a point at the front of the rover. | Y |
| M.5 | The rover body design should incorporate a storage area that can hold at least 20 canisters in an unordered layout, and ideally all 40 canisters. | Y |
| M.6 | The rover design should achieve a statically stable platform (on an incline of up to 30°), and provide a way of “braking” the rover wheels to keep the rover stationary. This is important for reliable autonomous collection functionality. | Y |

*Table 8: Technical requirements (derived from high-level requirements) for the mechanics.*

## 3.5.2 Suspension Design and Trade-Offs

2 approaches to the suspension system are considered in detail in the multi-factor analysis below, with weightings from 5 (most suitable) to 1 (least suitable).

| Criteria | Weight | 4-wheel simple suspension | | 6-wheel Rocker Bogie | | Notes / Calculations |
|---|---|---|---|---|---|---|
| | | Rating | Score | Rating | Score | |
| Mass / Volume | 2 | 3 | 6 | 2 | 4 | (5*40*30+4*7.5*7.5*10+25*20*4.5)/total available volume in cm^3 ≈35% usage for 4-wheel<br>(2.5*40*25*2+2*8*40*7+5*40*30) /total available volume in cm^3 ≈52% usage for rocker-bogie<br>Rocker-bogie requires 50-100% more mass, incl. added inefficiencies from 6 smaller motors. |
| Control complexity | 1 | 3 | 3 | 2 | 2 | 50% more wheels to drive and control, and more wheels will skid when turning for rocker-bogie. |
| Terrain traversability / static stability | 5 | 2 | 10 | 5 | 25 | Rocker-bogie can effectively have a lower centre of mass due to the smaller wheel diameters. Self-levelling feature of rocker-bogie greatly improves stability compared to 4-wheel, and significantly better traversability on sand/gravel. |
| Vibration resistance | 3 | 4 | 12 | 2 | 6 | For 4-wheel design, suspension design is well-understood and standard. Little information on adding vibration resistance to rocker-bogie, but the natural frequencies should be calculable. |
| Mechanical design complexity | 2 | 4 | 8 | 2 | 4 | 4-wheel design requires larger wheels but is simpler to implement. Much more design, analysis and construction work is required for the complex rocker-bogie assembly. |
| Sum | | | **39** | | **41** | |

*Table 9: Multi-Factor Analysis for Suspension Design.*

A rocker-bogie design was chosen as traversability and stability were prioritised over other factors. Estimates suggest that there is capacity in the mass/volume budgets for a rocker-bogie design – taking into account the additional mass of extra motors and a larger battery.

A rocker-bogie requires a differential to keep the rover body stable at an angle halfway between the angles of the two rockers. A differential gear design was chosen (over a differential bar design) as the gearbox was considered to be lighter and less fragile than an external bar, though it requires a channel of space directly through the centre of the body.

In order to save volume, the suspension design places the rocker-bogie bars on the outside of both the rover body and the wheel assemblies, and leaves clearance around the wheels to allow them to pivot while travelling. A CAD model of the rocker-bogie was used to identify how much clearance to give to the wheel travel, based on the expected terrain.

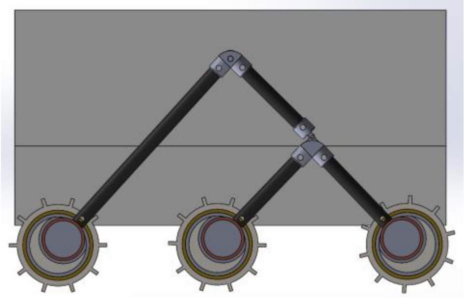


*Figure 4: Rocker-bogie side view.*

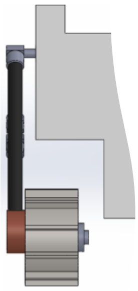


*Figure 5: Front view.*

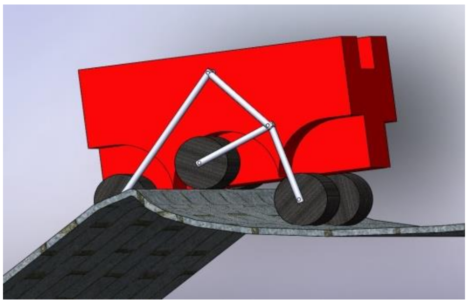


*Figure 6: Clearance test model.*

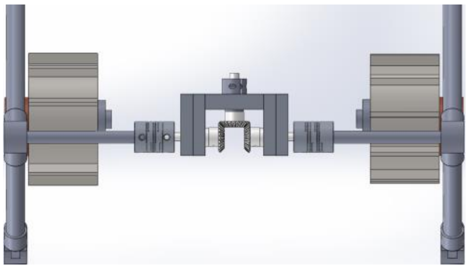


*Figure 7: Rocker/differential layout (body hidden).*

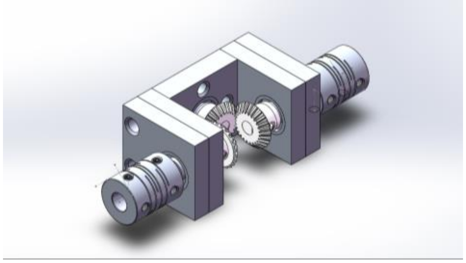


*Figure 8: Bevel-gear differential gearbox.*

Material selection comparisons were carried out for the rocker-bogie bars, which are 12mm OD, 9mm ID with space for cable routing. This gives a 2nd moment of area of $I_{zz} = 1.39 \times 10^{-9}$.

| Criteria | PVC | Steel | Carbon Fibre |
|---|---|---|---|
| Density (kg $m^{-3}$) | 1380 | 7850 | 15745 |
| Cost (£ $m^{-1}$) | 0.49 | 4.12 | 9.88 |
| Stiffness (GPa) | 2.89 | 210 | 228 |
| Mass (kg $m^{-1}$) | 0.085 | 0.486 | 0.097 |
| Optimality | 336 | 30 | 511 |

*Table 10: Rocker-bogie materials comparison.*

Optimality takes account of the weights given to each criteria.

= cost$^{-0.5}$ x stiffness$^{0.5}$ x mass$^{-2}$

Mass is given a high (negative) weighting as the mass budget allocation for the rocker-bogie is limited. This shows that pultruded carbon fibre rods are the most suitable for the connecting bars.

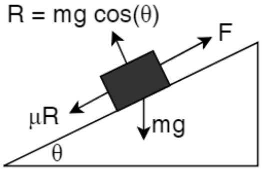
Hinges are planned to be made from a 3D printed polymer – either ABS, or a higher-performance part such as Nylon depending on 3D printing availability.

### 3.5.3 Drivetrain Design and Calculations

From the technical requirements in 3.5.1, brushed DC motors with integrated gearboxes on the output shaft were chosen as the most appropriate motor technology.

- Brushed DC motors have simple control circuitry compared to brushless/stepper.
- The integrated high-reduction gearbox should prevent the wheel turning when the motor is powered off (braking requirement M.6) and reduce the design effort required.

**Highest power/torque requirement (acceleration up a slope with friction):**



- ➔ Assume $\mu = 0.3$ (similar to a surface on Earth) and $g = 9.8\ \mathrm{ms}^{-2}$ (!)

$$F - mg\sin(\theta) - \mu R = ma \quad F = ma + mg\sin(\theta) + \mu R$$

- ➔ For worst-case force demand $\theta = 30°, m = 5\ \mathrm{kg}$. For $a = 0.5\ \mathrm{ms}^{-2}$:

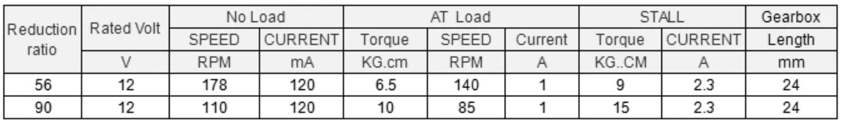
$$F = 5 \cdot 0.5 + 5 \cdot 9.8 \cdot \sin(30°) + 0.3 \cdot (5 \cdot 9.8 \cdot \cos(30°)) = 39.7\mathrm{N}$$

- ➔ 6 wheels each providing ~7N of force. For each wheel of radius 40mm, $T = 0.28\ \mathrm{Nm}$
- ➔ For a climbing speed of 0.3 ms$^{-2}$, rotation speed can be found from wheel radius:

$$\omega = 2\pi \cdot \left(\frac{0.3}{2\pi \cdot 40 \times 10^{-3}}\right) = 7.5 \qquad RPM = \frac{60}{2\pi}\omega = 71.6\mathrm{rpm} \qquad P = T\omega = 2.1\mathrm{W}$$

∴ Stall torque of at least $T = 0.84\ \mathrm{Nm}$ (in general, working torque requirement should be several times smaller than the stall torque – 3x in this case). Rated speed significantly higher than 71.6RPM (to achieve this speed at high torque). Peak power output of at least 4.2W (2x factor: 2.1W is required at lower efficiency point than the peak ~50% efficiency).

Taking into account the requirements and a reasonable performance margin, the JGY37-520 geared DC motor was selected and the following 2 gearbox ratios considered:



| Reduction ratio | Rated Volt | No Load | | AT Load | | | STALL | | Gearbox |
|---|---|---|---|---|---|---|---|---|---|
| | | SPEED | CURRENT | Torque | SPEED | Current | Torque | CURRENT | Length |
| | V | RPM | mA | KG.cm | RPM | A | KG..CM | A | mm |
| 56 | 12 | 178 | 120 | 6.5 | 140 | 1 | 9 | 2.3 | 24 |
| 90 | 12 | 110 | 120 | 10 | 85 | 1 | 15 | 2.3 | 24 |

*Figure 9: Gearbox options for JGY37-520.*

The 56 reduction ratio gearbox was chosen, but the identical dimensions mean there is scope to move to the higher-torque gearbox if needed.

### 3.5.3.1 Wheel Assembly Design

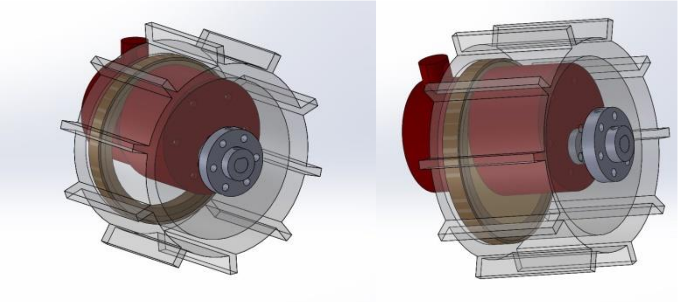


*Figure 10: Wheel/motor assembly design.*

The wheel/motor assembly integrates the gearmotor inside the wheel interior. The wheel (transparent grey) is 3D printed polymer, attached to the motor driveshaft with a steel hub. The motor is surrounded by 3D printed polymer (red) which bolts onto the front of the gearbox. To reduce radial torque on the driveshaft and hub, the other end of the wheel is supported by a 6811ZZ ball bearing (gold), which is supported on the inner side by 3D printed polymer around the motor housing. The rocker-bogie bar is attached to the motor housing by the red tube insert on the outside of the assembly. This design allows the wheel or motor to easily be swapped out, for prototyping and repairs.

### 3.5.3.2 Wheel Assembly - Wheel Grip Enhancement (Grousers)

Wheel grip enhancement with cleats or "grousers" were identified in the PDR as being a key design area to ensure drivetrain performance on the rocky, sandy ground conditions specified in the Rules & Requirements [1]. A study on grouser design for planetary rovers [5] was consulted to identify the ideal grouser spacing. Calculations (with assumed wheel sinkage of 1.5cm) suggested a minimum of 12 grousers per wheel (Figure 10 is set up with 10 grousers). Experiments with the actual rover and a test surface will be carried out once the wheel assemblies have been manufactured, which will allow the calculations to be refined to find the ideal number of grousers. Grouser thickness will depend on the material used.

### 3.5.4 Canister Collection

The canister collection system is comprised of a 4DOF articulated arm powered by standard RC servos. The custom pickup claw has integrated sensors to aid in canister collection. The collection arm folds flat on top of the rover body when the rover is moving, and the claw

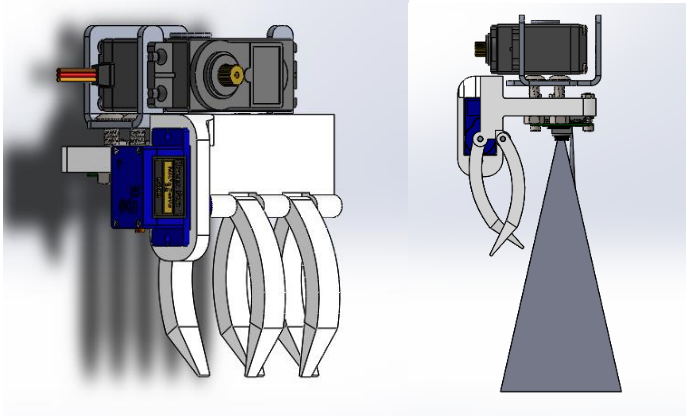


*Figure 11: Claw design, with field of view for Pickup Camera and Ground Distance Sensor.*

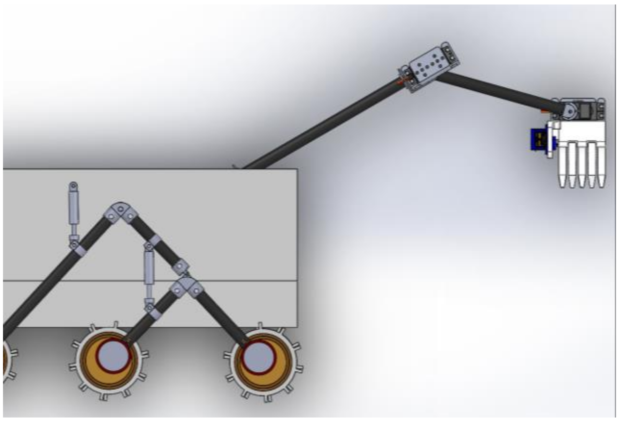


*Figure 12: Collection arm extended in front of rover*

assembly covers the canister collection/storage volume hatch while the arm is folded flat. Canister storage is an empty volume at the front of the rover body. The claw is 3D printed plastic, and the arm is constructed from carbon rod, 3D printed parts and steel brackets.

### 3.5.5 Vibration Analysis and Design

Key vibration modes were calculated by hand, and with SolidWorks vibration simulation. A basic summary of the vibration modes and frequencies is given in Table 9. The area of most concern (high damage potential) is the high-amplitude movement of the rocker bogie at low *f*.

| Mode no. | Source | f (Hz) |
|---|---|---|
| 1,2 | Swinging about hinges, rocker-bogie | 0.35 – 1.4 |
| 3 | Estimated body natural frequencies | 20-40 |
| 4 | Horizontal vibration, rocker-bogie | 65-250 |
| 5 | Material vibration, rocker-bogie | 90-950 |
| 6 | PCB / electronics parts natural freq. | ~1000 |

*Table 9: Predicted vibration modes for rover design.*

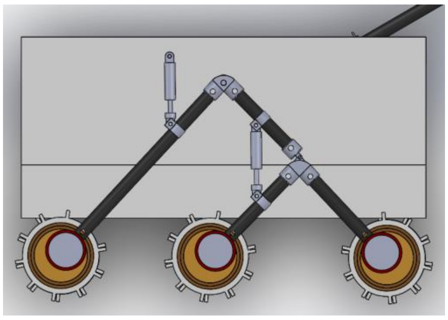


*Figure 13: Shock absorber placement.*

The key vibration management techniques chosen are:

- ➔ The rocker-bogie is fitted with a set of adjustable spring/dashpot shock absorbers, which should be tuned to attenuate low-frequency vibration while allowing full motion.
- ➔ Electronics are mounted on secure mounting hardware (e.g. nylon spacers), and locking connectors are used to avoid vibration-induced electronics failures.
- ➔ Keep motor drive PWM frequency much higher than any significant vibration modes.
- ➔ Test the feasibility of locking the collection arm in place when it is powered down.

### 3.5.6 Rover Body

The rover body is an ABS 3D printed part, comprised of a rear electronics compartment, a battery compartment designed to fit multiple battery sizes in the bottom channel (with a rear door that allows removal of the battery from outside), and the canister storage and collection arm mounting at the front. Mounting plate attachment holes as defined in [1] are provided at both the top and side of the rover, which have different advantages for vibration management The current body design is the most basic possible working model with the correct external dimensions – some simple shape updates still need to be made to reduce the mass. The body will either be a single 3D printed piece, or 4 pieces bolted together with standard metric nuts/bolts, depending on the available print volume.

## 3.6 Electronics Design

### 3.6.1 Technical Requirements

| Requirement | Description | Achieved? |
|---|---|---|
| E.1 | Battery subsystem should be capable of providing a constant current of 7A and a peak current of 16A at 12V. These figures are derived from the power budget, assuming the arm and wheels do not run at the same time. | Y |
| E.2 | The On-Board Computer and chosen primary communications link should be capable of fulfilling the communications requirements (Requirements 3.1-3.5). | Y |
| E.3 | The HWC (with its connected hardware) should be capable of controlling 8 standard RC servos. 4 servos are for arm manipulation, 1 for claw operation, 1 for the arm locking mechanism and 2 left spare. | Y |
| E.4 | The HWC and motor controllers should be capable of controlling the speed and direction of 6 brushed DC motors. The minimum level of speed and direction control should be for the speed and direction of the LHS and RHS of the rover to be set independently, to allow the rover to turn. | Y |
| E.5 | The HWC (with its connected hardware) should incorporate a system to allow the distance from the claw to the ground to be determined independently of the arm kinematics, for aiding canister pickup. | Y |
| E.6 | The power supply system should incorporate a kill switch (Requirement 4.3). | Y |

*Table 10: Technical requirements (derived from high-level requirements) for the electronics.*

### 3.6.2 Electronics Design Overview

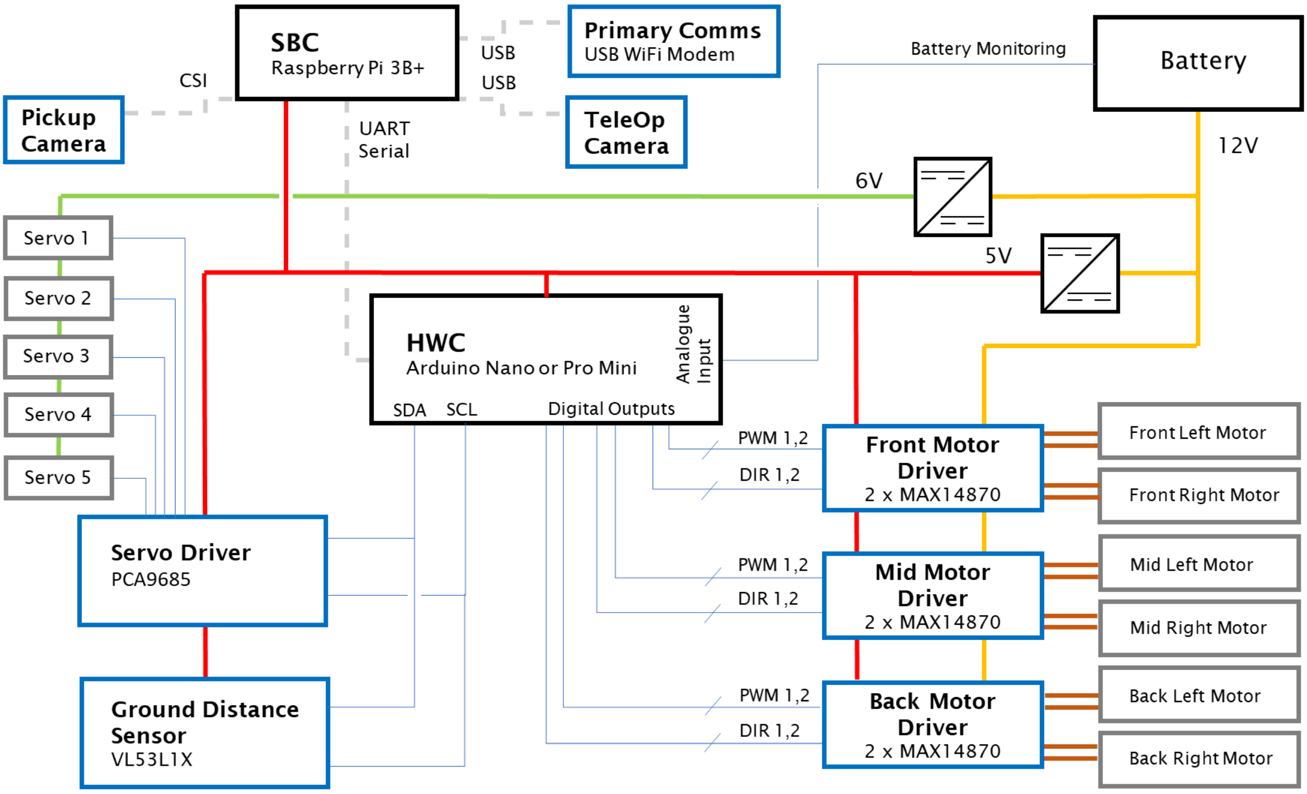


*Figure 14: Electronics power and data layout.*

- The Servo Driver and Ground Distance Sensor are connected to the HWC via I2C.
- Each dual motor controller requires a direction pin and speed (PWM) pin for each motor. There are enough digital and PWM output pins on the HWC for all 6 motors to be individually speed and direction controlled. If more pins are needed for other functionality, multiple motors on the same side can be controlled by a single direction or speed output pin from the HWC.
- The Pickup Camera is a RasPi Camera Module V2, connected via CSI to the SBC.
- The TeleOp Camera is a wide-angle USB webcam, connected via USB to the SBC.
- Standard buck DC/DC converters are used for the 5V and 6V rails.
- The Primary Comms link is a standard USB WiFi adapter with a dedicated antenna. The 802.11n link will have enough range and bandwidth to support video streaming.

### 3.6.3 Battery, Power Supply and Kill Switch systems

- The 5V (Logic) power rail supplies power to the SBC, HWC, and sensors.
- The 6V (Actuator) power rail supplies power to the RC servos used in the pickup arm.
- The 12V rail is the "main" power supply rail and directly powers the motors.

Two options are considered for battery technology: (rated from 1-5 in the table below)

| Criteria | Rechargeable Lithium Ion | Single-use Lithium AA cells – [7] |
|---|---|---|
| **Power density:** | **3** – a representative battery is 0.057g per milliamp-hour at ~12V. | **4** – a representative battery pack is 0.04g per milliamp-hour at ~12V. |
| **Peak Current:** | **4** – depending on the battery used, peak current can easily be high enough from one battery pack. A representative battery with enough capacity and peak current is ~400g. | **2** – standard AA cells are not designed for high current output, so at least 32 cells would be required for the peak current output in the power budget. This would give a battery pack mass of 480g for cells alone. |
| **Cost effectiveness:** | **4** – battery packs may be available to borrow from the department, and low-cost ones can be ordered from abroad. | **2** – L91 cells are high-cost (~£1.10 each) and single use. They are however easy to source at short notice. |
| **Design / build complexity:** | **3** – depending on the type used, another voltage regulator might be required for a steady 12V output (for example, with a 4S2P Li-Ion where max V=16.8V). If the battery full-charge voltage is more than 12V, this must be isolated to the battery compartment and not be exposed at any point on the rover. | **2** – constructing a reliable battery pack to hold 32 AA cells would require significant effort, and would add significant mass. |
| **Safety:** | **2** – battery charging adds another activity that must be risk assessed and approved by the department. | **5** – AA cells pose no effective safety risk and can easily be used. |

*Table 11: Comparison of battery technologies.*

The energy density advantage of single-use lithium AA cells is clearly offset by the peak current issues and the design complexity. The approach for this project is to proceed with sourcing a rechargeable Li-Ion battery, but leave open the option of using Lithium AA cells for the competition (as safety concerns may preclude a rechargeable cell being used). The battery compartment for the rover design has been designed to be able to work with either approach.

The kill switch (specified in Requirement 4.3) cuts off power to the 12V rail, removing power from all logic and power components. The switch chosen (C1350AGAAA) is a panel-mount rocker switch rated at 20A with a raised guard. The guard will reduce the likelihood of the switch being activated by accident during the competition, e.g. if the rover toppled sideways.

### 3.6.4 Wiring

Internal wiring layout will be manually designed and implemented based on the cable types available. Planning the wiring layout in detail in CAD is not considered necessary. As the rocker-bogie and arm are largely constructed from hollow tubing, wiring will be routed through this tubing where possible to protect the wires. All wires should be of the necessary gauge to handle the currents specified in the power budget.

- ➔ Wiring from motor controllers to motors should be shielded 2-core wire, at least 20AWG to carry the peak current (motor stall current of 2.3A). Shielded wire will reduce the EMI produced by the high-current PWM through the wires, which could interfere with data lines.
- ➔ Wiring from the 12V rail to the motor controllers should also be shielded if possible, and should either be at least 16AWG, or be two 20AWG wires in parallel.
- ➔ Wiring along the arm to the Ground Distance Sensor should be shielded to reduce the effect of EMI from the arm servos. At least 4 conductors are required – 2 for the I2C lines, 1 for ground and 1 for the +5V supply.
- ➔ Wiring from the Raspberry Pi to the Pickup Camera is a CSI ribbon cable. This interface is generally not used for distances longer than a few cm, so EMI from the arm servos may interfere with the unshielded CSI cable. If necessary, copper tape can be used to add shielding to the CSI camera cable.

### 3.6.5 Component Choices

Multi-Factor analysis was carried out to compare options for several components including Ground Distance Sensor, SBC and HWC. These are not included due to the page limit. The approach taken to component choice is to buy complete boards/modules which can be connected relatively simply, rather than spending the time to design custom PCBs etc.

| Component | Part chosen | Justification |
|---|---|---|
| SBC | **Raspberry Pi Model 3B+.** Also considered: NVIDIA Jetson, BeagleBone, HWC only. | Raspberry Pi was the best combination of price, power and level of support available. |
| HWC | **Arduino Nano (or Pro Mini).** Also considered: Mbed/STM32 , Teensy, Arduino Mega. | Arduino is underpowered but easy to learn and low cost, and has ROS node support. Flash size should be enough for this application. |
| Ground Distance Sensor | **ST VL53L1X Ranging ToF sensor.** Also considered : IR reflectance sensor, ultrasonic sonar ToF sensor, use of stereo cameras. | The VL53L1X is small, has a narrow field of view, is relatively insensitive to the ground material and has Arduino libraries available. |
| Motor Driver | **Pololu Dual MAX14870 Motor Driver.** Also considered: other brushed DC motor drivers. | This part has the correct current ratings for the motors used and the easiest to use control interface out of all parts considered. |
| Servo Driver | **PCA9685-based servo controller.** Also considered: other PWM servo controllers. | This part supports the number of servos required. NB. this does not power the servos. |
| Pickup Camera | **Raspberry Pi Camera Module V2.** Also considered: USB webcam. | Highest quality camera available for RasPi – important as canister image recognition is based on the images from this camera. |
| TeleOp Camera | **Generic wide-angle USB webcam.** Also considered: Raspberry Pi Camera Module V2. | Quality of this camera is less important as it is only used for driving the rover. |
| Primary Comms Link | **USB WiFi adapter with external antenna.** Also considered: built-in Pi 3B+ WiFi. | A separate part with a dedicated antenna was considered necessary as the built-in WiFi has a PCB antenna, with reduced signal strength and bandwidth. |

*Table 12: Component list for rover electronics design.*

## 3.7 Software Design

### 3.7.1 Technical Requirements

| Requirement | Description | Achieved? |
|---|---|---|
| S.1 | Software should be capable of supporting a video stream from the TeleOp camera at a usable resolution and frame-rate, with a latency of less than one second. | Y |
| S.2 | Software should ensure a high-reliability link between the rover platform (SFR) and the remote terminal (SRL). | Y |
| S.3 | Software should have an equivalent manual control alternative to every autonomous function, which can be switched to "on-the-fly" during normal operation. | Y |
| S.4 | Software should present an effective and well-designed user interface to the operator at the SRL. | Y |
| S.5 | Wireless communication software should be designed to take into account possible communications interruptions, and ensure sensible behaviour. | Y |
| S.6 | Software must be version controlled and well-documented to support an agile / iterative development workflow. | Y |

*Table 13: Technical requirements (derived from high-level requirements) for the software.*

### 3.7.2 Software Design Overview

The rover software is designed to enable autonomous functionality, use open-source software as far as possible to avoid complex implementation tasks where an OTS alternative is available, and to fulfil the requirements in 3.7.1.

As outlined in the PDR, the focus for autonomous functionality is on canister pickup and storage: this is a task that would be difficult for a human to perform remotely, but has narrow enough scope that it could be done autonomously (compared to attempting full autonomous navigation and driving). Another aspect of the architecture is the offloading of complex tasks from the rover to the SRL, as shown below.

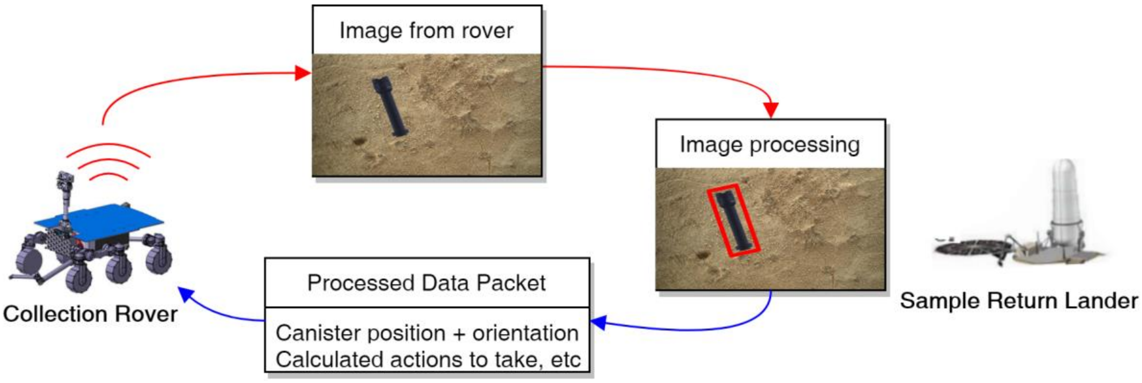


*Figure 15: Offloaded processing architecture.*

The software for the rover is almost completely based around the Robot Operating System (ROS), a collection of frameworks that enables a robot system to run multiple "nodes" that communicate between each other. This software environment provides a large number of useful open-source packages which can be leveraged to reduce development time, is well supported on the hardware chosen for the OBC and HWC, and provides a framework for writing our software for custom functionality. A layout of the ROS nodes and their functionality is provided below. Each card represents a ROS node (written in Python or C++), and each arrow/connection represents a ROS "topic" that a node can publish or subscribe to. ROS provides a transparent way of handling ROS nodes running on multiple machines, which greatly simplifies the implementation effort for the wireless link. Both the primary link (Wi-Fi) and backup link (Ethernet) set up a standard network between the SFR and SRL.

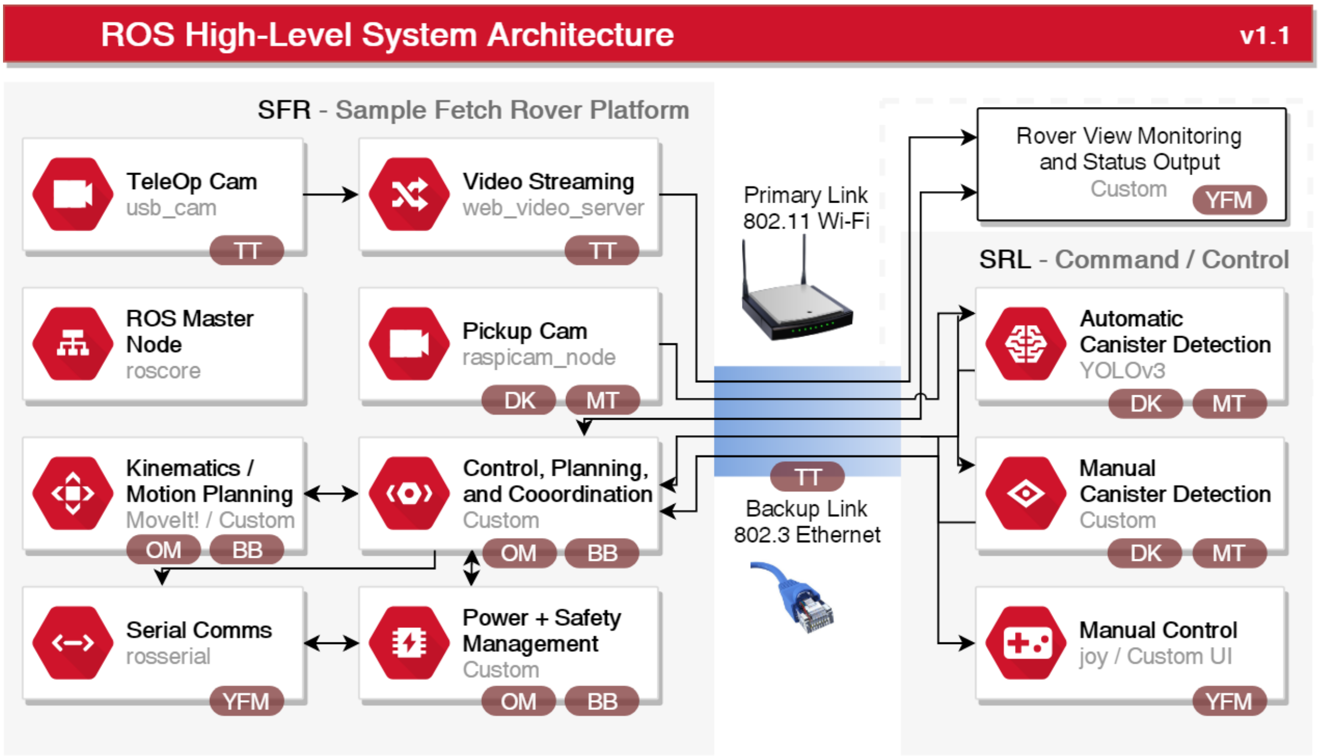


*Figure 16: Layout of functionality across ROS nodes, with assigned team members (initials).*

### 3.7.3 Rover Platform (On-Board Computer)

This is the main platform, and runs the "core" ROS node. Most nodes are run on this platform for low latency and to avoid communications-induced issues.

The `rosserial` node handles communication of ROS messages between the HWC and the SBC over the serial link. This lets the HWC act as a single ROS node, which can be addressed to control any of the hardware connected to the HWC. This serial link runs at 57600 bps.

Custom software on the SBC is written in Python, or C++ if the node communicates with the HWC and needs more insight into the data types used. Most custom functionality is contained in the Control, Planning and Coordination node, which specifies the rover's behaviour.

Custom software on the HWC is a standard Arduino sketch which ROS, sensor and motor driver libraries. This software is in the `HWController` directory in the Git repository.

*Figure 16: Test Platform*

### 3.7.4 Remote terminal (SRL)

The remote terminal is a laptop/PC running Ubuntu. Nodes on this machine include the canister detection node (which uses the more powerful hardware of the SRL to run image recognition software) and the manual control node which reads an attached USB game controller and publishes the controller output to a ROS topic.

➔ The custom robotic platform used by the Electronics/Software team to develop control/autonomy functionality before the rover platform is built is shown in Figure 16.

# 4 CONCEPT OF OPERATION

The SFR is remotely controlled by the operator at the SRL computer.

- The operator either has line-of-sight to the rover, or is viewing the rover through one of the test area cameras. The operator also has the live video feed from the TeleOp (forward-facing) camera, which has a wide field of view ( 130°)
- The operator steers the rover with a USB game controller (an Xbox 360 controller) connected to the SRL computer.
- When the operator has piloted the rover so that there is at least one sample canister within a ~25cm radius of the front centre of the rover, they stop the rover and press the "autonomous collect" button on the controller to hand over control to the autonomous program.
- The autonomous pickup program executes the following steps:
    - Move the pickup claw (with downwards-looking pickup camera) to the highest position above the collection area.
    - Capture a birds-eye-view image of the sample area and transmit it to the SRL.
    - The SRL computer runs an image recognition neural network on the received image, with a runtime upper limit of 5s. This neural network extracts a bounding box for at least one canister. The output of the neural network is then displayed on the SRL computer display. The operator can then either:
        - Approve the operation if the neural network has successfully found the canister
        - Override the bounding box by manually drawing a bounding box around the canister.
    - The SRL transmits the bounding box coordinates back to the SFR OBC.
    - The SRL calculates the location of the canister in the rover frame of reference using the Ground Distance Sensor, the pixel coordinate location of the bounding box, and basic trigonometry taking into account the camera field of view.
    - The rover moves its pickup arm to position the claw ~10-15cm above the canister calculated position.
    - The rover then repeats the image transmission/processing steps above to get another bounding box on the canister.
    - The rover adjusts the pickup claw position, and attempts to automatically pick up the canister, using the Ground Distance Sensor reading to position the claw correctly in the vertical axis.
    - Once the OBC determines whether a canister has been picked up, it returns the arm to the drop-off arm position and drops the canister into canister storage.
- At any point in the above process, the operator can use a button on the controller to switch to manual control.
    - Arm kinematics are enabled so that the left analogue stick controls the claw position in X and Y, and the right analogue stick controls the claw position in Z. This is the most intuitive/controllable approach when working from the top-down point of view of the Pickup Camera.
    - The reading from the Ground Distance Sensor and the video feed from the Pickup Camera are displayed on the SRL display to aid with manual pickup.
    - The operator can use buttons on the controller to move the pickup claw to pre-programmed positions: e.g. to move it automatically to the high position with a full field of view, or to the drop-off position once a canister has been picked up manually.
- Once all canisters in the range of the rover pickup arm have been collected, the operator presses a controller button to return the rover to manual control. Before enabling the motors again, the rover should automatically move the arm back to its folded position and locked the arm to the body.
- The steps above are then repeated until all canisters have been collected. The canister collection volume should allow all canister to be collected without the rover having to return to have canisters removed in the middle of the run.

# 5 COMPLIANCE MATRIX

(Provisional) compliance is based on the design and will be updated based on project progress and the pass/fail status of tests. Tests are as defined in Section 2.6.

| High-Level Requirement | Status | Reference(s) | Test(s) |
|---|---|---|---|
| 1.1 Mass | Compliant | 3.2 | T1, T8 |
| 1.2 Volume | Compliant | 3.3 | T1, T8 |
| 1.3 Vibration Environment | Compliant | 3.5.5 | T4, T8 |
| 1.4 Vibration Test Attachment Mechanism | Compliant | 3.5.5 | T4, T8 |
| 1.5 Static Stability | Compliant | 3.5.2, 3.5.3 | T2, T8 |
| 2.1 Atmosphere | Compliant | 3.5.2, 3.5.3 | T3, T8 |
| 2.2 Surface | Compliant | 3.5.2, 3.5.3 | T3, T8 |
| 2.3 Travel Distance | Compliant | 3.4, 3.6.3, 3.5.2, 3.5.3 | T3, T7, T8 |
| 3.1 Primary Communication | Compliant | 3.6.1, 3.6.2, 3.6.5, 4 | T3, T7, T8 |
| 3.2 Backup Communication | Compliant | 3.6.1, 3.6.2, 3.6.5, 4 | T3, T7, T8 |
| 3.3 Legality | Compliant | 3.6.1, 3.6.2, 3.6.5, 4 | T3, T7, T8 |
| 3.4 Equipment Placement | Compliant | 3.6.1, 3.6.2, 3.6.5, 4 | T3, T7, T8 |
| 3.5 Line of sight & sensing | Compliant | 3.6.2, 3.6.5, 4 | T6, T7, T8 |
| 4.1 Live Voltage | Compliant | 3.6.2, 3.6.3 | T5 |
| 4.2 Battery | Compliant | 3.4 | T3 |
| 4.3 Kill Switch | Compliant | 3.6.3 | T5, T8 |
| 4.4 Declaration of Autonomy | Compliant | Autonomous functionality detailed in Sections 4 and 3.7. | T5, T6, T7, T8 |

*Table 14: Compliance Matrix.*

## 5.1 Conclusion

The proposed design has been shown to provisionally satisfy all the requirements.

Small design updates are expected to be made in the course of manufacturing and testing the rover, and some scope in the schedule has been left for iterative design updates based on CDR feedback and test performance.

# APPENDIX A: ACRONYMS LIST

| | |
|---|---|
| CDR | Critical Design Review |
| HWC | Hardware Controller – low-level interface half of OBC, connected to EPC |
| OBC | On-Board Computer |
| OTS | Off-The-Shelf |
| OURS | Oxford University Rocketry Society |
| PDR | Preliminary Design Review |
| ROS | Robot Operating System – [www.ros.org](www.ros.org) |
| SBC | Single Board Computer – high-level half of the OBC, connected to HWC |
| SFR | Sample Fetch Rover – the rover platform itself |
| SRL | Sample Retrieval and Launch – the remote operation terminal |
| TRR | Test Readiness Review |
| WBS | Work Breakdown Structure |

# APPENDIX B: DOCUMENT REFERENCE LIST

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