AER 407 Space Systems Design

Canadian Red Dragon Mars Mission

Team HAL-407

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Executive Summary

The following document outlines system, subsystem and sub-subsystem requirements, operation scenarios, mechanical, electrical and control designs as well as mass, power and energy budgets for a proposed robotic system whose purpose is to investigate Mars and fulfill scientific objectives.

The first section addresses operational aspects of the mission, where the background, objectives and scope are presented, followed by operational policies and constraints taken from the Request for Proposal (RFP) by McDonald, Dettwiler and Associates Ltd. (MDA). Next, the description of the proposed system is provided together with a list of different modes of operation and user classes associated with the system. Lastly, a series of diagrams are used to provide some detailed information on the system's various operational scenarios.

The second section provides more details about the proposed robotic system. First, system and subsystem requirements are appropriately defined and categorized as functional, performance, environmental or constraint requirements. Next, a System Block Diagram (SBD) is provided to showcase the seven subsystems of the proposed design, as well as the system's external interfaces. A basic System Hierarchy Diagram is then used to show the relationship between the robotic system and its subsystems. Subsequent sections investigate key design drivers, followed by an analysis of system-level mechanical, electrical and control trade-offs.

The third section outlines the mechanical aspect of each subsystem within the proposed design. First, a table is provided to highlight which type of mechanical requirements each subsystem is subjected to. In addition, more detailed functional and performance requirements are added for each subsystem and sub-subsystem to take into account the mechanical considerations presented in the first section. In a subsequent section, trade studies are done for the mechanical components of each subsystem, where advantages and drawbacks of different options are analyzed and compared against each other. A final recommendation will also be made for each component based on how well each option meets the requirements. Next, preliminary system architecture diagrams are provided for the robotic system in both stowed and operating configurations to show system interfaces with the launch vehicle as well as where each subsystem will be located. Lastly, an estimate for the mass budget of all subsystems is presented, with an appropriate margin and justifications for each.

The fourth section gives a detailed analysis of the electrical aspect of each subsystem within the proposed design. First, a table is provided to highlight which type of electrical requirements each subsystem is subjected to. In addition, more detailed functional and performance requirements are added for each subsystem and sub-subsystem to take into account the electrical considerations outlined in the first section. Next, trade studies are done for the electrical components of each subsystem and a final recommendation is made for each component based on how well each option meets the requirements. Next, Electrical Functional Block Diagrams (EFBD) are provided for each subsystem together with a system-level diagram outlining the physical layout of all electrical components within the frame of the robotic system. Additionally, an estimate for the power budget of all subsystems is presented, with an appropriate margin and

justifications for each. From the power budget, estimates are made for the amount of power and energy the system will need for one operational cycle.

Lastly, the controls aspect of each subsystem within the robotic system is presented. First, an overview table is provided to highlight which type of control requirements each subsystem must fulfill. In addition, more detailed functional and performance requirements are added for each subsystem and sub-subsystem to take into account the controls considerations outlined in the previous section. In a subsequent section, trade studies are done for the concerning processor selection, autonomy, computing architecture, and redundancy. Next, the control architecture diagrams for each subsystem are shown. Finally, a table explaining the feedback loops that occur in the architecture diagrams is provided.

Revision Table

Revision	Description	Author
1.0	Creation of document	All
1.1	Addition and modification of all subsystem sections	All
1.2	Addition of sub-subsystem requirements, designs and architectures.	All
1.3	Addition of detailed designs	All
1.4	Final Revision and Formatting	All

List of Acronyms

CSA: Canadian Space Agency
DTE: Direct to Earth
EDL: Entry, Descent and Landing
MER: Mars Exploration Rover
MSL: Mars Space Laboratory
MSS: Mars Surface System
RFP: Request for Proposal
TBC: To be Con rmed
TBD: To be Determined
C&L: Chassis & Locomotion
C&DH: Command & Data Handling
NC: Navigation & Control
UHF: Ultra High Frequency
RHU: Radioisotope Heating Unit
MDA: Motor Drive Ampli er
RDC: Resolver-to-Digital Converter
Osc: Oscilloscope
Res: Resolver
EMI F: Electromagnetic Interference Filter
OCP: Over-Current Protection
PDU: Power Distribution Unit
TCU: Thermal Control Unit
PWM: Pulse Width Modulation
VC: Voltage Converter

List of Nomenclature

kbps: kilobits per second
km/h: kilometers per hour
sol: one day on Mars (roughly 24 hours, 39 minutes and 35.244 seconds)

Convention of Abbreviations

System Requirement: S.F/C/P/E.Num

S: System **F**: Functional **C:** Constraint **P** :Performance **E:** Environmental **Num:** number

Subsystem Requirement XX.F/P/C/E.Num

TH: Thermal Control CF: Chassis Frame PW: Power
CM: Communications CD: Command & Data Handling SC: Science
NC: Navigation and Control

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Section A Concept of Operations

1 Background, Objectives and Scope

1.1 Background

Due to Mars' similarities to Earth, several Martian missions have been developed since the 1960s. [1] Although not all of the missions were successful, they had a wide range of goals, including but not limited to habitability tests, atmospheric studies, radiations, geology, hydrology. [1] Previous Mars Exploration Rover Missions, namely MER-A (Spirit) and MER-B (Opportunity) were mainly used for studying Martian geology, while the goal of Mars Space Laboratory Mission's Curiosity rover was to study habitability and climate of the planet. [2] [3]

Over the years, Canada has contributed in several Mars missions, such as the NASA Phoenix Lander, the NASA Mars Science Lander and the ESA ExoMars Mission, as an instrument and subsystem provider. In the last 15 years, the Canadian Space Agency (CSA) has also engaged many Canadian companies in early studies to prepare for future Canadian Mars missions. However, Canada has never had sufficient budget to lead its own Mars mission.

SpaceX recently announced its plan to develop a launch vehicle, called "Red Dragon", that can transport payload mass to the surface of Mars. SpaceX provides Canadian Space Agency (CSA) with orbital transfer and Mars Entry, Descent and Landing (EDL). This mission will be able to deliver the vehicle to Mars in 2018. To seize this opportunity, CSA has bought available excess landed mass for 2025 Red Dragon Mars Mission. CSA is determined to achieve and enhance our knowledge about the red planet.

1.2 Objectives

The main goal of this mission is to build on existing Martian exploration projects, which will also help advance Canada's exploration technology. Detailed scientific goals are as follows:

Goal 1. Collect data from bio signatures to detect possible extinct/extant life (AB-5)
Goal 2. Maximize use of Canadian Capabilities and Technologies in the design
Goal 3. Help understand the distribution of water in all its states (vapor, water, ice) on Mars (PG-M1)
Goal 4. Help with the investigation of atmospheric water vapor, how they are affected by winds and exchanged between the atmosphere and the surface of Mars (AT-M-1)
Goal 5. Investigate the interaction between the atmosphere and the ground of Mars (AT-M-3)
Goal 6. Determine possible habitable environments on other planets (AB-1)
Goal 7. Characterize minerals on Mars' surface, and their chemical composition (PG-M-2)

After meeting with the client (MDA), the first two goals were determined to be of the highest priority, goals 3-6 have the same priority, whereas goal 7 is of the lowest priority if working with regolith, otherwise it is of the same priority as goals 3-6. Our objective will be to focus on goals with higher priorities, while still trying to achieve as many goals as possible. All operational trade-offs will be discussed in their own section, which will aid the design team in the decision making stage for the design concept.

The aforementioned goals helped to set 4 high level objectives for this mission. Therefore, the mission's objective is to design a space system that will:

Objective 1. Travel to/between investigation zones and landing site.
Objective 2. Investigate materials of as many forms as possible.
Objective 3. Interpret the investigation and collect "useful" data.
Objective 4. Communicate with orbiter/lander for the transfer of the collected data.

1.3 Scope

Our responsibility is to collect and transfer scientific data by studying predefined investigation sites.
As designers, our team is responsible for developing a proposal for such design, as requested by our customer MDA, who is in charge of analyzing the feasibility of building the proposed design concept, manufacturing the final product, and presenting it to users.

The user groups involved in this mission before the launch include Governmental Organizations and Launch Personnel, who are responsible for delivering the system safely to the landing site on Mars. From there, Scientists, Operation Users and Support Personnel, and Trainers will be in charge of mission control. All the detailed stakeholder responsibilities are summarized in Section 6. Our team will not be responsible for launch, entry, descent, landing and data transfer direct to Earth, as they will be provided by aforementioned stakeholders (mainly by SpaceX and International Space Agencies' orbiting spacecraft). The objectives are defined in subsections 1.2, and the team's only responsibility is to deliver a proposed design to achieve them.

The mission cannot solely rely on previous missions, as it needs to build on the prior Mars exploration achievements, and our team will try to maximize the scientific output from this mission. Therefore, the proposed design will have to achieve all the criteria and constraints, capable of delivering scientific goals, while maintaining feasibility and achieve all the required functionalities.

2 Tradeoffs

As listed in the RFP, there are six scientific goals that need to be considered and their significance are ranked from 1 (the most important) to 3 (the least important).

Rank	Goal	Description of Goal	Landing site	Traverse site A	Traverse site B
1	AB-5	search for direct evidence of extinct or extant life through bio-signatures			✔
2	PG-M-1	understand the hydrology and hydrogeology of present and ancient Mars	✔	✔	
2	AT-M-1	investigate atmospheric processes that affect the transport of water on Mars and the exchange of water with the surface		✔	
2	AT-M-3	investigate the integration between atmosphere and the Martian surface		✔	✔
2	AB-1	detect the presence of potentially habitable environments on other planets		✔	
3	PG-M-2	characterize the mineralogy and geochemistry	✔	✔	✔

*Table 1 Rank of Scientific Goals and Corresponding Locations of Conduction. * check mark indicates that the goal listed can be fulfilled at the corresponding site.*

The three major tradeoffs of the task are the completion of scientific goals, the complexity of system, and the amount and accuracy of data collections and analysis. The decisions can be made between reaching traverse site A or traverse site B only, or MSS to both sites separately or sequentially.

Idea A
In the case of a single MSS only reaching traverse site A, the prioritized scientific goal AB-5 cannot be fulfilled. The rest of the goals could be achieved by investigating landing site or traverse site A. DTE(direct to earth) signal is 0% at traverse site A, which means the MSS has to come back to landing site in order to transmit the collected data back. The total distance the entire MSS travelling is 0.2km in this case.

Idea B
Fortunately, the prioritized goal AB-5 can be accomplished under the circumstances of a single MSS only reaching traverse site B. Goals PG-M-1 and AT-M-3 (rank 2 each) can be achieved at landing site and traverse site B respectively and goal PG-M-2 (rank 3) can be accomplished around neither landing site nor traverse site B. Since the DTE signal is 100% at traverse site B, the MSS is capable of communicating with the Earth; thus the best-case scenario is that the MSS

will reach the traverse site B, study, and send back the collected data. Therefore, total distance to travel is 1 km.

Idea C

The third option is that the MSS travels to traverse sites A and B, in which case all scientific goals can be fulfilled. If the MSS goes to traverse site A before going to B, it is feasible to transmit data back to the orbiter without returning to the landing site, since the DTE at traverse site B is 100%, resulting a minimum travelling distance of 1.2 km. On the other hand, if the MSS directs to traverse site B first, due to the loss of signal at traverse site A, the total travelling distance will be 2.2 km.

Idea D

The fourth option is to have the MSS consist of two parts that can work independently. The advantage of having a system with two independent parts is that both traverse sites can be visited simultaneously. The main disadvantage of this separated system is that the complexity of the overall system increases compared to a system consisting of a singular component. Furthermore, a system composed of two detachable parts must still obey the payload mass and volume constraints of the Red Dragon, which limits the individual capabilities of each detachable component.

The length of Martian solar day (as known as *sol*) is 24h 39m 35.24409s, roughly equal to 1 day on the Earth. In order to simplify the calculations and have a quantitative analysis, minimum operating life of 120 sol on the surface [5] can be treated as 120 times 24 hours, equal to 2880 hours in total [5]. The ground speed of MSS is suggested to be around 4m/s to 5m/s (approximated 2.5m per minute) by Mars Science Laboratory in CIT [6]. According to the information provided, the travelling time for Idea A is roughly 1.4 hours, idea B 6.7 hours, Idea C at least 8 hours, and Idea D at least 0.67 hours. Travelling time is less than 1% of the minimum operating time of the MSS. Therefore, MSS performance of data collection will not be significantly affected by travel time loss.

Another tradeoff is between the amount and accuracy of data, and the number of goals completed. If we target less goals, more data per task can be generated to ensure higher accuracy for later analysis. Moreover, MSS will need to carry fewer experimental apparatus, which results in less power consumption.

The lack of communication available at traverse site A poses significant risk to the mission if it was a required travel site. If the MSS were to fail while at traverse site A, the ground team on Earth would not be able to communicate with the MSS and there is the possibility of losing the MSS indefinitely at the site. Furthermore, the lack of communication available at traverse site A means that the MSS must travel back to the landing site in order to communicate with the ground team on Earth, since it is the closest site where a 100% DTE signal is known. This need to travel back to the landing site has two major implications on the mission: significantly increased frequency of travel and significantly increased travel times. The increased frequency of travel exposes the MSS to increased risk at it could malfunction during any of the trips between the landing site and traverse site A. The significantly increased travel time means that more time is spent travelling for the sake of communication and less time is spent on performing science experiments, thus limiting the amount of science data that can be collected. For the significantly increased risk posed by traverse site A, any option involving travel to traverse site A will be rejected.

The rejection of traverse site A leaves 3 main options for the mission design: (i) stay at the landing site, (ii) travel to traverse site B, (iii) collect data at the landing site followed by traverse site B. Staying at the landing site poses the least risk to the MSS as no travel is required to any of the sites, however this comes at the tradeoff of having the least amount of science goals available to complete. Travelling to traverse site B introduces the risk of travel, however once the MSS reaches the site, it no longer has to perform any significant travel unlike traverse site A. The tradeoff of increased risk is met with being able to complete the most important goal as outlined by the customer, AB-5. The third option is a combination of the previous two options. The primary advantage is that the most science goals can be accomplished with this method with the same level of risk at option (ii). In addition, option (iii) introduces a level of fault tolerance within the mission design, where science data can be collected at the landing site first before exposing the MSS to the risk of travelling to traverse site B. The main tradeoff with option (iii) is dilution of effort, where time must be split between both the landing site and traverse site B. Due to having the most potential science goals being achievable under the exclusion of site A, and the added level of fault tolerance, the MSS will first collect science data at the landing site first and then travel to traverse site B and stay there for the remainder of the mission.

3 Operational Policies and Constraints

This section illustrates the policies and constraints that are applicable to the proposed system. These items are important in the decision-making process of the proposed designs. Policies will allow for discretion but limits some freedom of decision-making while constraints are limitations placed on the operation of the system.

3.1 Policies

- The design shall not make use of any radioisotope thermoelectric generators (RTG) for power generation at the request of the customer
- The design shall adhere to the Engineering Code of Ethics in Canada [8]
- The design shall adhere to space laws designed by the Committee on the Peaceful Uses of Outer Space [9]

3.2 Constraints

3.2.1 Landing Site

The landing site of the design is stated in Figure 1 The items taken will not be returned to the Earth.

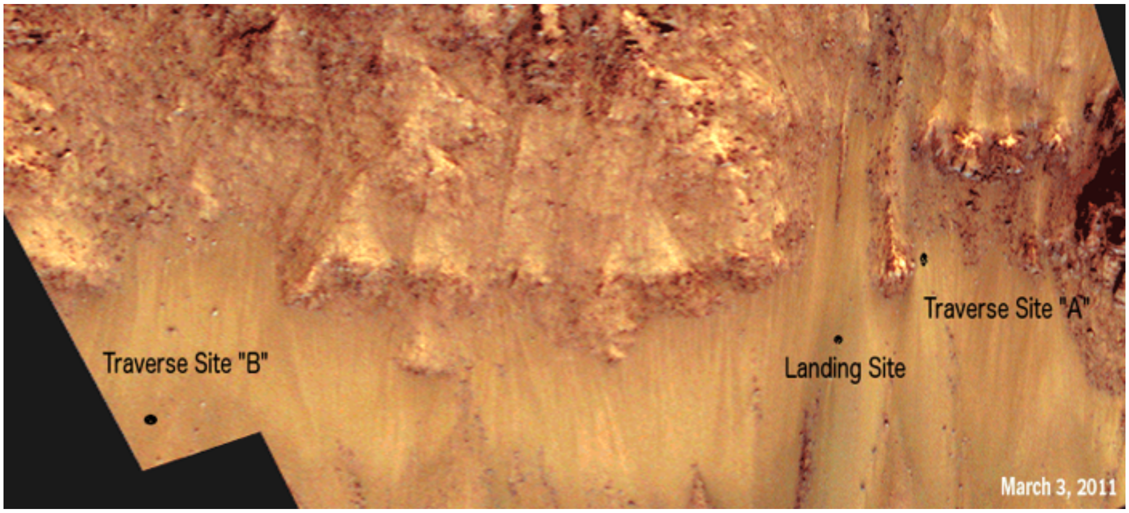

Figure 1 Landing site and traverse sites

3.2.2 Payload

The maximum payload mass of the Canadian robotic system is set to be 140 kg. The payload volume envelope is defined as 0.8m x 1.2m x 1.2m, seen in Figure 2.

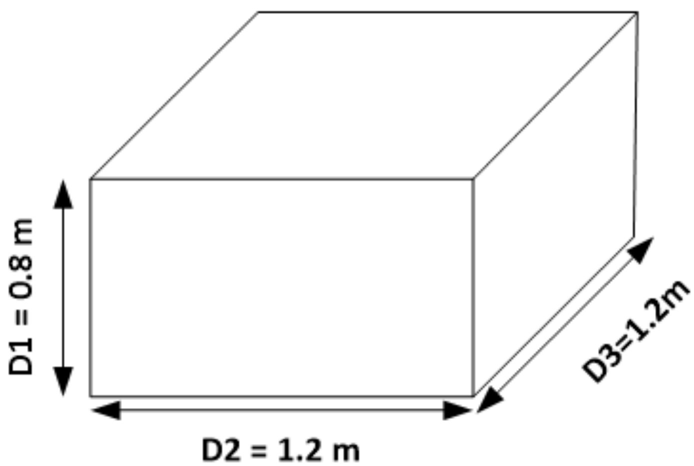

Figure 2 Dimension Constraints

3.2.3 Power

The keep-alive power provided is set as 15 Watts average with 20 Watts Peak during the Red Dragon Earth-Mars transfer. Once landed, the Red Dragon will provide NO power or data capabilities to the Canadian payload.

3.2.4 Communications

The communication data is set to be 256 kB total checkout data once per week and at landing, communicated half duplex with the host spacecraft at 115.2 kbps.

3.2.5 Environment

During launch, the payload may experience extensive g-forces. Extra consideration must be made for the worst axis to be 8.5g and the other axes to be 4g according to the RFP. The design should be manufactured considering worst-case temperature environments as listed below:

Operating: -65 to +50 deg C
Survival: -128 to +50 deg C

3.2.6 Mechanical Interface Points

The two mechanical interface points will be in the form of cup-cone type hold-down & release mechanisms, 12cm diameter and 8 cm long provided in Figure 3.

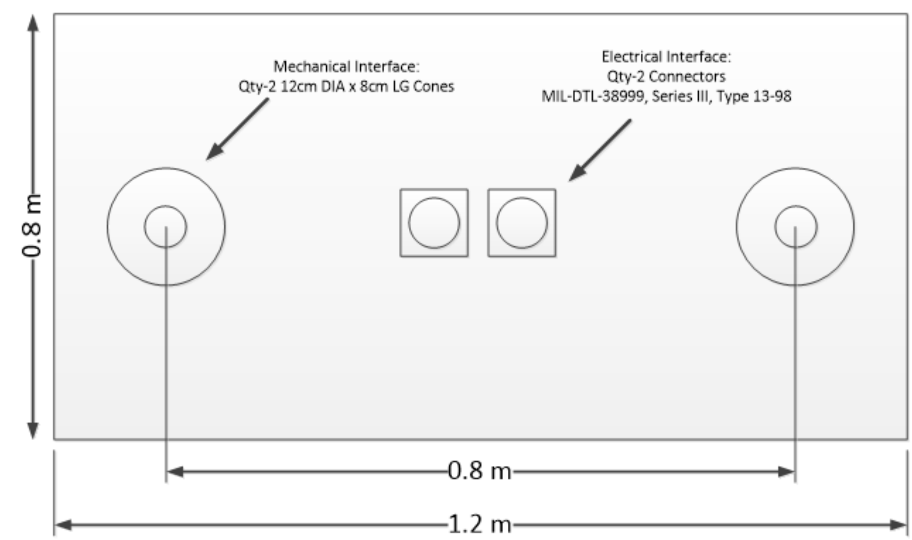

Figure 3 Mechanical Interface Points

3.2.7 Electrical Interface Points

We will be provided two in-flight disconnect electrical interface points located at the payload separation plane by connector types MIL-DTL-38999, Series III, Type 13-98 (qty-1020-AWG contacts).

4 Description of the Proposed Design

4.1 Operational Environment and Its Characteristics

This section outlines major environmental factors affecting day-to-day operations of the proposed design. These factors are summarized in Table 2 below.

Environment	Characteristics
Temperature range	Operating: -65°C to 50°C Survival: -128°C to 50°C
Surface conditions	Landing site: relatively benign terrain, hard-packed regoliths and/or rocks Traverse site A: benign terrain, loose regoliths Traverse site B: benign terrain, loose regoliths and small rocks
Mars' weather	can expect regular heavy dust storms capable of covering the entire planet and can last for months
DTE signals	Landing site: 100% Traverse site A: 0% Traverse site B: 100%
Atmosphere	~ 1% of Earth's
Pressure	~ 0.6% of Earth's atmospheric pressure
Gravity	~ 0.38 of Earth's
Vibrational loads	launch vibration of 8.5g in the worst axis and 4g in each of the other two axes

Table 2 Operational Environment and Characteristics

4.2 Major Components and the Interconnections among these Components

Please refer to Section 7 for the full Mission-Level Block Diagram.

4.3 Interfaces to External Systems or Procedures

Please refer to Section 7 for the full Mission-Level Block Diagram.

4.4 Capabilities and Functions of Proposed System

The system will be able to:

- Travel from the landing site to traverse site B
    - Travel a distance 1000m between the landing site and traverse site B
    - Autonomously navigate towards traverse site B
- Perform experiments and collect scientific data related to the goals discussed in section 1.2
- Save scientific data for transmission back to Earth
- Analyze the samples and transfer collected data to the orbiter, which in turns transfer these data to Earth for further analysis
- Communicate with the orbiter for any transfer of data/information from Earth
    - Transmit collected scientific data
    - Receive commands from CSA Mission Operations Centre
    - Receive updated science objectives from the science team on Earth

4.5 Charts and Descriptions Depicting Inputs, Outputs, Data Flow and Manual and Automated Processes

Please refer to Section 7 and Section 8 for the full Mission-Level Block Diagram and FFBDs of the system.

4.6 Operational Risk Factors

This section highlights major risks associated with the proposed design, taking into account risks introduced by the operational environment as well as by possible damages in the system, launch vehicle and orbiter.

Risk	Cause	Countermeasures
Component malfunctions	Malfunctioning parts, damage during launch	TBD
Component damages due to weather conditions	Harsh weather conditions on Mars	TBD
Loss of components	Obstacles on Mars' surface, harsh weather conditions	TBD
Loss of power	Malfunctioning parts in power supply	TBD
Signal loss	Malfunctioning antenna, malfunctioning parts in orbiter, obstacles on Mars' surface (such as at traverse site A)	TBD
Launch failure	Malfunctioning of launch vehicle, issues with surface interfaces	TBD

Table 3 Operational Risk Factors

4.7 Performance Characteristics

This section provides a list of performance characteristics of the proposed design.

- The system will have a minimum travel speed of 0.1 km/h
- The number of scientific goals that the system can achieve within the mission timeline
- The impact of the scientific data collected during the mission timeline
- The system will fit within a 0.8m x 1.2m x 1.2m envelope
- The system will have a mass under 140kg
- The system will have a data transfer frequency of 8 kbps
- The system will have an operational life of minimum 120 sols
- The system will withstand vibration loads of 8.5g in the worst axis and 4g in each of the other two axes
- The system will operate under the worst case temperature ranges of -65 to +50 °C (operating) and -128 to +50 °C (survival)

5 Modes of Operation

This section describes different modes of operation as well as states/commands of the system.

5.1 Modes

Testing Mode: system performs testing to verify viability and safety of all phases of operation prior to launch.

IDLE Mode: keep-alive mode during Red Dragon Earth-Mars transfer and landing (15 Watts average, 20 Watts peak).

Emergency Mode: system that deals with emergency situations such as tough weather conditions, loss of communication signal, extraterrestrial life encounter and etc.

Energy-saving Mode: system that maintains high importance level operation tasks a lower energy level.

Stowed Mode: system enters a folded configuration state for interfacing with the Red Dragon lander. Necessary to fit within the allotted payload volume of the Red Dragon.

Deployed Mode: system enters a deployed state for normal operation.

<u>Normal Operating Modes:</u>

Mars Surface Travelling Mode: system responsible for traveling on Mars surface among the two traverse sites and landing site.

Task Operation Mode: perform series of actions such as digging, grabbing samples, collecting samples and etc. Tasks operation are scripted based on different scientific goals and task definitions.

Communications Mode: system responsible for communication direct back to Earth.

5.2 States

Off: system is completely turned off.
Initialize: system is switched on.
Standby: system ready for both scripted and manual commands.
Execution: task being executed on manual or scripted commands.
Sleep: system goes to IDLE Mode.
Stowed: folded configuration to fit within Red Dragon payload volume
Deployed: unfolded configuration for normal operation

5.3 Transition between modes

Manual Transition: transition to Testing Mode, IDLE Mode are manual and determined by operation and launch support personnel.

Scripted Transition: Emergency Mode will be triggered automatically when the emergency situations are detected. Transitions to Communication Mode, Mars Travelling Mode, Task Operation Mode, as well as Energy-saving Mode are also scripted according to operation phases and their sequence.

6 User Classes

This section described groups of users of the system.

Customer and Governmental Organizations: propose policies and constraints on the design, also provide means for communication and negotiation about the project details, as well as budget and material supply.

Launch Preparation Personnel: responsible for testing procedures prior to launch and all launching procedures, which include loading the designed landed mass onto Red Dragon launch vehicle.

Scientists & Engineers: design experimental procedures and apparatus to accomplish outlined scientific goals in the mission. Experimental apparatus to be included on the landed mass.

Operation Users: responsible for monitoring and controlling all levels of operation tasks, receiving collected data, and ensuring operation tasks implementation quality.

Operation Support Personnel: responsible for system monitoring and maintenance, detecting any problems or potential problems during operation, and interfere when needed to ensure operation safety.

Trainers: have expertise in all operational tasks as well as landed mass design features, they are responsible for knowledge transfer to operation users, operation support personnel, scientists, as well as launch preparation personnel.

7 Mission-Level Block Diagram

The mission level block diagram shown below depicts how the Mars Surface System will interface with the other main systems present in the mission. Labels for each interface are explained below.

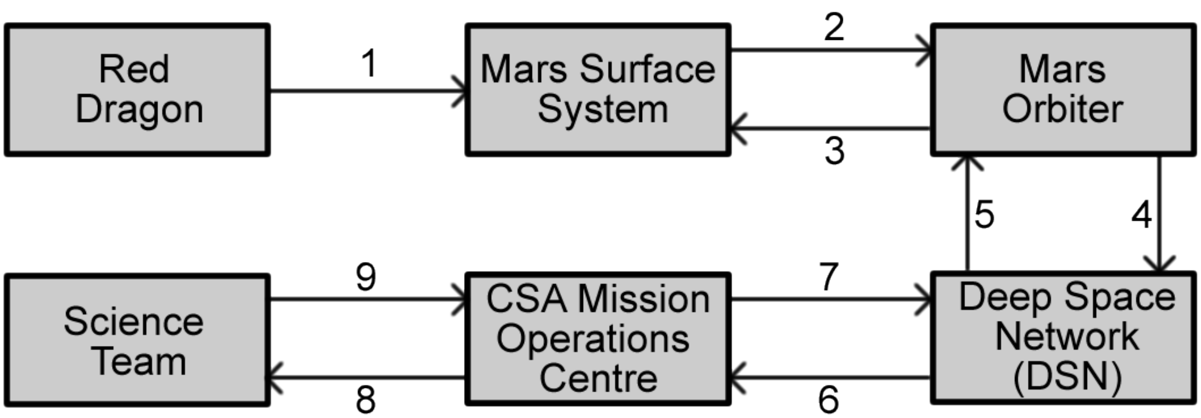

Figure 4 Mission-Level Block Diagram for MSS

1. The Red Dragon is responsible for all Mars EDL functions. The MSS is transported as a payload. Once landed, the Red Dragon will not provide any power or data capabilities to the payload.

2. The MSS will relay scientific data to the Mars Orbiter during designated communications periods.

3. The MSS can receive new updated objectives from the science team relayed through the Mars orbiter.

4. The scientific data received by the orbiter is then relayed to NASA's Deep Space Network.

5. Updated mission objectives from the science team can be relayed to the MSS via the DSN to the Mars Orbiter.

6. The data relayed from the DSN is then sent to CSA Mission Operations Centre.

7. New objectives from the science team can be relayed back to the MSS via the DSN.

8. The science team is able to analyze the data received by the MSS.

9. The science team can send updated mission objectives and data to CSA's mission operations center to relay to the DSN.

8 Operational Scenarios

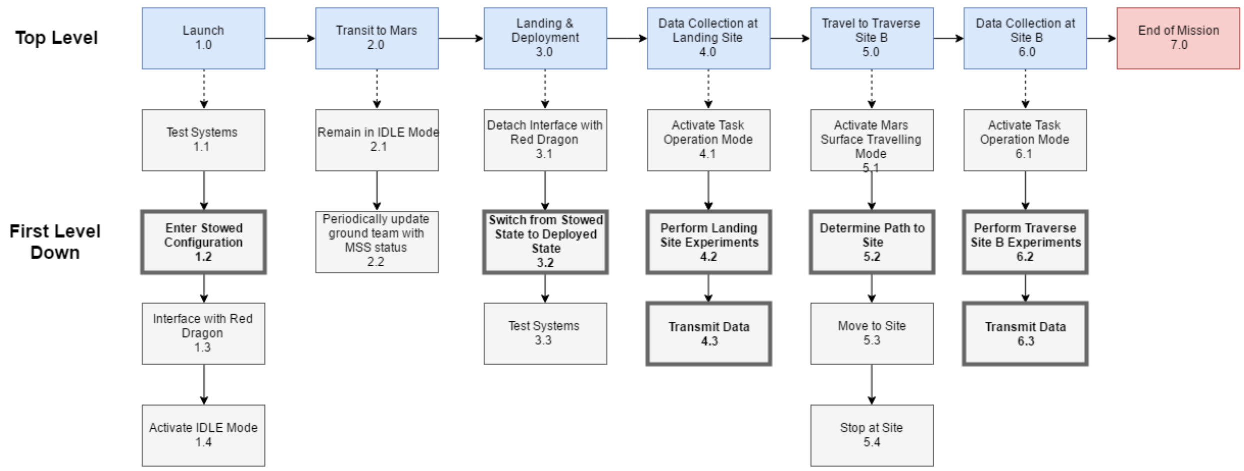

Figure 5 Top level and first level down of functional flow block diagram for the normal operating mode of the MSS. The bolded blocks in the first level down represent blocks that go down further to a second level.

The functional flow block diagram for the normal operating mode of the MSS consists of seven phases at the top level: Launch (1.0), Transit to Mars (2.0), Landing & Deployment (3.0), Landing Site Data Collection (4.0), Travel to Site B (5.0), Data Collection at Site B (6.0), and the End Mission (7.0) phase.

Phase 1.0 details the steps necessary for the MSS system to prepare prior to launch with the Red Dragon. The first level down from this phase consists of testing the MSS's systems prior to interfacing with the Red Dragon (1.1). After the systems are tested and no complications occur, the MSS will enter a stowed configuration to fit within the allotted Red Dragon payload volume (1.2). At this point the MSS will interface with the Red Dragon mechanically and electrically (1.3). Once the MSS has interfaced with the Red Dragon successfully it will initiate IDLE mode to ensure survival during the launch, transit and landing phases of the mission.

Phase 2.0 describes the behavior of the MSS system while in transit to Mars as a part of the Red Dragon's payload. During this phase of the mission, the MSS will remain in IDLE mode for survival (2.1).

Phase 3.0 details the procedure that the MSS will follow once the Red Dragon has landed at the landing site. Once the Red Dragon has successfully landed, the MSS will be detached from the Red Dragon (3.1). Following detachment, will switch from its stowed state to its deployed configuration (3.2) and perform a diagnostic test on itself to confirm all systems are operational to perform the mission (3.3). All launch, entry and descent operations of the Red Dragon lander are out of the scope of our mission as these operations will be handled by SpaceX; these phases in the FFBD are only concerned with the actions that the MSS needs to take during these phases, not with what the Red Dragon must do during these phases. The MSS begins its mission after phase 3.0.

Phase 4.0 details the general procedure that the MSS will take to conduct research at the landing site. First, it will initiate its task operation mode (4.1) and select an appropriate sampling area within the landing site based on its current mission objectives or on new objectives received from the science team on Earth. Once an appropriate sampling area is selected, the MSS will perform experiments related to its current mission objective at the site (4.2). As the MSS performs experiments at the site, it will save the data to transmit to Earth at a later time. When a communication window is open, the MSS will transmit its saved science data to the science team via the Mars orbiter (4.3).

After sufficient data is collected at the landing site, phase 5.0 of the mission begins, where the MSS must travel to traverse site B. This phase consists of switching from task operation mode to Mars surface travelling mode (5.1). Once the MSS has switched modes, it must determine an appropriate navigation path (5.2) and move towards traverse site B (5.3). Once the MSS reaches traverse site B, it will stop (5.4) and initiate phase 6.0.

Once the MSS reaches traverse site B, phase 6.0 of the mission begins, where the MSS will spend most of the mission time. The procedure described in the first level down of this phase is identical to the procedure described for phase 4.0. The primary difference between phase 4.0 and phase 6.0 are the types of experiments that will be performed due to the landing site and traverse site B having different achievable science goals.

Phase 7.0 marks the end of the 120 sols allotted for the mission. Once this point is reached, our obligations are fulfilled and we are no responsible for the operation of the MSS. The following FFBDs below detail the second level down from the bolded blocks in the first level down of the main operating mode FFBD.

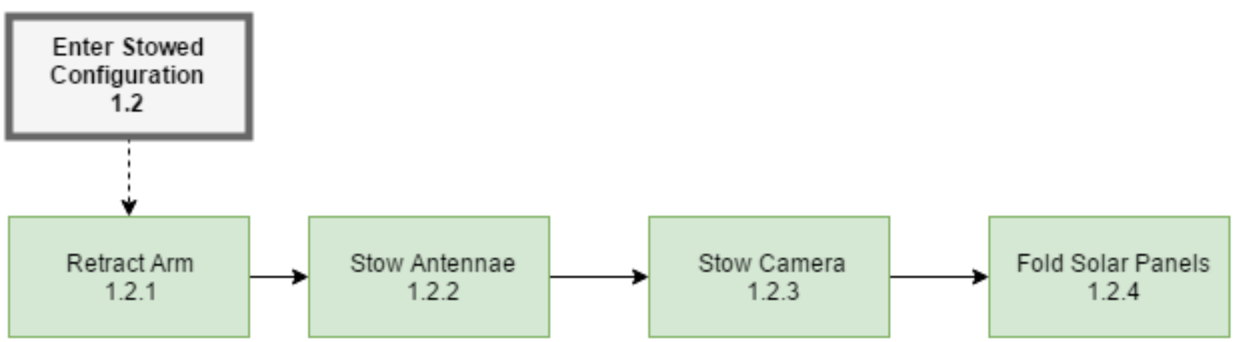

Figure 6: Second level down FFBD for outlining how the MSS will enter the stowed state from the deployed state.

The above FFBD shows how the MSS will enter its stowed configuration prior to launch. Each block in this FFBD represents the type of component that will have to be folded or contracted in order to fit within the Red Dragon's payload volume.

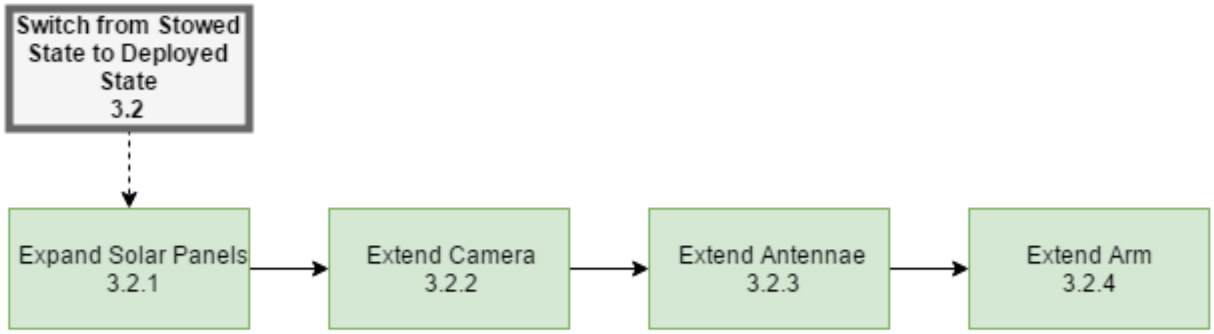

Figure 7: Second level down FFBD for outlining how the MSS will switch from the stowed configuration back to its deployed state

The above FFBD details the opposite procedure to that depicted in Figure 6. Any external component of the MSS that was retracted or folded is now expanded or extended when switching to the deployed configuration from the stowed configuration.

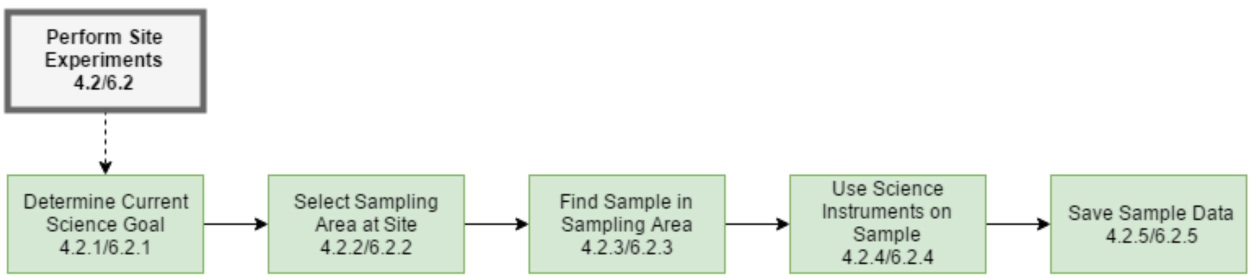

Figure 8: Second level down FFBD for outlining how the MSS will perform experiments at each of the sites visited. This process is the same for both 4.2 and 6.2.

The above FFBD details the general procedure the MSS will follow at each site of interest (landing site, traverse site B). The procedure remains the same at both sites, with the science objectives being the main difference between the two sites. The current science goal can be determined either via an updated command from the science team on Earth or accepting its previous objective if no update or change was made.

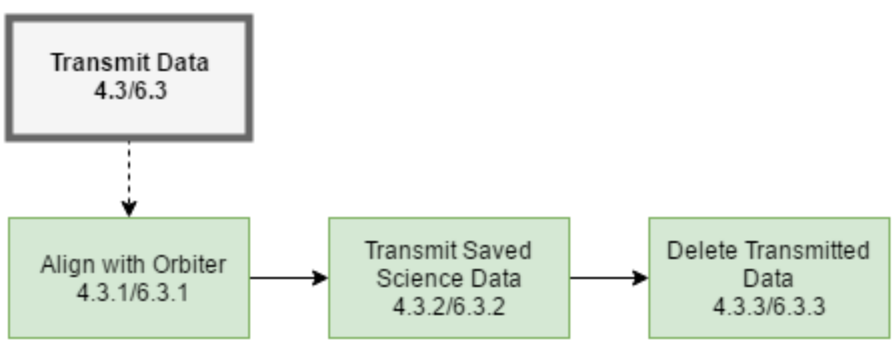

Figure 9: Second level down FFBD for the transmit data blocks (4.3 and 6.3) in the normal operating mode FFBD. This process is the same in both scenarios.

The above FFBD details the general prodcedure for data transmission to Earth via the Mars orbiter. First the rover must align with the time window allotted by the orbiter's orbit and target its directional antennae to the orbiter. Once aligned the MSS will proceed to transmit the saved over the course of the experiments performed in block 4.2/6.2. In order to make more storage space available for continued experiments, the MSS will delete the data it has successfully transmitted.

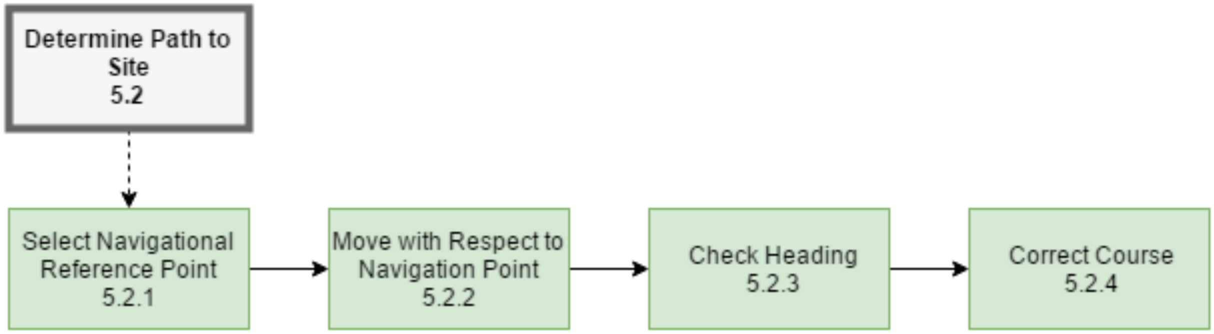

Figure 10: Second level down FFBD outlining how the MSS will determine a path to travel to traverse site B.

The above FFBD details how the MSS will determine a navigational path to traverse site B from the landing site. First, the MSS must select a navigational reference point such as a cliff face or stars. Then the MSS will be able to move and correct its course based on that reference point. This process is conducted over the course of its journey to traverse site B.

Section B System Design

1 Introduction

As the program enters its design phase, it is important to decompose the system into smaller components and assess different constraints and requirements, as well as design drivers and tradeoffs of the proposed system. This divides the work into smaller tasks and makes the problem more approachable. In the Concept of Operations document, several requirements and constraints were defined for the robotic system. As a second phase of the program, the system is decomposed into its first-level subsystems where requirements for each subsystem are defined. Major subsystem design drivers and tradeoffs are also discussed in detail.

This report outlines the systems component of the program, where system and subsystem requirements are discussed extensively to provide more structured guidelines for the design of the robotic subsystems. Section 1 of the report presents a list of system requirements, which are further categorized into functional, performance, environmental and constraint requirements. Section 2 contains the System Block Diagram (SBD) where the subsystems as well as their interactions with each other and external environments are presented. Section 3 contains the System Hierarchy Diagram (SHD). Section 4 outlines all subsystem requirements, which correlate directly with the higher-level system requirements. Finally, section 7 discusses design drivers and tradeoffs for some of the major subsystem components.

2 System Requirements

2.1 Constraint Requirements

S.C.01 The system shall have a maximum mass of 140 kg. (Verified by measurement)

Rationale: to satisfy mass constraint.

S.C.02 The system shall fit in a volume envelope of 0.8m x 1.2m x 1.2m. (Verified by measurement)

Rationale: to fit into Red Dragon Launch Vehicle during Earth – Mars transfer.

S.C.03 The system shall two electrical and two mechanical interfaces that interact with the Red Dragon launch vehicle. (Verified by ground testing)

Rationale: two electrical and two mechanical interfaces are required for deployment, as specified in the RFP.

S.C.04 The system shall sustain balance during traversal. (Verified by ground testing)

Rationale: to ensure chassis can support all operations.

S.C.05 The system shall be able to send data to the orbiter. (Verified by ground testing)

Rationale: to transmit science data to ground control via the orbiter.

S.C.06 The system shall be able to receive commands from the orbiter. (Verified by ground testing)

Rationale: to enable the MSS to work under commands of ground control.

S.C.07 The system shall have a power usage of maximum TBD W. (Verified by ground testing)

Rationale: to ensure sufficient power usage.

S.C.08 The system shall rely on non-nuclear means of energy.

Rationale: constrained by customer.

2.2 Functional Requirements

S.F.01 The system shall have a data transmission rate of 8 kbps. (Verified by ground testing)

Rationale: to ensure data and command are sent and received in a timely manner.

S.F.02 The system shall rely on itself for power generation. (Verified by ground testing)

Rationale: no power supply station or any other source of power supply unit on Mars, except for the MSS itself.

S.F.03 The system shall store generated power. (Verified by ground testing)

Rationale: to ensure sufficient power during traversal and science operations.

S.F.04 The system shall have a thermal control mechanism. (Verified by ground testing)

Rationale: due to the extreme temperature condition in Martian environment, this requirement ensures that all system components operate in desired temperature range.

S.F.05 The system shall complete at least one scientific goal. (Verified by simulation testing)

Rationale: minimum number of objective to ensure mission completeness.

S.F.06 The system shall navigate on the Martian surface. (Verified by simulation)

Rationale: to reach traverse sites.

S.F.07 The system shall collect scientific data on Mars. (Verified by simulation)

Rationale: to capture data for scientific analysis.

2.3 Performance Requirements

S.P.01 The system shall have an operating life of at least 120 sols. (Verified by simulation tests and calculation)

Rationale: required minimum mission duration specified in RFP.

S.P.02 The system shall be able to collect a minimum of 512 GB of data per sol. (Verified by ground testing)

Rationale: Refer to Appendix 1 [10]

S.P.03 The system shall be able to collect data from at least 2 forms of matter (solid, liquid, gas)

Rationale: required for science objectives of interest.

S.P.04 The system shall travel with a minimum velocity of 0.10km/hr.

Rationale: Refer to the Mechanical Design Requirements [11]

S.P.05 The system shall be able to go to emergency mode. (Verified by ground testing)

Rationale: to ensure that the MSS can deal with emergency situations (for example sand storm, hit by obstacle or rocks)

S.P.06 The system shall be able to go to energy-saving mode. (Verified by ground testing and simulation)

Rationale: in case of power shortage, only keep high priority tasks running and shut down unnecessary power consuming components.

S.P.07 The system shall have IDLE mode. (Verified by ground testing and simulation)

Rationale: MSS will be switched to IDLE mode during Earth – Mars transfer inside Red Dragon launch vehicle.

S.P.08 The system should complete three of the six scientific goals during its operational lifespan. (Verified by simulation)

Rationale: the goal is to do as much science as possible during the mission.

2.4 Environmental Requirements

S.E.01 The system shall be able to operate between -65 and 50 °C. (Verified by ground testing)

Rationale: operational environment conditions outlined in RFP.

S.E.02 The system shall be capable of sustaining temperatures between -128 and 50 °C.

Rationale: survival environment conditions outlined in RFP. (Verified by ground testing)

S.E.03 The system shall be able to withstand any obstacles while traveling to investigation zones. (Verified by ground testing)

Rationale: the MSS should be able to detect and avoid any obstacles on Mars surface to maintain steady operation.

S.E.04 The system shall tolerate a wind speed of 96km/hour. (Verified by ground testing)

Rationale: the MSS need to survive bad Martian weather conditions, refer to [10].

S.E.05 The system shall tolerate dust storms. (Verified by simulation)

Rationale: the MSS need to survive bad Martian weather conditions.

S.E.06 The system shall tolerate solar flares. (Verified by simulation)

Rationale: the MSS need to survive bad Martian weather conditions, refer to [11].

S.E.07 The system shall tolerate rock/foreign object collision of TBD kg*m/s

Rationale: the MSS need to survive rock impact.

S.E.08 The system shall withstand vibration of 8.5g in the worst axis.

Rationale: magnitude of vibration referenced from RFP.

S.E.09 The system shall withstand vibration of 4g in each of the other two axes

Rationale: magnitude of vibration referenced from RFP.

3 System Block Diagram

The figure below illustrates the System Block Diagram of the MSS. The seven subsystems of the MSS includes C&DH Subsystem, Power Subsystem, Science Subsystem, Thermal Control Subsystem, Navigation & Control Subsystem, Communications Subsystem, Chassis Subsystem.

There are five interfaces connecting these subsystems, in categories electrical, mechanical, data, commands and thermal.

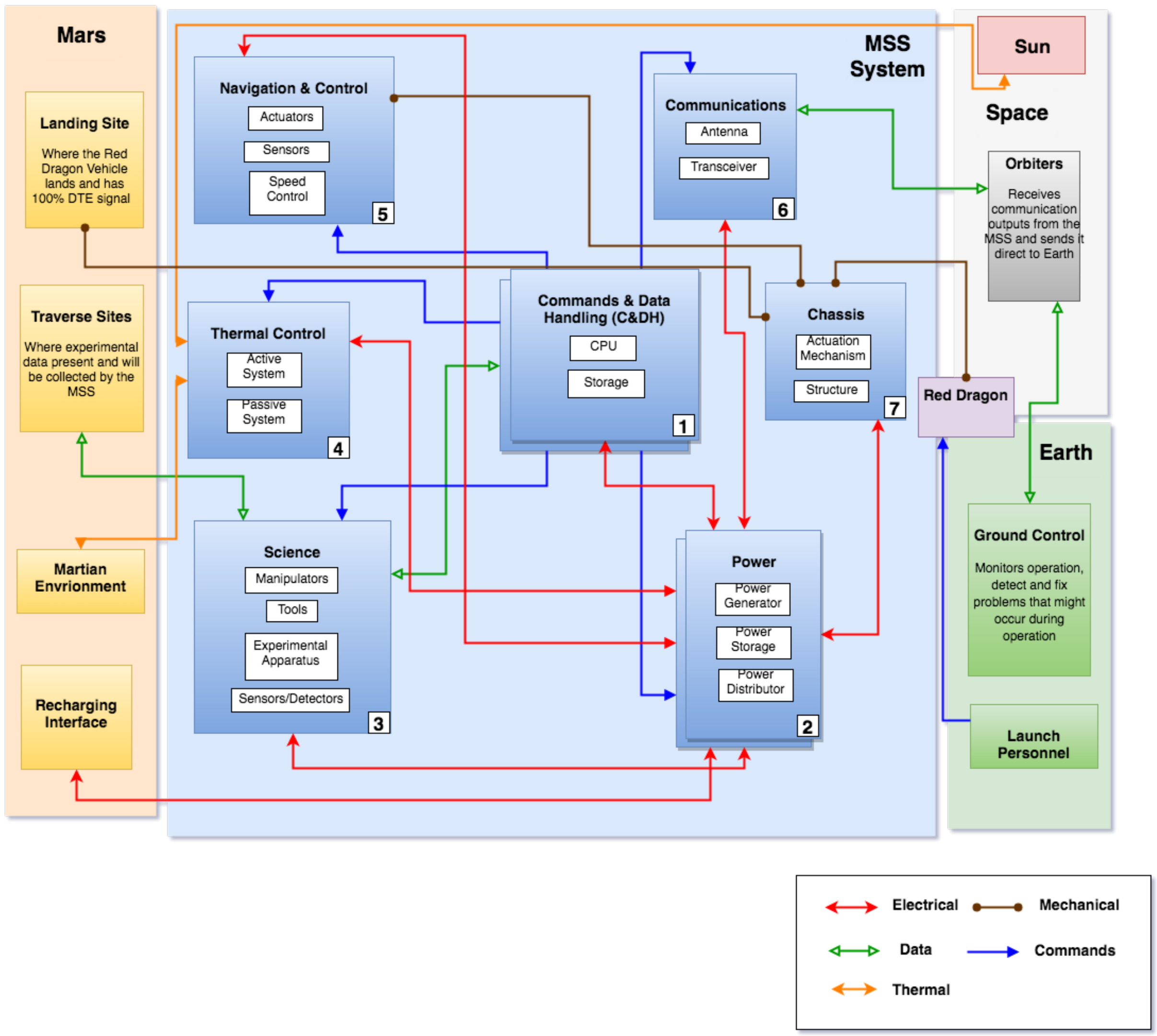

Figure 11 System Block Diagram

3.1 Subsystems

C&DH: this subsystem behaves like a brain of the MSS, and is responsible for data processing and storage, as well as commands to all other subsystems. *(higher significance as implied in SBD)*

Power: this subsystem is responsible for generating, storing and distributing power to all other subsystems. *(higher significance as implied in SBD)*

Science: this subsystem contains experimental equipment, manipulators, sensors and detectors as well as tools needed to perform scientific tasks.

Thermal Control: this subsystem monitors and adjusts the temperature of all components on the MSS, and may contain both active and passive systems components.

Navigation & Control: this subsystem contains actuators, sensors and speed control mechanisms that allow the MSS to travel on Mars surface under different surface conditions. In addition, this subsystem is also responsible for guiding the MSS to different traverse sites and landing site.

Communications Subsystem: this subsystem handles all communications required in the operation, this may include communication with the orbiters as well as interactions with C&DH subsystem.

Chassis Subsystem: this subsystem contains the base and frame of the MSS, as well as actuation mechanism to allow mobility of the MSS.

3.2 Interfaces

Mechanical: Physical interactions, involving direct contact/connection

Electrical: Electric power interactions, which operate the necessary subsystems. This interface is exclusive between power and other subsystems.

Data: Means of the data transfer and communication to and from the MSS. Collected data from the science subsystem will be using this interface.

Command: Electronic signal interactions. The C&DH subsystem of the MSS will be determining the operations of the subsystems.

Thermal: This “interface” describes the means of the heat transfer, in the forms of conduction, convection and radiation.

4 System Hierarchy Diagram

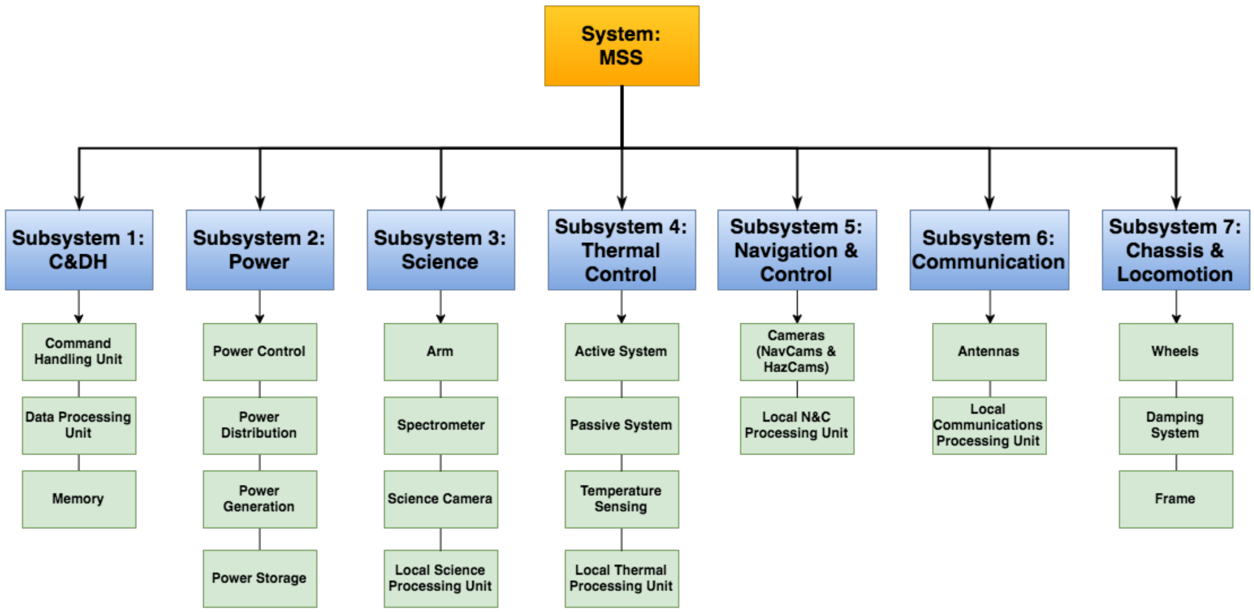

Figure 12 System Hierarchy Diagram

5 Subsystem Requirements

5.1 C&DH Subsystem Requirements

5.1.1 Constraint Requirements

CD.C.01 The C&DH subsystem shall have a maximum weight of 2.31 kg. (Verified by measurement)

Rationale: to satisfy mass constraint, refer to mass budget section for details.

CD.C.02 The C&DH subsystem shall consume a maximum average power of 8 W. (Verified by ground testing)

Rationale: to satisfy power constraint, refer to power budget section for details.

5.1.2 Functional Requirements

CD.F.01 The C&DH subsystem shall establish correct response to commands. (Verified by ground testing)

Rationale: to ensure subsystem integrity.

CD.F.02 The C&DH subsystem shall be able to have reliable connections established to send out commands to all other subsystem. (Verified by ground testing)

Rationale: stable connections is import to ensure commands are passed onto to other subsystems successfully and in a timely manner.

CD.F.03 The C&DH subsystem shall be able to receive data collected from Science subsystem to complete scientific tasks. (Verified by ground testing)

Rationale: science data is one of the most significant aspect of operations.

CD.F.04 The C&DH subsystem shall process data collected from Science subsystem. (Verified by ground testing)

Rationale: to prepare and process scientific data to send back to ground control via communication subsystem and the orbiters.

CD.F.05 The C&DH subsystem shall send transmissions to Earth ground control via communication subsystem and the orbiters. (Verified by ground testing)

Rationale: to transfer all required data for operation.

CD.F.06 The C&DH subsystem shall receive transmissions from Earth ground control via communication subsystem and the orbiters. (Verified by ground testing)

Rationale: to receive commands for operation.

CD.F.07 The C&DH subsystem shall can switch modes of operation of the MSS. (Verified by ground testing)

Rationale: to achieve maximum efficiency and save power consumption.

CD.F.08 The C&DH subsystem shall process signals collected from sensors in all other subsystems. (Verified by ground testing)

Rationale: to detect any component malfunction, or emergency due to Martian surface conditions.

CD.F.09 The C&DH subsystem shall be powered by the power subsystem. (Verified by ground testing)

Rationale: to receive power for operation.

5.1.3 Performance Requirements

CD.P.01 The C&DH subsystem shall send transmissions at a minimum of TBD kbps. (Verified by ground testing)

Rationale: to ensure data gets sent in a timely manner.

CD.P.02 The C&DH subsystem shall receive transmissions at a minimum of TBD kbps. (Verified by ground testing)

Rationale: to ensure data gets received in a timely manner.

CD.P.03 The C&DH subsystem shall be capable of detecting subsystem failures. (Verified by ground testing)

Rationale: to protect the MSS from any dangerous situation.

CD.P.04 The subsystem shall can respond to subsystem failures. (Verified by ground testing)

Rationale: to provide appropriate command and instructions in response.

CD.P.05 The subsystem shall have a minimum storage GB of data. (Verified by ground testing)

Rationale: to have enough space for science data and other necessary data during operation.

5.1.4 Environmental Requirements

CD.E.01 The C&DH subsystem shall be able to operate between -65 and 50 °C. (Verified by ground testing)

Rationale: to ensure subsystem normal operation in Mars environment, temperature range referenced from RFP.

CD.C.02 The C&DH subsystem shall be able to survive temperatures ranging between -128 and 50 °C. (Verified by ground testing)

Rationale: to ensure subsystem survival in Mars environment, temperature range referenced from RFP.

5.2 Power Subsystem Requirements

5.2.1 Constraint Requirements

PW.C.01 The power subsystem shall weigh less than 15.38 kg. (Verified by measurement)

Rationale: to satisfy mass constraint, refer to mass budget section for details.

PW.C.02 The power subsystem shall be able to provide required energy to the whole system for at least 120 sols. (Verified by simulation and calculation)

Rationale: to distribute power to all other subsystems for operation.

5.2.2 Functional Requirements

PW.F.01 The power subsystem shall contain a charging interface. (Verified by ground testing)

Rationale: to charge from solar panels.

PW.F.02 The power subsystem shall store the generated power. (Verified by ground testing)

Rationale: to store power in battery for nighttime operation since solar panel only operate during daytime (sunlight exposure).

5.2.3 Performance Requirements

PW.P.01 The power subsystem shall have a minimum charging speed of TBD W/s. (Verified by ground testing)

Rationale: to ensure efficient charging to supply power without interruption.

5.2.4 Environmental Requirements

PW.E.01 The power subsystem shall have the capacity to power the rover travel with a minimum velocity of 0.15km/h on the surface of Mars. (Verified by ground testing)

Rationale: to ensure subsystem normal operation in Mars environment, temperature range referenced from RFP.

PW.E.02 This power subsystem shall operate constantly and uninterruptedly between the temperature -128 and 50 °C. (Verified by ground testing)

Rationale: to ensure subsystem survival in Mars environment, temperature range referenced from RFP.

PW.E.03 The power subsystem shall be able to withstand vibration 8.5g in the worst axis. (Verified by ground testing)

Rationale: to tolerate vibration along the worst axis, number referenced from RFP.

PW.E.04 The power subsystem shall be able to withstand vibration 4g in the other two axes. (Verified by ground testing)

Rationale: to tolerate vibration along the other two axes, number referenced from RFP.

5.3 Thermal Control Subsystem Requirements

5.3.1 Constraint Requirements

TC.C.01 The thermal control subsystem shall weigh less than 5.38 kg. (Verified by measurement)

Rationale: to satisfy mass constraint, refer to mass budget section for details.

TC.C.02 The thermal control subsystem shall consume a maximum average power of 20 W. (Verified by ground testing)

Rationale: to satisfy power constraint, refer to power budget section for details.

TC.C.03 The thermal control subsystem shall fit into an envelope of TBD cm^2. (Verified by measurement)

Rationale: to satisfy volume constraint and fit into launch vehicle.

TC.C.04 The thermal control subsystem shall be attached to the main frame. (Verified by ground testing)

Rationale: to ensure thermal control subsystem gets protected from outside Martian environment.

TC.C.05 The thermal control subsystem shall be fixed/non-detachable. (Verified by ground testing)

Rationale: to protect thermal control subsystem from obstacle impact.

5.3.2 Functional Requirements

TC.F.01 The thermal control subsystem shall be able measure temperature of all components. (Verified by ground testing)

Rationale: to provide real-time temperature monitoring.

TC.F.02 The thermal control subsystem shall regulate the temperature of all components. (Verified by ground testing)

Rationale: main purpose of thermal control subsystem.

TC.F.03 The thermal control subsystem shall get power from the power subsystem. (Verified by ground testing)

Rationale: to receive power for normal operation.

5.3.3 Performance Requirements

TC.P.01 The thermal control subsystem shall operate for more than 120 sols. (Verified by simulation and calculation)

Rationale: lifetime required in RFP.

TC.P.02 The thermal control subsystem shall receive desired temperatures of all components from C&DH subsystem. (Verified by ground testing)

Rationale: to receive reference information for temperatures of system components.

5.3.4 Environmental Requirements

TC.E.01 The thermal control subsystem shall be able to operate between -65 and 50 °C. (Verified by ground testing)

Rationale: to ensure subsystem normal operation in Mars environment, temperature range referenced from RFP.

TC.E.02 The thermal control subsystem shall be capable of sustaining temperatures between -128 and 50 °C. (Verified by ground testing)

Rationale: to ensure subsystem survival in Mars environment, temperature range referenced from RFP.

TC.E.03 The thermal control system shall withstand vibration of 8.5g in the worst axis. (Verified by ground testing)

Rationale: to tolerate vibration along the worst axis, number referenced from RFP.

TC.E.04 The thermal control system shall withstand vibration of 4g in each of the other two axes. (Verified by ground testing)

Rationale: to tolerate vibration along the other two axes, number referenced from RFP.

TC.E.05 The thermal control subsystem shall withstand tolerate rock/foreign object collision of TBD kg*m/s

Rationale: to minimize impact of rock and foreign object on the subsystem.

TC.E.06 The thermal control subsystem shall tolerate dust storms. (Verified by ground testing)

Rationale: to protect the subsystem from extreme Martian weather conditions.

5.4 C&L Subsystem Requirements

5.4.1 Constraint Requirements

CL.C.01 The C&L subsystem shall fit in an area of 1.2m x 1.2m. (Verified measurement)

Rationale: to fit into Red Dragon launch vehicle and work with launch vehicle interface.

CL.C.02 The C&L subsystem shall have a mass less than 43.85 kg. (Verified by measurement)

Rationale: to satisfy mass constraint, refer to mass budget section for details.

CL.C.03 The C&L subsystem shall hold mass of at least 64.84 kg. (Verified by ground testing)

Rationale: to provide support for all MSS components, number referenced from mass budget section.

CL.C.04 The C&L subsystem shall be able to function for at least 120 sols. (Verified by simulation and calculation)

Rationale: minimum lifetime as required in RFP.

5.4.2 Functional Requirements

CL.F.01 The C&L subsystem shall hold all other subsystem. (Verified by ground testing)

Rationale: to provide support and protection for all system components.

CL.F.02 The C&L subsystem shall have an actuation mechanism to move the system to the investigation zones. (Verified by ground testing)

Rationale: to enable the MSS traverse on Mar surface.

5.4.3 Performance Requirements

CL.P.01 The C&L subsystem shall be able to move at 0.15km/hr. (Verified by ground testing)

Rationale: to ensure travel efficiency.

CL.P.02 The C&L subsystem shall sustain the balance of the MSS during all operations. (Verified by ground testing)

Rationale: to ensure normal operation do not get disturbed by surface obstacles.

5.4.4 Environmental Requirements

CL.C.01 The C&L subsystem shall be able to operate between -65 and 50 °C. (Verified by ground testing)

Rationale: to ensure subsystem normal operation in Mars environment, temperature range referenced from RFP.

CL.E.02 The C&L subsystem shall be capable of sustaining temperatures between -128 and 50 °C. (Verified by ground testing)

Rationale: to ensure subsystem survival in Mars environment, temperature range referenced from RFP.

CL.E.03 The C&L system shall withstand vibration of 8.5g in the worst axis. (Verified by ground testing)

Rationale: to tolerate vibration along the worst axis, number referenced from RFP.

CL.E.04 The C&L system shall withstand vibration of 4g in each of the other two axes. (Verified by ground testing)

Rationale: to tolerate vibration along the other two axes, number referenced from RFP.

CL.E.05 The C&L subsystem shall withstand tolerate rock/foreign object collision of TBD kg*m/s. (Verified by ground testing)

Rationale: to minimize impact of rock and foreign object on the subsystem.

CL.E.06 The C&L subsystem shall tolerate solar flares. (Verified by simulation)

Rationale: to protect the subsystem from extreme Martian weather conditions, refer to [11].

CL.E.07 The C&L subsystem shall withstand wind of at least 96km/hour. (Verified simulation)

Rationale: to protect the subsystem from extreme Martian weather conditions, refer to [10].

5.5 Communication Subsystem Requirements

5.5.1 Constraint Requirements

CM.C.01 The communication subsystem shall have a maximum mass of 10 kg. (Verified by measurement)

Rationale: to satisfy mass constraint, refer to mass budget section for details.

CM.C.02 The communication subsystem shall be able to fit within a volume of TBD cm^3. (Verified by measurement)

Rationale: to fit into Red Dragon launch vehicle.

5.5.2 Functional Requirements

CM.F.01 The communication subsystem shall be able to communicate with the C&DH subsystem for any data transfer to and from Earth. (Verified by ground testing)

Rationale: to pass on commands to C&DH from ground control, and send data from C&DH back to Earth via the orbiters.

CM.F.02 The communication subsystem shall have a data transfer rate of 8 kbps. (Verified by ground testing)

Rationale: to ensure data get transferred in a timely manner.

CM.F.03 The communication subsystem shall be able to receive any data sent from the orbiter. (Verified by ground testing)

Rationale: communications is directly related to the orbiters.

CM.F.04 The communication subsystem should have an IDLE mode for times in which it is not communicating with the orbiter. (Verified by ground testing)

Rationale: to save power consumption.

5.5.3 Performance Requirements

CM.P.01 The communication subsystem shall be able to transfer data to the orbiter up to a maximum distance of approximately 77 000 km (TBC). (Verified by ground testing)

Rationale: to establish connections as much as possible.

CM.P.02 The communication subsystem should be able to receive up to 500 kB of data from the orbiter per sol. (Verified by ground testing)

Rationale: to ensure sufficient data is collected every sol.

5.5.4 Environmental Requirements

CM.E.01 The communication subsystem shall be able to withstand 8.5g in the worst axis. (Verified by ground testing)

Rationale: to tolerate vibration along the worst axis, number referenced from RFP.

CM.E.02 The communication subsystem shall be able to withstand 4g in the other two axes. (Verified by ground testing)

Rationale: to tolerate vibration along the other two axes, number referenced from RFP.

CM.E.03 The communication subsystem shall be able to operate between -65 and 50 °C. (Verified by ground testing)

Rationale: to ensure subsystem normal operation in Mars environment, temperature range referenced from RFP.

CM.E.04 The communication subsystem shall be able to survive temperatures ranging between -128 and 50 °C. (Verified by ground testing)

Rationale: to ensure subsystem survival in Mars environment, temperature range referenced from RFP.

5.6 Science Subsystem Requirements

5.6.1 Constraint Requirements

SC.C.01 The science subsystem shall have a maximum mass of 13.85 kg. (Verified by measurement)

Rationale: to satisfy mass constraint, refer to mass budget section for details.

SC.C.02 The science subsystem shall consume a maximum average power of 8 W. (Verified by ground testing)

Rationale: to satisfy power constraint, refer to power budget section for details.

5.6.2 Functional Requirements

SC.F.01 The science subsystem shall be capable of physically interacting with the Martian environment. (Verified by ground testing)

Rationale: to acquire samples from Martian environment.

SC.F.02 The science subsystem shall be able to record and relay data extracted from the Martian environment to the C&DH subsystem. (Verified by ground testing)

Rationale: to pass data to C&DH for processing and analysis.

SC.F.03 The science subsystem shall consist of instruments capable of analyzing the Martian atmosphere. (Verified by ground testing)

Rationale: to perforce subsystem level analysis.

SC.F.04 The science subsystem shall have instruments capable of analyzing the geochemistry and mineralogy of the Martian surface. (Verified by ground testing)

Rationale: to perforce subsystem level analysis.

SC.F.05 The science subsystem shall identify potential samples at traverse site. (Verified by ground testing)

Rationale: to wisely select samples to collect.

5.6.3 Performance Requirements

SC.P.01 The science subsystem shall be able to accomplish a minimum of two scientific goals during the entire mission. (Verified by ground testing)

Rationale: to ensure subsystem integrity.

SC.P.02 The science system shall be able to collect data from at least 2 forms of matter (solid, liquid, gas). (Verified by ground testing)

Rationale: to ensure science sample variety.

5.6.4 Environmental Requirements

SC.E.01 The science subsystem shall be able to operate between -65 and 50 °C. (Verified by ground testing)

Rationale: to ensure subsystem normal operation in Mars environment, temperature range referenced from RFP.

SC.E.02 The science subsystem shall be capable of sustaining temperatures between -128 and 50 °C. (Verified by ground testing)

Rationale: to ensure subsystem survival in Mars environment, temperature range referenced from RFP.

SC.E.03 The science system shall withstand vibration of 8.5g in the worst axis. (Verified by ground testing)

Rationale: to tolerate vibration along the worst axis, number referenced from RFP.

SC.E.04 The science system shall withstand vibration of 4g in each of the other two SC.E.05 axes. (Verified by ground testing)
Rationale: to tolerate vibration along the other two axes, number referenced from RFP.

SC.E.06 The science subsystem shall withstand tolerate rock/foreign object collision of TBD kg*m/s.

Rationale: to minimize impact of rock and foreign object on the subsystem.

SC.E.07 The science subsystem shall tolerate solar flares. (Verified by ground testing)

Rationale: to protect the subsystem from extreme Martian weather conditions, refer to [11].

SC.E.08 The science subsystem shall withstand wind of at least 96km/hour. (Verified by ground testing)

Rationale: to protect the subsystem from extreme Martian weather conditions, refer to [10].

5.7 N&C Subsystem Requirements

5.7.1 Constraint Requirements

NC.C.01 The N&C subsystem shall weigh less than 6.15 kg. (Verified by measurement)

Rationale: to satisfy mass constraint, refer to mass budget section for details.

NC.C.02 The N&C subsystem shall consume maximum average power of 20 W. (Verified by ground testing)

Rationale: to satisfy power constraint, refer to power budget section for details.

5.7.2 Functional Requirements

NC.F.01 The N&C subsystem shall send data C&DH subsystem. (Verified by ground testing)

Rationale: to provide data for map computation.

NC.F.02 The N&C subsystem shall accept power from the power subsystem. (Verified by ground testing)

Rationale: to receive power for operation.

NC.F.03 The N&C subsystem shall detect objects within a TBD m radius range. (Verified by ground testing)

Rationale: to detect potential hazard.

5.7.3 Performance Requirements

NC.P.01 The N&C subsystem shall be capable of detecting failures in sensors or actuators. (Verified by ground testing)

Rationale: to detect component failures.

NC.P.02 The N&C subsystem shall respond to sensor or actuator failures. (Verified by ground testing)

Rationale: to report component failures.

5.7.4 Environmental Requirements

NC.E.01 The N&C subsystem shall be able to operate between -65 and 50 °C. (Verified by ground testing)

Rationale: to ensure subsystem normal operation in Mars environment, temperature range referenced from RFP.

NC.E.02 The N&C subsystem shall be capable of sustaining temperatures between -128 and 50 °C. (Verified by ground testing)

Rationale: to ensure subsystem survival in Mars environment, temperature range referenced from RFP.

NC.E.03 The N&C system shall withstand vibration of 8.5g in the worst axis. (Verified by ground testing)

Rationale: to tolerate vibration along the worst axis, number referenced from RFP.

NC.E.04 The N&C system shall withstand vibration of 4g in each of the other two axes. (Verified by ground testing)

Rationale: to tolerate vibration along the other two axes, number referenced from RFP.

NC.E.05 The N&C subsystem shall withstand tolerate rock/foreign object collision of TBD kg*m/s. (Verified by ground testing)

Rationale: the MSS minimize rock impact.

NC.E.06 The N&C subsystem shall tolerate dust storms. (Verified by simulation)

Rationale: the MSS need to survive bad Martian weather conditions.

6 Design Drivers and Rationale

6.1 Design Driver 1 - S.C.01 The system shall have a maximum mass of 140 kg

The mass requirement is a design driver because the changes could lead to potential modifications in the choice of material used, hardware and components. The mass budgeting will be crucial to our decision-making process, as it will be constraining all the subsystems and their corresponding sub-subsystems. The science and chassis subsystems will be the most affected, as they require the heaviest equipment. This also constrains power subsystem, as the team must rely on a higher power generation per mass. Thermal, navigation and data control subsystems will be the least affected due to their relative low masses.

6.2 Design Driver 2 - S.E.01 The system shall be able to operate between -65 and 50 °C

The thermal control subsystem is an important component of the MSS as it regulates the temperature of each subsystem to ensure all components are at their operational temperature range. Components that operate at temperatures outside their operational temperature range, especially over prolonged periods of time, are often prone to structural damage, which affects their performance and in turns affects the performance of the MSS. Component damages also directly affect the durability of the MSS and could potentially reduce the minimum required system lifespan of 120 sols. Thus, the reasons discussed make the thermal control subsystem an important design driver.

6.3 Design Driver 3 - CD.F.01 The Commands & Data Handling (C&DH) subsystem shall establish correct response to commands

This constraint on the C&DH subsystem is crucial to the entire operation because all other subsystems listens to C&DH. In order to pass on the correct sub-level commands, C&DH subsystem will need to first correctly process its commands, either autonomous or human-in-the-loop ones. Autonomous commands can include scripted programs loaded on C&DH prior to launch, containing scientific experiment schemes and procedures, emergency mode operation schemes etc. Human-in-the-loop commands may include commands sent from ground control on Earth to interrupt operations if needed.

6.4 Design Driver 4 - S.C.08 The system shall have a power usage of maximum TBD W

The power constraint is important to the design of the MSS because this limits how many subsystems can be used and powered simultaneously. This limitation on the number of subsystems that can be powered simultaneously places a restriction on how many and which tasks the MSS can perform at once. In addition, this constraint on the maximum power usage limits the number of possible tools that can used to for scientific analysis. If one subsystem or one component of a subsystem draws too much power, then the power available for the remaining subsystems is limited, restricting which actions the MSS can perform.

6.5 Design Driver 5 - S.E.07 The system shall tolerate rock/foreign object collision of TBD kg*m/s

The possibility of collision with foreign objects play a significant role in the material choice for the frame of the MSS, the way the internal components must be shielded, positions of scientific apparatus, and most importantly, the chassis subsystem's design. The latter should be designed in a way that the system will not fall over, i.e. it needs to overcome the moment about the opposite wheels, created by this collision. This will further affect the mass and volume budget, creating a domino effect. Although relatively low winds speeds don't make Mars a hostile environment, [13] safety measures must be taken to hit the expected 120 sols operation time constraint.

7 System Level Trade-offs

7.1 Mechanical Trade-off – Thermal Control

There are two main types of thermal control systems, Active Thermal Control System and Passive Thermal Control System. Active thermal control involves the use of heating and cooling tools to actively control the temperature of the subsystems while passive thermal control uses insulation to provide a protective coating around the subsystems which controls the amount of heat being released and absorbed. The table below lists major tradeoffs between each type of thermal control system.

Type	Complexity	Need for Power Supply	Rate of Heat Removal	Cost
Active Thermal Control	More complex	Yes	Higher	More expensive to implement
Passive Thermal Control	Less complex	No	Lower	Less expensive to implement

Table 4 Thermal Control method comparison

Based on the tradeoffs listed above, it is recommended that both active and passive thermal controls be incorporated into the MSS. However, passive thermal control should be the main method used as it is more energy efficient and can save energy for other functions of the MSS. Active thermal control should be utilized when passive thermal control alone is not sufficient.

7.2 Electrical Trade-off – Power Source

The main types of power sources applicable to Mars exploration missions are solar arrays, radioisotope thermoelectric generators (RTGs) and batteries [14]. Solar arrays can generate power during periods of sunlight, thus acting as a source of renewable energy for the MSS with a high lifetime. The amount of power generated by a solar array is dependent on the amount of sunlight it receives; power cannot be generated during the night. RTGs are a nuclear power source that convert the heat produced from radioactive decay of plutonium-238 into electrical energy [15]. RTGs have the advantage of requiring no moving parts, have a long operating life and can operate during the night. Batteries are a chemical power source that provide a large amount of power over a short duration of time and can be coupled with either solar arrays or RTGs as a secondary power source. Batteries can be used outside the normal operation time of a primary power source, but need to be recharged during the normal operating hours of the primary power source to see repeated use [14].

Type	**Weight/Power**	**Nuclear**	**Feasibility**	**Life Time**	**Renewable**
Solar	Low	No	High	High	Yes
RTG	Med	Yes	Low	High	No
Batteries	Med-High	No	High	High	Yes*

Table 5 Power source comparison (Requires another power source to recharge)*

7.3 Control System Trade-offs

There are two major trade-offs that influence the software design of the MSS: computer architecture and autonomy.

7.3.1 Computer Architecture

Two types of computer architectures can be considered: centralized and decentralized computer architecture. Centralized computing is data processing at a central location (C&DH in this case), whereas decentralized computing involves the allocation of both hardware and software to different workstations or subsystems. For instance, data collected by Science subsystem can be processed within the Science subsystem then transferred to C&DH, or Science subsystem can directly transfer raw data collected from Mars environment to C&DH for central processing.

The advantage of using centralized architecture lies in the more economic hardware options, and better control over programming standards, data structures as well as communication equipment and protocols [16]. Although the application of centralized architecture requires highly skilled professionals to maintain daily routine, this may not be as problematic within the scope of the project.

On the other hand, the advantage of decentralized computer architecture is that data processing schemes can be customized according to different needs of different subsystems. Moreover, decentralized computer architecture reduces the impact of system failure, since failure of one data processing workstation will not have significant impact on the others. Finally, decentralized architecture offers flexibility in hardware and software growth as well as replacements.

Type	Complexity	Failure Impact	Sustainability	Efficiency
Centralized	High	High	Medium	High
Decentralized	Low-Medium	Low	High	Medium

Table 6 Computer architecture comparison

7.3.2 Autonomy

There are two major trade-offs that influence the software design of the MSS: autonomy and computer architecture. The MSS can be completely automated by loading pre-written scripts to C&DH subsystem. However, this requires very intensive programming as well as a completely thorough understanding of every possible operation scenarios. For instance, the program needs to be able to detect any form of emergency and provide solution in a timely manner, which may include profound level of machine learning. On the other hand, operations with both autonomy and human interactions can bring certain degree of complexity to the other subsystems (e.g. Communications Subsystem).

Type	Programming Complexity	System Complexity	Efficiency
Complete Autonomy	High	Medium	High
Partial Autonomy	Low-Medium	Low	Low

Table 7 Level of autonomy comparison

Section C Mechanical System

1 Overview

The following mechanical functions were derived for each subsystem and their appropriate sub-subsystems of the MSS. Due to environmental factors, all subsystems are subjected to thermal requirements. As the system will consist of deployed and stowed configurations, all the subsystems except C&DH and Thermal Control will have moving parts. Finally, the Chassis & Locomotion and Science subsystems will be the only subsystems to have load-bearing requirements.

Subsystems	Sub-subsystems	Load Bearing Requirement	Movement Requirements	Thermal Requirements
Thermal		No	No	Yes
	Active Control	No	No	Yes
	Local PU	No	No	Yes
	Temperature Sensing	No	No	Yes
	Passive Control	No	No	No
Chassis & Locomotion		Yes	Yes	Yes
	Wheels	Yes	Yes	Yes
	Frame	Yes	No	Yes
	Suspension System	Yes	Yes	Yes
Power		No	Yes	Yes
	Battery	No	No	Yes
	Power Control Unit	No	No	Yes
	Solar Panels	No	Yes	Yes
C&DH		No	No	Yes
	C&D PU	No	No	Yes
	Memory	No	No	Yes
Science		Yes	Yes	Yes
	Arm	Yes	Yes	Yes
	Spectrometer	No	Yes	Yes
	Cameras	No	Yes	Yes
	Local PU	No	No	Yes
Communication		No	Yes	Yes
	Antennas	No	Yes	Yes
	Local PU	No	No	Yes
Navigation & Control		No	Yes	Yes
	NavCam	No	Yes	Yes

	HazCams	No	No	Yes
	Local PU	No	Yes	Yes

Table 8: Overview of the Requirements

2 Requirements

The following section outlines all mechanical requirements of each subsystem. Justifications for all mass, volume and temperature requirements can be found in Appendix 1 as well as Mass Budget and Architecture sections (sections 4 and 5). The major components, which impact the design decisions by occupying a larger volume, are discussed in the architecture section, but the volume budget for smaller subsystems will be allocated during the detailed design stage.

2.1 C&DH Subsystem Requirements

The C&DH module is the central control unit for the rover. This module mainly consists of electronic components and thus is not mechanical intensive. Only physical requirements of the C&DH module are discussed here.

2.1.1 Functional Requirements

CD.F.01 The C&DH module shall be attached rigidly onto the chassis. (Verified by design)
Rationale: This module contains only electronic components that do not require movement, thus to avoid unwanted damage and proper wire connections, this module is fixed on the chassis.
CD.F.02 The C&DH module shall be protected from impingement of sand and regolith. (Verified by design)
Rationale: Debris such as sand and gravel can affect the system during dust storms on Mars. This leads to a required barrier around the command unit to ensure functionality.

2.1.2 Performance Requirements

CD.P.01 The C&DH module shall be kept between -40◦C to 40◦C (Verified by design)
Rationale: This is the thermal requirement, as the electronic components will fail in extreme temperatures. The values are derived from Sojourner rover. Please refer to the Appendix [3].
CD.P.02 The C&DH module shall be able to sustain vibrations during traversal (verified by testing).
Rationale: To ensure that the components aren't damaged while moving.
CD.P.03 The C&DH module shall remain functional for at least 120 sols. [57] (Verified by design and simulations)
Rationale: This was determined as the duration of the mission in order to complete all desired tasks in the operations report.
CD.P.04 The C&DH module shall weigh under 2.31 kg. (Verified by ground testing)
Rationale: Please refer to the mass budget section [Section 5].
CD.P.05 The C&DH module shall have maximum dimensions of TBD dimension. (Verified by ground testing).
Rationale: To ensure the subsystem doesn't push against the system's allocated mass budget. The exact figure will be determined in the detailed design stage.

2.2 Chassis & Locomotion Subsystem Requirements

This subsystem contains the base and frame of the MSS, as well as a locomotion mechanism (consisting of the suspension system and actuation mechanism for mobility).

2.2.1 Functional Requirements

CL.F.01 The C&L subsystem shall provide static support all other subsystems throughout the mission (in Red Dragon and on Mars). (Verified by ground testing)
Rationale: To decrease the complexity, and have a reliable system, the subsystem's main functionality will be holding all other subsystem together. This can be verified by the test before the launch, by applying the ultimate vibrational loads.
CL.F.02 The C&L subsystem shall have an actuation mechanism to move the system. (Verified by design).
Rationale: By definition, this subsystem is responsible for mobility.
CL.F.03 The C&L subsystem shall shield inner parts/subsystems from outside environment. (Verified by design)
Rationale: The chassis needs to protect sensitive components, such as C&DH, Power or any inner subsystem from collisions. This can be achieved by "hiding" the necessary components inside the frame and can be verified by inspection.

2.2.2 Performance Requirements

CL.P.01 The C&L subsystem shall operate for at least 120 sols [57]. (Verified by design and simulations).
Rationale: This requirement was set by RFP and can be verified by determining the expected lifetime of important components.
CL.P.02 The C&L subsystem shall be able to move at a minimum speed of 0.1 km/hr. (Verified by testing)
Rationale: This requirement was established by using Opportunity rover as the reference design [17] and can be verified by testing.
CL.P.03 The C&L subsystem shall weigh less than 43.85 kg. (Verified by testing)
Rationale: Please refer to the mass budget (Section 5). This requirement can be verified by determining the weights of each sub- subsystem, and later confirmed during the fabrication.
CL.P.04 The C&L subsystem shall withstand a vibration environment of 8.5g in the worst axis and 4g in each of the other two axes during the launch [57]. (Verified by testing)
Rationale: This was established by the RFP. [57]
CL.P.05 The C&L subsystem shall overcome tilts up to 25 degrees on Mars. (Verified by testing)
Rationale: Information on the slopes was not specified by the RFP, but judging from the satellite views of the landing sites, there seems to be no significant uphill or downhills. However, to increase the safety factor, the MSS shall at least overcome hills of 25 degrees, which is comparable to the reference designs (Opportunity's 30 degrees) [18].
CL.P.06 The C&L subsystem shall be able to operate between -65◦ C and 50◦ C of ambient temperature [57]. (Verified by testing)
Rationale: To ensure the operability. This requirement can be met by an appropriate material selection process (whether the thermal expansion hinders the operation).

CL.P.07 The C&L subsystem shall be capable of sustaining ambient temperatures between -128 and 50 degrees Celsius [57]. (Verified by testing)
Rationale: To ensure the survival. This requirement is set by RFP and can be met by an appropriate material selection process (whether these conditions result in plastic deformations), and can be addressed by the thermal subsystem.
CL.P.08 The C&L subsystem shall fit in an area of 1.2m X 1.2m in an stowed configuration. [57] (Verified by design)
Rationale: to ensure the MSS fits Red Dragon.

2.2.3 C&L Sub-Subsystem Requirements

2.2.3.1 Wheels Requirements

CL-W-F-01 The wheels' system shall contain six individually controlled wheels. (Verified by ground testing)

CL-W-P-01 The wheel's system shall have a maximum mass of 3.85 kg. (Verified by ground testing)
Rationale: to satisfy mass constraint, refer to mass budget.

CL-W-P-02 The wheel's system shall fit into a volume of TBD cm^2 in stowed configuration. (Verified by ground testing)
Rationale: to satisfy volume constraint.

CL-W-P-03 The wheel's system shall be able to move at a minimum speed of 0.1 km/hr. (Verified by ground testing)
Rationale: This requirement was established by using Opportunity rover as the reference design.

CL-W-P-04 The wheel's system shall overcome tilts up to ±25 degrees on Mars. (Verified by ground simulation)
Rationale: referenced from Opportunity rover, and based on subsystem requirement.

2.2.3.2 Damping system (Suspension)

CL-D-F-01 The damping system shall follow a Rocker-bogie suspension design. (Verified by ground testing)
Rationale: decision based on system-level trad-off for damping systems.

CL-D-P-01 The damping system shall have a maximum mass of 8 kg. (Verified by ground testing)
Rationale: to satisfy mass constraint, refer to mass budget.

CL-D-P-02 The damping system shall fit into a volume of TBD cm^2 in stowed configuration. (Verified by ground testing)
Rationale: to satisfy volume constraint.

CL-D-P-03 The damping system shall withstand a vibration environment of 8.5g in the worst axis and 4g in each of the other two axes during launch. (Verified by ground testing)
Rationale: to satisfy RFP constraints.

2.2.3.3 Frame

CL-F-F-01 The frame system shall support all MSS components. (Verified by ground testing)
Rationale: to provide containment and protection for all MSS components.

CL-F-P-01 The frame system shall have a maximum mass of 32 kg. (Verified by ground testing)
Rationale: to satisfy mass constraint, refer to mass budget.

CL-F-P-02 The frame system shall have a fit into a volume of TBD cm^2 in stowed configuration. (Verified by ground testing)
Rationale: to satisfy volume constraint.

2.3 Power Subsystem Requirements

The following section discusses the subsystem requirements for power subsystem. The physical constraints of the mission put this mission in the same class as previous Mars Exploration Rovers Spirit and Opportunity (1.5m x 1.6m, 174kg) [3, 4, 5, 6]. Many of the specifications are derived from nominal values similar to these rovers, as well as the Sojourner that is smaller [7, 8, 9]. Only physical considerations of the power source will be discussed here. Nevertheless, an investigation of the type of power source must be done in order to determine the physical size given the power constraints. In previous reports, it was discussed that both solar panels and chemical batteries offer great methods for powering the rover. It was mentioned in previous requirements that nuclear energy shall not be used (RTG similar to the one on the Curiosity rover). Many of the following requirements share similar rationale to the previous section 2.1, and thus not explained here.

2.3.1 Functional Requirements

PW.F.01 The power module shall fit in the electronics enclosure. (Verified by design)
Rationale: Having power module within the same enclosure shortens the wiring required, as well as the heat from the power supply can aid in warming the electronics.
PW.F.02 The power module shall be rigidly attached to the rover. (Verified by design)
Rationale: To ensure the compactness and minimal moving parts.
PW.F.03 The power module shall have physical space to deploy. (Verified by design)
Rationale: Since the use of solar panels is considered, it must have sufficient space to fully deploy. The space required depends on panel size, which will be discussed in the Architecture section.
PW.F.04 The power module shall operate uninterrupted throughout the mission. (Verified by testing)
Rationale: In previous requirements, it was determined that the rover shall not turn off during the night, and thus the power must be supplied non-stop throughout the duration of the mission
PW.F.05 The Power module shall be able to sustain the forces experienced during transit and EDL. (Verified by ground testing).

Rationale: To ensure the MSS is operational when it reaches Mars. This was established by the RFP. [57]

2.3.2 Performance Requirements

PW.P.01 The power module shall be able to fully charge the batteries during the day. (Verified by ground testing)
Rationale: Solar panels typically get around 4 hours of equivalent sunlight during each Martian sol, this means the batteries must be fully charged during that time, in order to operate in the night.
PW.P.02 The power module shall weigh under 20kg. (Verified by ground testing)
Rationale: The value obtained from looking at past space missions including Sojourner, Spirit/Opportunity, as well as some other reference designs [34]. This weight includes the solar panels. Please refer to the mass budget.
PW.P.03 The power module shall be kept under TBD dimensions. (Verified by testing)
Rationale: Size is important in space missions. The exact value is discussed in the Architecture section below.
PW.P.04 The power module shall be kept under tolerable temperature. (Verified by testing)
Rationale: The solar panels are expected to remain functional from -110◦C to 110◦ C. However, batteries have much stricter constraints, and must be kept over -20◦ C survival and 0◦ C charging. Values obtained from OEM of Sojourner Rover Applied Solar Energy Corporation [26] and SAFT America [27]
PW.P.05 The power module shall withstand a vibration environment of 8.5g in the worst axis and 4g in each of the other two axes during the launch [57]. (Verified by ground testing)
Rationale: To ensure the MSS is operational once it reaches Mars.
PW.P.06 Power module shall survive and remain functional for at least 120 sols [57]. (Verified by design and simulations).
Rationale: This requirement is set by the RFP.

2.4 Science Subsystem Requirements

The science subsystem is responsible for carrying out the science objectives at traverse site B and the landing site. Here only the physical requirements of the science subsystem are discussed.

2.4.1 Functional Requirements

SC.F.01 The science subsystem shall be functional under the effect of Martian gravity. (Verified by ground testing)
Rationale: To ensure the operability.
SC.F.02 The science subsystem shall have a stowed configuration for Earth-Mars transfer and a deployed configuration for operations on the Martian surface. (Verified by design)
Rationale: To ensure the MSS fits in Red Dragon.
SC.F.03 The science subsystem shall be capable of interacting with an environment comparable to the Martian environment. (Verified by ground testing)
Rationale: To ensure the operability.

2.4.2 Performance Requirements

SC.P.01 The science subsystem shall not exceed a total mass of 13.85 kg. (Verified by testing)
Rationale: Please refer to the mass budget section [Section 5].
SC.P.02 The science subsystem shall fit into the constrained volume of stowed configuration. (Verified by testing)
Rationale: To ensure the MSS subsystem fits into Red Dragon.
SC.P.03 The science subsystem shall be operational in a temperature range from -128◦C to 40◦C (Verified by testing).
Rationale: To ensure the operability.
SC.P.04 The science subsystem shall survive in a temperature range from -65◦C to 50◦C. (Verified by testing)
Rationale: To ensure the operability. Please refer to Appendix [3].
SC.P.05 The science subsystem shall withstand a vibration environment of 8.5g in the worst axis and 4g in each of the other two axes during the launch. (Verified by ground testing)
Rationale: To ensure the MSS is operational when it reaches Mars.

2.4.3 Science Sub-subsystem requirements

2.4.3.1 Arm Requirements

SC-A-F-01 The arm system shall fit into designated compartment during stowed configuration. (Verified by ground testing)
Rationale: to fit into Red Dragon launch vehicle.

SC-A-P-01 The arm system shall have a maximum mass of 11.3 kg. (Verified by ground testing)
Rationale: to satisfy mass constraint, refer to mass budget.

SC-A-P-02 The arm system shall have a maximum volume of TBD cm^2. (Verified by ground testing)
Rationale: to satisfy volume constraint.

SC-A-P-03 The arm system shall operate in designated task space of TBD cm^2. (Verified by ground testing)
Rationale: to reach samples to achieve scientific goals

SC-A-P-04 The arm system shall have a total of 6 degrees of freedom. (Verified by ground testing)
Rationale: to reach samples to achieve scientific goals

SC-A-P-05 The arm system shall have a gripper to capture samples from Martian terrain. (Verified by ground testing)
Rationale: to obtain samples to achieve scientific goals

SC-A-P-06 The arm system shall operate within the temperature range of -65 and 50 degrees Celsius. (Verified by ground testing)
Rationale: to ensure joint motors operate in appropriate temperature range.

SC-A-P-07 The arm system shall be able to survive within the temperature range of -128 and 40 degrees Celsius. (Verified by ground testing)
Rationale: to ensure joint motors are able to survive in the given temperature range.

2.4.3.2 Optical Spectrometer Requirements

SC-S-F-01 The optical spectrometer system shall send data to the local science processing unit. (Verified by ground testing)
Rationale: to pass data for analysis.

SC-S-P-01 The optical spectrometer system shall have a maximum mass of 2 kg. (Verified by ground testing)
Rationale: to satisfy mass constraint, refer to mass budget.

SC-S-P-02 The optical spectrometer system shall have a maximum volume of TBD cm^2. (Verified by ground testing)
Rationale: to satisfy mass constraint.

SC-S-P-03 The optical spectrometer system shall produce analysis with a TBD% accuracy. (Verified by ground testing)
Rationale: to maintain system integrity.

SC-S-P-04 The optical spectrometer shall operate within the temperature range of -65 and 50 degrees Celsius. (Verified by ground testing)
Rationale: to ensure spectrometer operate in appropriate temperature range.

SC-S-P-05 The optical spectrometer shall be able to survive within the temperature range of -128 and 40 degrees Celsius. (Verified by ground testing)
Rationale: to ensure spectrometer are able to survive in the given temperature range.

2.4.3.3 Science Camera Requirements

SC-C-F-01 The science camera system shall send images/videos to the local science processing unit. (Verified by ground testing)
Rationale: to send data for analysis

SC-C-P-01 The science camera system shall have maximum mass of 0.5 kg. (Verified by ground testing)
Rationale: to satisfy mass constraint, refer to mass budget.

SC-C-P-02 The science camera system shall have a maximum volume of TBD cm^2. (Verified by ground testing)
Rationale: to satisfy volume constraint.

SC-C-P-01 The science camera system shall have a resolution of at least 480 x 800 pixels. (Verified by ground testing)
Rationale: to ensure images/videos are clear enough for analysis.

SC-C-P-02 The science camera shall operate within the temperature range of -65 and 50 degrees Celsius. (Verified by ground testing)
Rationale: to ensure the camera operate in appropriate temperature range.

SC-C-P-03 The science camera shall be able to survive within the temperature range of -128 and 40 degrees Celsius. (Verified by ground testing)
Rationale: to ensure the camera are able to survive in the given temperature range.

2.5 Thermal Control Subsystem Requirements

The thermal control subsystem is responsible for providing thermal protection, by using both active and passive components, to all subsystems of the MSS. The centralized active control unit will be located inside the MSS body to help maintain operational temperatures for all thermally sensitive electronics.

2.5.1 Functional Requirements

TC.F.01 The Thermal control subsystem shall measure and regulate the temperature of all thermally sensitive components. (Verified by ground testing)
Rationale: This is the definition of the subsystem.
TC.F.02 The Thermal control subsystem shall provide thermal protection for non-electronic parts of the MSS (i.e. Chassis subsystem). (Verified by ground testing)
Rationale: To ensure the operability and survival.

2.5.2 Performance Requirements

TC.P.01 The Thermal control subsystem components shall weigh under 5.38 kg in total. (Verified by testing)
Rationale: This value was derived from the mass budget (Section 5).
TC.P.02 The Thermal control subsystem shall contain an active control component that fits in a TBD volume. (Verified by design and testing)
Rationale: To ensure the subsystem meets the volume budget. Please refer to the architecture section for the actual dimensions.
TC.P.03 The Thermal control subsystem shall withstand a vibration environment of 8.5g in the worst axis and 4g in each of the other two axes during the launch. (Verified by ground testing)
Rationale: To ensure the MSS survives until it reaches Mars.
TC.P.04 The Thermal control subsystem components shall operate under -65◦C to 50◦C. (Verified by ground testing.)
Rationale: To ensure the operability. Please refer to [Appendix 3]
TC.P.05 The Thermal control subsystem components shall survive under -128◦C to 50◦C. (Verified by ground testing)
Rationale: To ensure the survival.

2.5.3 Thermal Sub-Subsystem Requirements

2.5.3.1 Temperature Sensing Requirements

TC-TS-F-01 The temperature sensing system shall send temperature readings to the local thermal control processing unit. (Verified by ground testing)
Rationale: to pass data for analysis

TC-TS-P-01 The temperature sensing system shall have maximum volume of TBD cm^2. (Verified by ground testing)
Rationale: to satisfy volume constraint.

TC-TS-P-02 The temperature sensing system shall measure temperatures of components with a TBD% accuracy. (Verified by ground testing)
Rationale: to maintain system integrity

TC-TS-P-03 The temperature sensing system shall operate within the temperature range of -65 and 50 degrees Celsius. (Verified by ground testing)
Rationale: to ensure sensors operate in appropriate temperature range.

TC-TS-P-04 The temperature sensing system shall be able to survive within the temperature range of -128 and 50 degrees Celsius. (Verified by ground testing)
Rationale: to ensure sensors are able to survive in the given temperature range.

2.5.3.2 Active Thermal Control Requirements

TC-AC-F-01 The active thermal control system shall receive commands from C&DH subsystem via the local thermal control processing unit. (Verified by ground testing)
Rationale: to send data for analysis.

TC-AC-F-02 The active thermal control system shall regulate temperatures of system components in corresponding desired temperature range. (Verified by ground testing)
Rationale: to ensure all MSS components operate in desired temperature range.

TC-AC-P-01 The active thermal control system shall have a maximum mass of 4.33 kg. (Verified by ground testing)
Rationale: to satisfy mass constraint, refer to mass budget.

TC-AC-P-02 The active thermal control system shall have maximum volume of TBD cm^2. (Verified by ground testing)
Rationale: to satisfy volume constraint.

TC-AC-P-03 The active thermal control system shall adjust temperatures of system components to desired temperature range in TBD seconds. (Verified by ground testing)

Rationale: to ensure that temperature gets adjusted in a timely manner in order to avoid component malfunction.

TC-AC-P-04 The active thermal control system shall operate within the temperature range of -65 and 50 degrees Celsius. (Verified by ground testing)
Rationale: to ensure heaters operate in appropriate temperature range.

TC-AC-P-05 The active thermal control system shall be able to survive within the temperature range of -128 and 50 degrees Celsius. (Verified by ground testing)
Rationale: to ensure heaters are able to survive in the given temperature range.

2.6 N&C Subsystem Requirements

The navigation and control subsystem contains actuators, sensors and speed control mechanisms that allow the MSS to travel on Mars surface under different surface conditions. In addition, this subsystem is also responsible for guiding the MSS to different traverse sites and landing site.

2.6.1 Functional Requirements

NC.F.01 The N&C subsystem shall compute traverse path through cameras. (Verified by design)
Rationale: The MSS needs to navigate through Mars.
NC.F.02 The N&C subsystem must be able to detect objects within a TBD m radius range. (Verified by testing.
Rationale: The navigation subsystem will be able to detect the obstacles on its path, to avoid any hazards.

2.6.2 Performance Requirements

NC.P.01 The N&C subsystem shall withstand a vibration environment of 8.5g in the worst axis and 4g in each of the other two axes during the launch. (Verified by ground testing)
Rationale: To ensure the MSS survives until it reaches Mars.
NC.P.02 The N&C subsystem shall fit into volume dimension in stowed configuration. (Verified by testing)
Rationale: To ensure the MSS fits into Red Dragon. Please refer to the architecture section [Section 4].
NC.P.03 The N&C subsystem shall be able to operate between -65◦C and 40◦C. (Verified by ground testing)
Rationale: To ensure the operability.
NC.P.04 The subsystem shall be capable of sustaining temperatures between -128◦C and 50◦C. (Verified by testing)
Rationale: To ensure the survival.
NC.P.05 The N&C subsystem shall weigh less than 6.15kg. (Verified by testing)
Rationale: The value used for this requirement was derived from the mass budget (Section 5).

2.6.3 N&C Sub-Subsystem Requirements

2.6.3.1 N&C Cameras Requirements

NC-C-F-01 The N&C cameras system shall contain 2 NavCams and 2 HazCams. (Verified by ground testing)
Rationale: to obtain 360 degrees view of the environment and to protect the MSS from obstacles.

NC-C-F-02 The N&C cameras system shall send data to C&DH subsystem via the local N&C processing unit. (Verified by ground testing)
Rationale: to send data for analysis.

NC-C-P-01 The N&C cameras system shall have a maximum mass of 5.1 kg. (Verified by ground testing)
Rationale: to satisfy mass constraint, refer to mass budget.

NC-C-P-02 The N&C cameras system shall have a maximum volume of TBD cm^2. (Verified by ground testing)
Rationale: to satisfy volume constraint.

NC-C-P-03 The N&C cameras system shall detect obstacles on Martian surface during traversal. (Verified by ground testing)
Rationale: to ensure the MSS travels safely.

NC-C-P-04 The N&C cameras system shall have NavCams with a resolution of at least 600 x 800 pixels. (Verified by ground testing)
Rationale: to ensure that images/videos are clear enough for analysis

NC-C-P-05 The N&C cameras system shall have HazCams with a resolution of at least 480 x 800 pixels. (Verified by ground testing)
Rationale: to ensure that images/videos are clear to detect obstacles.

NC-C-P-06 The N&C cameras system shall operate within the temperature range of -65 and 40 degrees Celsius. (Verified by ground testing)
Rationale: to ensure cameras operate in appropriate temperature range.

NC-C-P-07 The N&C cameras system shall be able to survive within the temperature range of -128 and 50 degrees Celsius. (Verified by ground testing)
Rationale: to ensure cameras are able to survive in the given temperature range.

2.7 Communication Subsystem Requirements

The communication subsystem handles all communications required in the operation, this includes communication with the orbiters as well as interactions with C&DH subsystem. There are two mechanical aspects associated with the communication subsystem, a mechanism to fold and unfold the antennas for stowed and deployed configurations, respectively, and thermal control.

2.7.1 Functional Requirements

CM.F.01 The communication subsystem shall have a mechanism to unfold its antennas from stowed configuration. (Verified by design)
Rationale: To ensure the MSS fits into Red Dragon.

2.7.2 Performance Requirements

CM.P.01 The communication subsystem shall fit into the constrained volume of stowed configuration. (Verified by design and testing)
Rationale: To ensure the MSS fits into Red Dragon.
CM.P.02 The communication subsystem shall have a maximum mass of 10 kg. (Verified by testing)
Rationale: The value used for this requirement was derived from the mass budget (Section 5).
CM.P.03 The communication subsystem shall be able to operate between -25°C and 60°C. (Verified by ground testing)
Rationale: The communication consists of antennas, transponders and amplifiers, of which the transponders and amplifiers have a tighter operational temperature range. Thus the operational temperature requirement for this subsystem is taken to be that of the transponder. [Appendix 3]
CM.P.04 The communication subsystem shall be able to survive between -40° C and 70° C. (Verified by ground testing)
Rationale: The communication consists of antennas, transponders and amplifiers, of which the transponders and amplifiers have a tighter survival temperature range. The survival temperature requirement for this subsystem is taken to be that of the transponder. [Appendix 3]

CM.P.05 The communication subsystem shall be able to withstand launch vibrational loads of 8.5g in the worst axis and 4g in the other two axes. (Verified by ground testing)
Rationale: This was established by the RFP. [57]

2.7.3 Communication Sub-Subsystem Requirements

2.7.3.1 Antenna Requirements

CM-A-F-01 The antennas system shall consist of one low gain antenna, one high gain antenna, and one UHF antenna. (Verified by ground testing)
Rationale: decision based on system-level trade-offs.

CM-A-F-02 The antennas system shall be responsible for communications between the MSS and the orbiters. (Verified by ground testing)
Rationale: to satisfy system-level requirement, pass on commands from Earth and send data back to Earth through the orbiters.

CM-A-P-01 The antennas system shall have a maximum mass of 9.95 kg. (Verified by ground testing)
Rationale: to satisfy mass constraint, refer to mass budget.

CM-A-P-02 The antennas system shall have a maximum volume of TBD cm^2. (Verified by ground testing)
Rationale: to satisfy volume constraint.

CM-A-P-03 The antennas system shall be able to operate within the temperature range of -25 and 60 degrees Celsius. (Verified by ground testing)
Rationale: to ensure antennas operate in appropriate temperature range.

CM-A-P-04 The antennas system shall be able to survive within the temperature range of -40 and 70 degrees Celsius. (Verified by ground testing)
Rationale: to ensure antennas can survive in the given temperature range.

3 Trade Studies

This section discusses trade studies for mechanical components, including locomotion, suspension system, number of wheels, power supply, thermal control, material, motors etc. Some designs will be compared and the preferred one will be highlighted.

3.1 Locomotion: Wheels vs tracks

An important mechanical component of the robotic system is the locomotion system, which allows the system to travel between the landing site and traverse site B. The scientific goals that need to be achieved by this program require that the robotic system collects samples on the surface of Mars. This leads to 2 considerations for the locomotion system – wheels and tracks. The table below lists important mechanical properties for each.

Type	**Wheels**	**Tracks**
Complexity	Less complex	More complex
Mass	Lighter	Heavier
Steering	Easier to steer	More difficult to steer
Energy required	Less	More
Ground impact	More	Less
Production cost	Low	High

Table 9: Means of Locomotion

In terms of wheels, each wheel operates on separate actuators where certain wheels can actually have passive actuation (rely on the movement of other wheels). Tracks require actuators and more wheels inside the track (at least more than 6 wheels) therefore causing the design to

become more complicated. In addition, the incorporation of a suspension system is more difficult in terms of the track design. [28]
Due to the sheer weight of materials required to operate tracks, it is much heavier than wheels. Moreover, steering on a track will require reliance on differentiating the speed of the two tracks while steering with wheels relies simply on an actuator that turns the wheels around, further simplifying the process. With the added components required and the further complexity of the design of tracks, an increase in production cost can be foresighted. [28]
It is clear that wheels have a preferable characteristics compared to tracks. In addition, wheels require less energy to operate, which is very significant considering that the robotic system must generate and store its own power. Though there is more surface area to the tracks, it is obvious that the impact of the ground will be less when it comes to tracks but in the meantime, the added surface in contact though very useful for traction will incur more energy consumption. For these reasons, it is recommended that wheels be used in the robotic system.

3.2 Suspension System

Two different passive (mechanical) suspension systems are considered in this trade study. Any exotic or active suspension system ideas were abandoned due to their complexity, maintenance problems and lack of reliable reference designs. Specifically, conventional rocker-bogie [29] and spring-system [30] suspensions are considered. Spring system acts as a damper to minimize the vertical vibrations, whereas the rocker-bogie is a design to keep all the wheels on the ground, with revolute joints.

System	**Spring system**	**Rocker-bogie**
Vibration damping	Yes	No
Tilt performance	Satisfactory	Outstanding
Load distribution in operation	Uneven	Uniform
Stability	Low	High
Lifetime	Low	High
Overall complexity	Low	Medium
Reliable Reference Design	No	Yes

Table 10: Suspension systems

Vibration damping: The rocker-bogie is designed to offset the vibrations caused by translational motion. The spring system, on the other hand, can also act as a damper during the launch, entry and descent, to the interior components from unfavorable oscillations. [31] However, this can also be achieved in subsystem level, by considering vibrations for each individual part of the system.

Tilt performance: Rocker-bogie can overcome obstacles very effectively, as they can sustain tilts of 50 degrees in any direction, while spring systems can handle hills of up to 30 degrees. [32] Although these stats are based on the Earth's gravity, the rocker-bogie will still outperform the spring system on Mars. Both configurations meet the tilt performance requirements, but rocker-bogie will provide additional safety.
Load distribution in operation: Rocker-bogie overcomes the obstacles by keeping all the wheels on the ground, thus providing a more even load distribution on the wheels than the spring systems. [33] Each wheel can be steered independently, whereas the spring system incorporates this versatility. [34] This prevents overturning, and provides even traction and friction force distribution.
Stability: As the result of the superior tilt performance and even load distribution, the rocker-bogie is more stable. The spring systems are susceptible to tip-overs. [35]
Lifetime: As the springs are prone to frequent compressive and tensile stresses, and oscillations, rocker-bogie systems outperform them, because the latter rely on the free-rotating pivots, rather than material deformations. [36]
Overall complexity: Rocker-bogies require 6 motors to operate, and it provides several high-level challenges during the design and fabrication. [37] It can also limit the system's payload con- figuration, due to its moving parts. The spring system mainly needs a material selection process. However, as no previous missions involved a spring suspension system, its possible complications are not well-known.
Reliable Reference Design: Rocker-bogie configuration is NASA's preferred design. [33] Both Curiosity and Opportunity rovers on Mars rely on this configuration. [38] This further rein-forces the choice of rocker-bogie over spring system.
PREFERENCE: Rocker-bogie has the edge on head-to-head comparisons. CF.P.01 and CF.P.05 are considered to be driving requirements to prefer this system over the spring suspension system.

3.3 Number of wheels

In this section, trade study of the number of wheels is considered. In the previous section, it was established that the rocker-bogie is preferred design, which means that we propose a 6-wheeled design. However, to make sure that all the requirements are met, we will adopt iterative decision-making process. Therefore, a 4-wheeled system will also be considered, and if it outperforms its 6-wheeled counterpart, we will need to revaluate the impact of choosing one preferred option over the other.

Number of wheels	**4**	**6**
Ideal Suspension System	Spring system	Rocker-bogie
Mass	Light	Medium
Stability	Low	High
Safety Factor	Low	High

Relative Power Requirement	Low	High
Overall Complexity	Low	Medium
Reliable Reference Design	No	Yes

Table 11: Number of wheels comparison

Ideal Suspension System: It was already established that one of the main superiorities of the 6-wheeled design is the possibility of implementing the rocker-bogie suspension system. [39]
Mass: Having an extra pair of wheels increases the total mass by around 50% more.
Stability: Extra wheels provide additional support to the frame and prevent turning-overs. A problem in one of the front wheels will be offset by the wheel next to it, which will act as a passive controller to help the MSS to carry on the trip. [40] As the weight is distributed more evenly, the system will have a superior vibrational stability too. [41]
Safety Factor: Curiosity's current struggles with wheel damage emphasizes how important are the safety precautions. [42] In a 6-wheeled configuration, each wheel will need to carry around 50% more weight, as opposed to 4-wheeled design. This additional pressure on a rocky environment will lead to faster wheel deteriorations. Furthermore, a problem in one of the wheels will hurt the system more, as the rear or front traction depends on both wheels. [40] Therefore, having an extra pair of wheels adds to the safety factor of the design.
Relative Power Requirement: Increasing the number of wheels increase the number of motors or the power usage by the locomotive motor, the total power usage will increase. However, as the team aims to have just 1 journey to the investigation site B, additional 50% power usage will not push against power budget.
Overall Complexity: There are no significant design differences between the candidates, but the presence of additional wheels will push against the volume requirement, and the subsystem will need to be designed to fit the frame. This will increase the complexity of design process because we still need to conserve all the aforementioned benefits.
Reliable Reference Design: We have reliable design examples of 6-wheeled rovers in Curiosity and Opportunity. [22, 27]
PREFERENCE: To keep the system simple and reliable, only traditional 4 and 6 wheeled rover designs were considered, and 6-wheeled design is the team's preferred option. Fortunately, this is consistent with our possible rocker-bogie suspension system. The driving requirements for this decision were CF.P.01 and CF.P.03. Although we will push against our mass budget (but not exceed it), we can still save weight thanks to the rocker-bogie system (owing to the lack of additional springs).

3.4 Power Supply

Typical sources of power for space missions relies on either onboard batteries of solar panels. Depending on the specifications of these missions (size, weight, durations, etc.), one is chosen over another. In this section, a trade-off study is done comparing the use of an on-board battery vs. the use of a deployable solar panel (it is assumed that in order to make solar panels useful, they must be deployable).

*For the functionalities of the rover, using purely batteries would result in the battery being heavy.

Power Source	Weight	Size	Simplicity	Period of Effectiveness	Amount of Power Stored	Sustainability	Thermal Requirement
Batteries	Heavy*	Compact	Simple to store and use	Any time	Moderate	No	Strict
Solar Panels	Moderate	Large	Complex due to deployment	Day time only	Infinite	Yes	Lenient

Table 12: Comparison of power generation and storage

Table 12 shows a comparison between batteries and solar panels, subjected to the metrics of weight, size, simplicity, period of effectiveness, the amount of power stored, sustainability, as well as thermal requirement. Metrics such as power discharge rate are left to be discussed in detail in the electrical report. Using onboard batteries for power has many benefits including compact in size and simple to store and use. Referring to the system requirements and constraints, the compact size and simplicity are very important in space mission designs, and therefore batteries are an excellent choice in this perspective. In addition, batteries have the benefit operating both day and night, which is required for the operation. However, batteries tend to have stricter thermal requirements, and the weight scales with power consumption, both of which can lead to additional design problems.

The use of solar panels, however, relaxes the thermal requirements, as well as providing theoretically infinite amount of power. For the power consumption of the rover, using solar panels will be lighter in weight than solely using a battery. However, it is complex to use due to the large size, deploying mechanisms, as well as only functional during the day, which limits the rover's functionality.

The winning design that arises from the above discussion will be a combination of both solar panels and batteries. Batteries are essential if desired to traverse during night time. However, the use of a solar panel allows for a smaller battery size, therefore, the entire device becomes lighter (which is a significant criterion to meet). The combination of the two allows for a smaller battery and a smaller solar panel, and also acts as redundancy which is critical for space missions.

3.5 Thermal Control

To ensure the control unit maintains at an operating temperature throughout the mission, thermal control must be implemented. Thermal control could provide cooling when electrical components heat up too much during operations, as well as providing enough heat to keep components functional in the frigid environment on the Martian surface. Typically, thermal control is classified into two major categories: passive and active thermal control.

Passive thermal control refers to a component that does not require any command and will moderate temperature by itself. This can include using a heat sink for dissipating heat, adding extra heat insulation such as Aerogel, and heating electronic components using the heat of power supplies. This is a simple method of thermal control, as no active components are required and no power is required. However, the range of controllable temperature is often limited. The heat generated from batteries as well as solar panels are typically not enough to sustain the functional temperature of electronic components, as past space missions all use some form of heat generator. The only viable way to generate heat using a passive thermal control is with the use of RHU (radioisotope heater unit) which were used in Sojourner and MER rovers. RHU uses the decay of radioisotopes to provide heat by itself. This unit does not require electrical power to function and will provide a constant heat output throughout the entirety of its lifetime. However, as we are forbidden to use any radioactive elements in this project, RHUs will be used as a reference, to compare between other possible means of heating. Please see the heating type trade study in Electrical Design.

Active thermal control uses power to actively generate heat through heaters, or cool using heat exchangers. This allows for a wider range of controllable temperature. However, this makes the system more complex, and is larger and heavier than the passive counterparts. Electrical heaters generate heat by using the electrical power provided by the power supply to generate heat. This is a common method for generating heat, but it drains the power supply, and is inefficient in the heat conversion process. Table 13 below shows a comparison between passive and active thermal control, subjected to the metrics of size, weight, the range of controllable temperature, simplicity, and lifetime, as indicated in the requirement discussion.

Thermal Control Type	**Active**	**Passive**
Size	Larger	Smaller
Weight	Heavier	Lighter
Controllable Temperature Range	Wide and Varying	Narrow and Fixed
Simplicity	Complex	Simple
Lifetime	Limited	Unlimited

Table 13: Means of Thermal Control

From table 13, it seems that the use of a passive thermal controller will be beneficial as it is smaller, lighter, and much simpler to use. However, the temperature on the Martian surface varies significantly throughout the day, dropping to -120◦ C at night and over 60◦ C at the peak. A passive thermal controller will not be able to moderate the temperature at such a wide temperature range, and thus some form of active thermal control device is required. The final design will use RHU for portion of the heating. Electrical heaters will be used during extremely cold conditions to aid in the RHU, and will be turned off in other cases. In conjunction with the heaters, passive means of heat insulation (such as gold painting, Aerogel and Kapton MLI are used in Mars Exploration rovers and Sojourner) are also used to minimize the amount of work the heater have to go through. Local component cooling will be done passively using heat sinks to spread the heat throughout the warm electronic box.

3.6 Materials: Frame/Chassis

The chassis and frame is a major contributor to the total mass of the MSS, therefore, a proper material selection is integral to minimize the weight of the frame, while retaining sufficient strength to survive 120 sols on the Martian surface. The materials considered are shown in the table below, with their relevant material properties directly compared.

The most important driver in the design is to not exceed the maximum weight of 140kg for the Red Dragon lander. While CRES 445 has qualities of high strength and stiffness, it is significantly heavier than all the other options presented in table 7. Ti 6Al-4 is the second heaviest material featured in table 7, but boasts comparable strength to CRES 445, moderate stiffness and has the lowest CTE of all materials considered. Al 2090, Al 7075 and AlBeMet are all different alloys

Material	Density (g/cc)	Tensile Strength (Yield) (MPa)	Coefficient of Thermal Expansion (CTE) (μm/°C)	Young's Modulus (GPa)
Al 2090 [44]	2.59	520	23.6	76
Ti 6Al-4 [45]	4.47	1100	9.7	114
CRES 445 [46]	7.76	1345	12	200
AlBeMet [47]	2.071	322	13.91	193
Al 7075 [48]	2.81	503	25.2	71.7

Table 14: Frame material selection

of aluminum. Of these three aluminum alloys, AlBeMet is the lightest, with the lowest CTE, highest stiffness, but lowest yield strength. Al 7075 is the heaviest of the three aluminum alloys with the lowest stiffness, highest CTE and second highest yield strength. Al 2090 is lighter than Al 7075, with higher yield strength, stiffness and a slightly smaller CTE in comparison. The recommended material for the chassis is Ti 6Al-4 due to being significantly lighter than CRES 445, while retaining many of the advantages of CRES 445 such as high yield strength, moderate stiffness and low CTE. While further savings in mass are possible with the other aluminum alloys, each of these alloys have significantly reduced strength, and higher CTE, making these materials more sensitive to the extreme variations in temperature on the Martian surface.

3.7 Motors

There are multiple motor applications on the MSS, major parts include locomotion, solar array drive, robotic arm manipulator as well as antenna pointing if needed. The following section will discuss the trade-offs between different motor selections for each application. The three types of motors are considered and their performances are compared corresponding to different applications. The three motor options considered are stepper motors, brushless DC motors and brush DC motors. Despite the differences in performance considerations that vary across different applications, their driver and related system complexity, as well as mass/volume ratio are relatively consistent with different applications. The driver for stepper motors is generally simpler than any other options (open loop, full step). The electronic drive of a brushless DC motor is rather more complex, but system complexity can be reduced with the presence processed by controls. It is also easy to handle in terms of mechanism design tolerance or mechanical integration. Lastly, Brush DC Motors only require a simple DC electrical interface since the brushes replace the power bridge and the commutation position sensor [49]. Recommendations of motor type for different applications are discussed and highlighted as below:

Locomotion [49] [50]

Motor Type	Performance	Complexity	Mass/Volume
Stepper Motors	**Low** (high torque/power ratio only at low speed/power, but poor performance under varying load, and not good for locomotion over uneven surfaces)	**Low**	**Medium** (No position sensor required)
Brushless DC Motors	**High** (high torque/power ration can be achieved at any speed, high peak torque value: than five times more than nominal demand)	**Medium**	**Medium-High** (Needs position sensor)
Brush DC Motors	**Medium** (Similar to torque/power ratio as brushless motor, except the drawbacks of the brushes in space environments are major and often forbidden (i.e. brushes maintainability, wear, disruptive voltages – arcs - restartability after a dormant period)	**Medium**	**Medium**

Table 15: Types of motors for Locomotion

Solar Array Drive [51] [52]

Motor Type	Performance	Complexity	Mass/Volume
Stepper Motors	**High** (Solar array drive assembly requires high precision in positioning of the photovoltaic panels, which can be attained through the use of stepper motor.)	**Low**	**Medium** (No position sensor required)
Brushless DC Motors	**Medium** (Not sufficient precision to provide positioning of the photovoltaic panels.)	**Medium**	**Medium-High** (Needs position sensor)
Brush DC Motors	**Medium** (Similar arguments for brushless DC motors.)	**Medium**	**Medium**

Table 16: Types of motors for Solar array drive

Robotic Arm Manipulator [53] [54]

Motor Type	Performance	Complexity	Mass/Volume
Stepper Motors	**Medium** (Capable of achieving better precision, but can only achieve high torque at low speed. Even though high torque might be exploited during scientific tasks, it is might not be an as important requirement.)	**Low**	**Medium** (No position sensor required)
Brushless DC Motors	**Medium-High** (High torque can be achieved at all speed, which might be useful during scientific tasks, good precision. Moreover, high torque/power ratio can be exploited in certain experiments.)	**Medium**	**Medium-High** (Needs position sensor)
Brush DC Motors	**Low** (Similar arguments as brushless DC motors and drawbacks indicated in the previous table)	**Medium**	**Low**

Table 17: Types of motors for Arm Manipulator

Antenna Pointing [49]

Motor Type	**Performance**	**Complexity**	**Mass/Volume**
Stepper Motors	**High** (Capable of achieving better precision, but can only achieve high torque at low speed. However, high torque is not a crucial requirement for antenna pointing.)	**Low**	**Medium** (No position sensor required)
Brushless DC Motors	**Medium-High** (Can achieve good precision, high torque/power ratio not necessary for antenna pointing)	**Medium**	**Medium-High** (Needs position sensor)
Brush DC Motors	**Medium** (Similar to argument for brushless DC motors.)	**Medium**	**Medium**

Table 18: Types of motors for Antenna Pointing

3.8 Deployable vs Non-Deployable

The deployability properties of the Mars rover is important as it plays a key role in the design of the rover. As Requirement CF.P.08 states, the device must fit into an area of 1.2m X 1.2m. And the RFP further requires a maximum height of 0.8m. Due to the dimension constraints implemented on the device, it is advisable to consider having a deployable structure. Some reasons to have a deployable structure include fitting more on the rover and having more surface area for solar panels. Having the wheels spread out more also allows for better stability. Referencing other Mars rovers used, namely Spirit, Opportunity and Curiosity, all of them had a deployable structure [34]. The complexity of a rover containing a deployable structure will be much higher than that of the stowed structure. This is because there are more moving parts. This contributes to an increase in the risk of failure which is an obvious trade-off.

The cost in developing a stowed device vs. a non-deployable device can be disputed since trying to achieve the same goals as the deployable device may be more difficult. Conversely, having to design the mechanisms that deploy the device may add further burdening to the development process.

Since the deployable device must include extra actuators to deploy, this will result in a heavier weight and therefore increase the weight factor.

Type	**Complexity**	**Risk of Failure**	**Volume**	**Cost**	**Weight**
Non-deployable	Less complex	Low	Higher	Depends	Lighter

Deployable	More complex	High	Lower	Depends	Heavier

Table 19: Deployability comparison

In this case, though a non-deployable interface benefits from reduced complexity, risk of failure, cost and weight, the higher volume is needed for the testing devices and the solar panels, thus a decision has been set to use a deployable device.

3.9 Types of Antenna

One of the most crucial parts of the communication subsystem is the antenna, without which the robotic system cannot transmit or receive any data/commands to and from Earth. In this trade study only mechanical properties of the antennas will de discussed. Their electrical properties will be addressed in the next Electrical Design section. The three most common antennas used in past Mars rovers are High Gain (HGA), Low Gain (LGA) and Ultra High Frequency (UHF) antennas [39, 40]. A table listing mechanical properties of each antenna is presented below.
Steering: the HGA is a directional antenna that focuses a beam of information in a particular direction, thus it requires a steering mechanism to align it with the orbiter for the transfer of data.

Type	**Steering**	**Energy Required**	**Volume**	**Mass**
High Gain	Yes	High	No	High
Low Gain	No	Medium	Medium	Medium
Ultra High Frequency	No	Low	Medium	Medium

Table 20: Comparison of mechanical properties of antennas

The LGA and UHF antennas, however, are omnidirectional antennas, which means they send out information in every direction and therefore do not need to be aligned [56].
Energy required: since HGA antennas require an additional component, they need more energy to operate compared to LGA and UHF antennas. Also, the UHF antenna is a close-range antenna that does not transmit information as far as the long-range LGA antenna, which means it requires less energy to operate.
Volume: HGA antennas, such as dish-shaped and Yagi antennas, are generally larger than LGA and UHF antennas, thus they take up a larger volume on the robotic system.
Mass: The combination of size and a steering mechanism makes the HGA the heaviest antenna compared to the other two antennas.
Since the UHF antenna is a close-range antenna, it is best used for communicating with the orbiter. An LGA can be used for communicating directly with a ground station on Earth. The LGA does not require as much energy to operate thus it is a better option compared to the HGA. Therefore, it is recommended that a UHF antenna be used for close-range communication with the orbiter, and an LGA antenna be used for additional data transfer directly to Earth as well as a mean to communicate the status and location of the robotic system with a ground station on Earth.

3.10 NavCam type

This trade study weighs the camera functionalities against to their physical and data processing requirements.

Functionality	Mass impact	Power impact	Volume impact	Data size
View angle	Small	Large	Large	Large
Panoramic	Small	Small	Small	Large
3D imagery	Large	Large	Large	Large
Focus	Small	Small	Small	Small
Resolution	Small	Large	Small	Large
Color	Small	Large	Large	Large

Table 21: NavCam type comparison

The table summarizes the impact of having different functionalities to mass, power, volume and the amount of data. In order to have a wide scanning range, the NavCam will be placed on the boom, which can rotate and have translational motion. Therefore, we can sacrifice large view angles, and opt for the cameras with around 45-degree view angles. This is consistent with Opportunity rover. [74] However, we need panoramic and 3D imagery options, as we are planning to create a map of the surroundings as we move to the traverse site.
And finally, high focusing and resolution capabilities can also be sacrificed in the process, as the map creating doesn't require high definition photos. This also applies to color, as the map can be obtained in black/white. Therefore, we can significantly save from our allocated power budget and data size, while the total mass and volume won't be affected much. The table above highlights the desired functionalities of the NavCam.

3.11 HazCam positioning

This study briefly justifies how the team came up with the position of the HazCams.

Position	Effectiveness	Safety	Volume impact	Mass distribution
Boom	Low	High	High	Uneven
Front	High	Medium	Low	Even

Sides	Low	Low	Low	Even
Manipulator arm	Low	Medium	High	Uneven

Table 22: HazCam positioning comparison

The HazCams would be most effective if it was placed in the front of the rover, because we need to be aware of the obstacles right in front of the MSS. Manipulator arm and boom might miss the immediate hazards in front of the rover, therefore they won't be as effective.
However, placing them in front of the rover can result in collisions with foreign objects, as it won't be shielded in any way. The sides are the most dangerous, because the rover won't recognize the danger in the direction of the motion.
Placing them on the boom or arm will push against their volume constraints, as additional cameras on the moving parts will have to be considered with caution. Additional heavy components on these parts will result in an uneven mass distribution, and will require additional power to move.

3.12 Wheels Materials

This trade study investigates different types of wheel materials for the MSS locomotion system.

Material	**Ease of Rolling**	**Load Carrying Ability**	**Resiliency**	**Impact Resistance**	**Abrasion Resistance**	**Moist & Chem Resilience**	***Temperature range (°C)**
Cast Iron	Excellent	Excellent	Poor	Fair	Excellent	Excellent	-65~800
Forged Steel	Excellent	Excellent	Poor	Excellent	Excellent	Excellent	-65~800
Polyolefin	Excellent	Excellent	Poor	Fair	Good	Excellent	-40~230
Aluminum Alloy	Excellent	Excellent	Excellent	Excellent	Excellent	Fair	Compatible with Martian Environment
Hard Rubber	Excellent	Good	Poor	Poor	Fair	Fair	-40~180
Mold-On Rubber	Fair	Fair	Good	Excellent	Fair	Fair	-40~200

Soft-Rubber	Fair	Fair	Good	Excellent	Fair	Fair	-40~200
Urethane on Iron	Good	Excellent	Fair	Good	Excellent	Fair	-40~175

Table 23 Wheels material comparison

Due to the extremely low temperature on Mars surface, a lot of the tire material options can be since they get extremely brittle. In addition, it is crucial to design the wheels to be as lightweight as possible. The size of the wheels suggest that a slight design change can add substantial amount to the MSS's total mass. Particularly, during the process where the wheel is deployed, the MSS will be suspended from the bridle underneath and descent stage. The sudden drop of the wheel will exert substantial force on the locomotion system, therefore a as lightweight as possible design will greatly reduce the degree of impact. Rubber tires are very heavy compared to other options, therefore they are eliminated. In the end, aluminum alloy is selected based on references from the Curiosity Rover.

4 Mechanical Architecture

The following section will describe the mechanical architecture in subsystem level, and sub-subsystem level, if applicable.

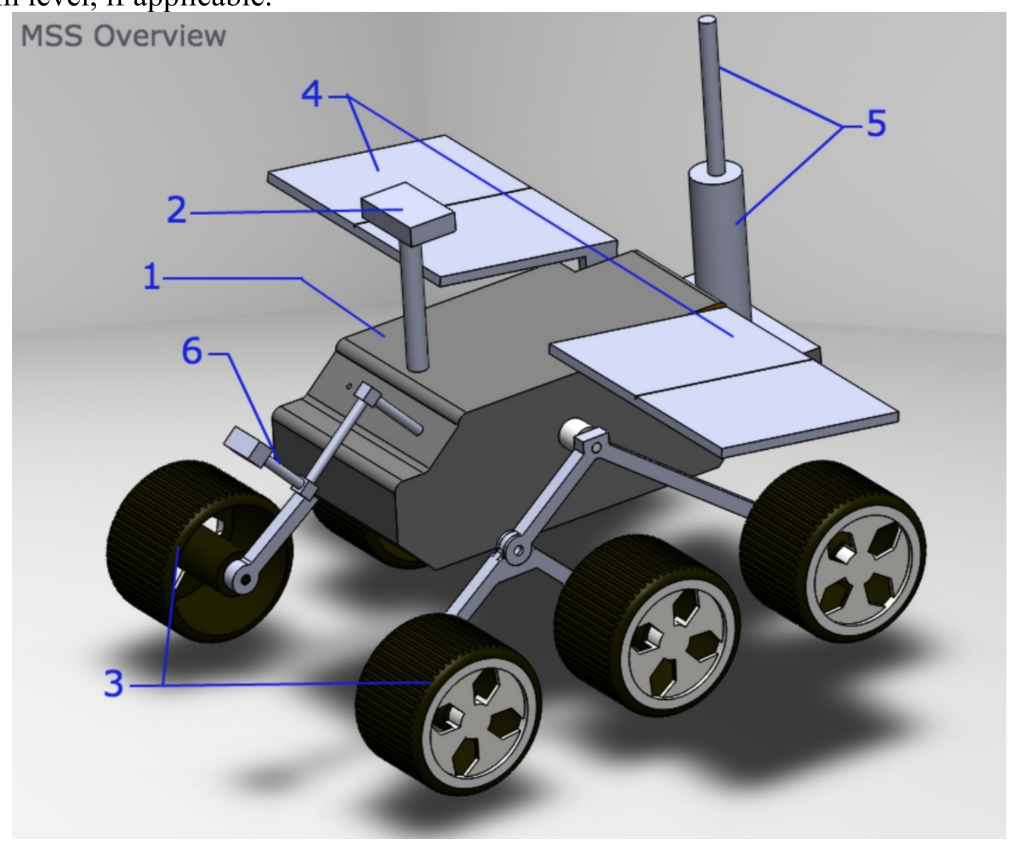

Figure 13: Overall structure of the MSS in deployed configuration

1 Body (Thermal Box)
The body of the MSS will contain all electronics and circuits of each subsystem. In particular, battery as part of power subsystem will reside inside the MSS body. In addition, inside the MSS body, active thermal control will be implemented using a centralized structure and concentrating all thermally sensitive electronics in compartments.

- Stowed & Deployed Configuration: The MSS will be capable of transforming from stowed configuration (when inside Red Dragon) to deployed configuration. As shown in Figure 2, the transformation involves extensions of wheels, antennas, head, robotic arm as well as solar panels when charging.
- HazCameras: They are mounted on front end of the MSS body, and are responsible for detecting any hazardous ground obstacles that may affect operation of the MSS. Obstacles may include large rocks, trenches, sand dunes and etc.

2 Head

- NavCameras The main functionality of navigation cameras is to provide aid for autonomous navigation. Navigation cameras consist of two cameras acting as 'traveling eyes' of the MSS, mounted on the head of the MSS which rises up in deployed configuration. The two cameras will be taking pictures of Mars surface and the map will be calculated based on the pictures taken.

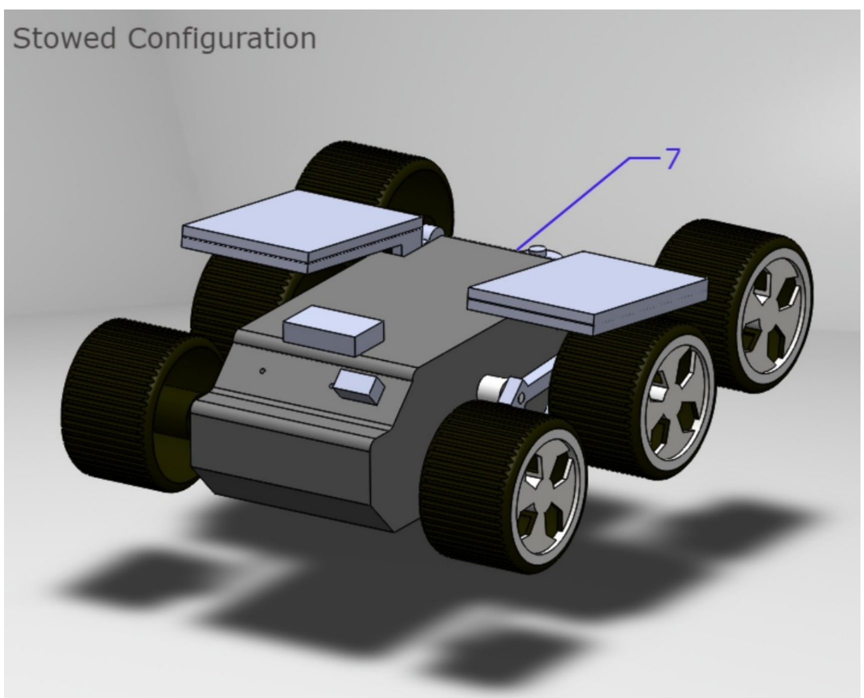

Figure 14: Stowed configuration of the MSS

- MastCameras act like real 'human eyes' of the MSS, and are responsible for collecting color images, 3D stereo images and videos of Martian terrains, with better resolution than all other cameras. Images and videos collected by Mastcameras can be used for scientific research purposes.

- ChemCamera is used to detect chemical composition of rocks or other samples obtained from Martian environment.
- HazCameras are mounted on both rear and front end of the MSS and are responsible for detecting any hazardous ground obstacles that may affect the operation of the MSS. Obstacles may include large rocks, trenches, sand dunes and etc.

3 Wheels Suspension System

As discussed in the trade-offs section, the MSS will be driven by 6 wheels (three on each side) and built on top of the rocker-bogie suspension system.

4 Solar Panel

The solar panels are attached to both sides of the MSS, the full extension requires two folds out, in order to maximize surface area for exposure.

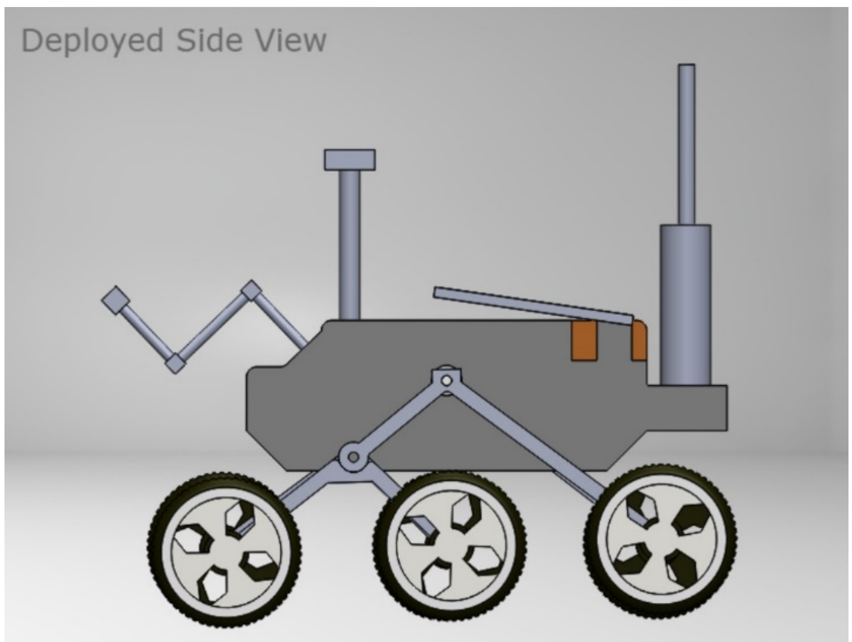

Figure 15: Deployed Configuration - side view

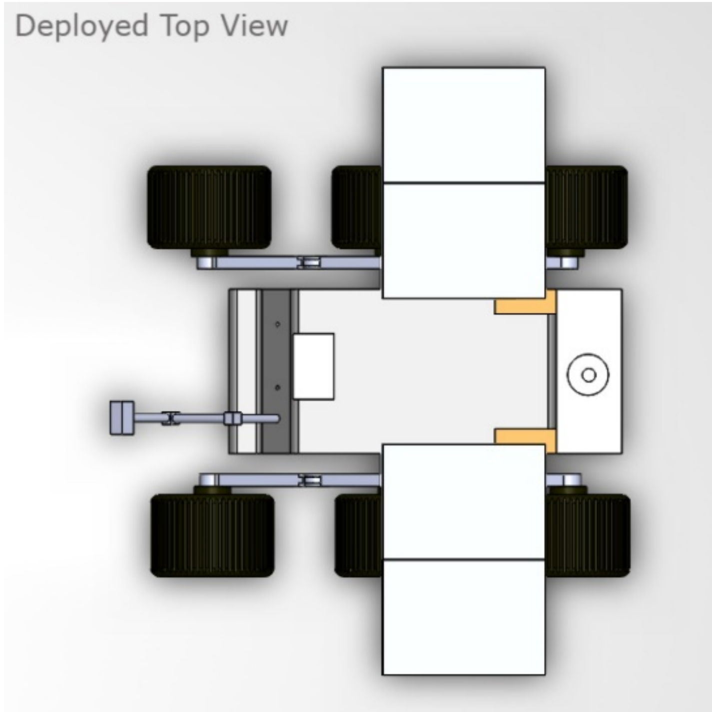

Figure 16: Deployed configuration - top view

5 Antennas

Both the LGA and UHF antennas are placed at the rear end of the robotic system, away from the cameras. This provides a more even mass distribution and also prevents the antennas from interfering with the cameras, as both antennas are vertical structures.

6 Arm

The arm of the robotic system is attached to one side of the MSS and will be folded back to the side to fit into volume constraints in stowed configuration. The manipulator arm will have 6 degrees of freedom and is capable of extension in deployed configuration and generally used for collecting samples for scientific analysis.

7 Interface with Red Dragon

The interface with Red Dragon will locate on the rear end of the MSS, as shown in stowed configuration. According to RFP, the Red Dragon payload deployment system contains two mechanical interface points in the form of cup-cone type hold-down release mechanisms, 12 cm DIA x 8 cm LG.

And finally, the interior of the thermal box will have temperature sensitive electrical components. The sub-subsystems included in thermal box are as follows:

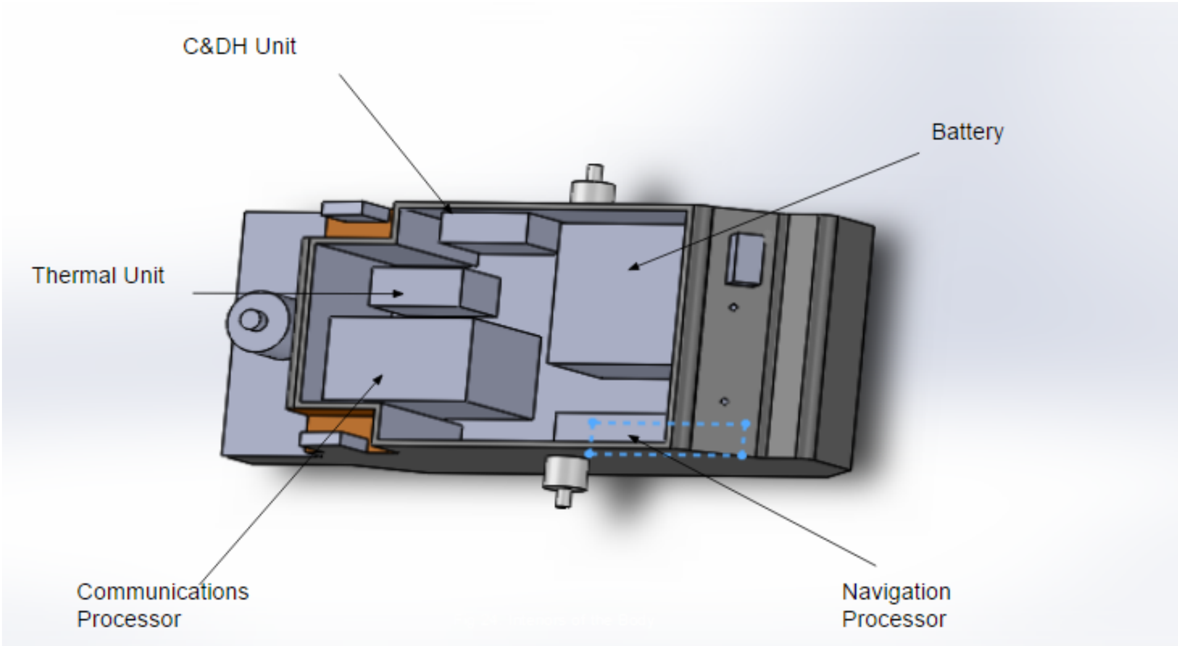

Figure 17: Thermal box - inside

Dimensions
In order to meet the volume requirements, set by the customer, the team suggests the following preliminary dimensions for each subsystem and their corresponding components (if applicable at this stage of the design process). The dimensional requirements (set for the system by the customer, and allocated to each subsystem by the team) need to be met during the transfer to Mars, and therefore, they are applicable to the stowed configuration. The provided stowed architecture is not to scale, and following maximum allowed dimensions are proposed. The thermal box will contain all the temperature sensitive components, such as battery, data processor, active control, and therefore all these electronic components need to fit in the casing.

Major Component	Height (m)	Width (m)	Length (m)	Volume (litres)
Rocker-bogie (with wheels)	0.4	0.2	1.2	96
Electronics box	0.6	0.75	1.2	540
Solar Panels	0.05	0.6	1	30
Battery	0.5	0.3	0.6	90
NavCams	0.2	0.2	0.3	12
ChemCam	0.2	0.2	0.3	12
Active Control	0.5	0.3	0.5	75

Table 24: The volume budget table

5 Mass Budget

Subsystems	Sub-subsystems	Allocated Mass (kg)	Allocated Mass (%)	Margin	Final Mass (kg)
Thermal		5.38	5%	0.3	7
	Active Control	4.33			5.63
	Local PU	0.05			0.07
	Passive Control	1			1.30
Chassis & Locomotion		43.85	41%	0.3	57
	Wheels	3.85			5.01
	Frame	32			41.60
	Suspension System	8			10.40
Power		15.38	14%	0.3	20
	Battery	3.35			4.36
	Power Control Unit	0.03			0.04
	Solar Panels	12			15.60
C&DH		2.31	2%	0.3	3
	C&D PU	1.31			1.70
	Memory	1			1.30
Science		13.85	13%	0.3	18
	Arm	11.3			14.69
	Spectrometer	2			2.60
	Cameras	0.5			0.65
	Local PU	0.05			0.07
Communication		10	9%	0.3	13
	Antennas	9.95			12.94
	Local PU	0.05			0.07
Navigation & Control		6.15	6%	0.3	8
	NavCam	3.1			4.03
	HazCams	2			2.60
	Local PU	0.05			0.07
Cables		10.77	10%	0.3	14
TOTAL		**107.69**	**100%**		**140**

Table 25: Mass budget

- Total Mass: This requirement was specified by the customer. [57]
- Thermal: Opportunity has allocated 5% of its mass for the thermal subsystem. [58]

- Chassis & Locomotion: Opportunity has allocated 50% its mass for is C&L subsystem. [58] Due to the relatively short travel distance, we can save a little mass for other subsystems.
- Power: Opportunity has allocated 40% its mass for is C&L subsystem. [58]
- C&DH: The team decided to allocate similar mass the C&DH subsystem of the Curiosity rover. [59]
- Science: Curiosity has allocated 10% of its mass budget for its scientific equipment. Due to more conservative locomotion system, we can allocate a little higher mass. [59]
- Communication: Curiosity has allocated 10% of its mass budget to its telecoms.
- Navigation & Control: As the navigation will depend on the NavCam and two HazCams, the team allocated a similar mass to the reference cameras. [60] The system will also have a control component, which needs additional mass.
- Cables: Allocated to be 10% of the total mass of the system.

6 Detailed design

6.1 Thermal Box

Due to the low density of greenhouse gases in Martian atmosphere, the main source of heating and heat loss will be thermal radiation. This creates such big variations between maximum and minimum temperature throughout each Martian day. As discussed, the MSS contains a thermal box, with all temperature sensitive components shielded from the ambient temperature and heated with the patch heaters. Therefore, the power generated by the patch heaters will have to match the heat lost through radiation. The thermal box insulation trade study wasn't specifically conducted, as the multi-layer insulation (MLI) is the most widely used and reliable means of passive thermal control. [65]
Using Stefan-Boltzmann relationship for radiation, $P_{rad} = \varepsilon\sigma A(T^4 - T_c^4)$, where P is the emitted power in [Watt], ε is the material emissivity, $\sigma = 5.6703\times10^{-8}$ in [Watt.m^{-2}.K^{-4}], T is the surface temperature of the thermal box in [K], and T_c is the ambient temperature. [66] Using this equation to estimate heat loss by taking $\varepsilon_{TiAl} = 0.4$ (from trade studies), T=20^{o}C and T_c=-128^{o}C, we get heat loss of 650W, which is unacceptable. Therefore, we need an insulation.
The thermal box will be a square box with the dimensions 0.6mx0.75mx1.2m, resulting in a total surface area of 2*0.6*0.75+2*0.6*1.2+2*0.75*1.2=4.14m^2. As each layer of MLI is approximately 6 micrometers, and the density of the layer is ρ_{Kapton}=1420kgm^{-3}, each layer will have a mass of 1420*4.14*6E-6=35g. [67]
The heat transfer coefficient between N layers of MLI is given by the equation: [68]

$$U = 4A\sigma T^3 \frac{1}{N(2/\varepsilon - 1) + 1}$$

The heat absorption from the Sun will help with the heating, which can be found using the equation:

$$P_{absorp} = S_0 A a \xi$$

Where S_0=590Wm^{-2} is the solar irradiance on Mars, A is the total surface area in [m^2], a is the absorptivity of the surface, and ξ is the irradiance decrease factor, based on the location of the rover on Mars. [69]

The total surface area, subjected to solar radiation will approximately be 40% of the total surface area, as most of the parts will be shielded by other components. And ξ is taken is taken to be 0.2, which is a deliberate underestimation to find the maximum heating power required to heat the box.
The absorbing material and layers will be Kapton, the emitting material will be Ti 6Al-4 from the trade studies of chassis materials. Therefore, we will use $a_{kapton} = 0.2, \varepsilon_{kapton} = 0.1$ [70] and $\varepsilon_{TiAl} = 0.4$ (approximate values from the sources) [71].
And finally, to calculate the extreme conditions, we will consider -128°C outside temperature and 20 °C inner temperature, and we will start by using 3 layers of kapton.
By balancing the equations: P_{heater} = U*ΔT - P_{absorp}=5.67E-8*4*4.14*(293^4-145^4)/58) - 4.14*0.4*0.2*590*0.2=112-39=73W. Adding another two layers will result in 67.7-39=29W, which can be achieved by just adding 70g more mass. These results are in well agreement with our power and mass budgets, as we will have an unused mass and power, which can be used for active thermal control.

6.2 Antenna pointing motor

For our directional antenna, which needs to be pointed to the orbiter using the rotation motors, we require:

1. Rotate the antenna constantly to determine if the orbiter is within the communication vicinity
2. Once the orbiter is detected, continue to follow the orbiter for 15 minutes (from RFP)
3. Standby mode for another 2 hours, as the orbiter will be pass three times a sol (exact timeline wasn't set, and therefore we assume it won't be in the vicinity for at least 2 hours)

During the first stage, the antenna can rotate with a speed of 1rpm, with the worst case scenario of one-minute delay. During the second stage, the antenna needs to rotate with a speed of 1/30 rpm. This approximation is obtained by recognizing that a half turn during these 15 minutes will be necessary to communicate with the orbiter. And for the last stage, this 1/30 rpm will be decreased to 0, and to 1 rpm after 2 hours.
By estimating the moment of inertia (I) of the antenna, and using the equation τ=Iω, torque requirements for the aforementioned stages can be achieved. Using a paraboloidal antenna with a radius of b=0.1m, height of h=0.05m, we can overestimate moment of inertia for our thin parabolic dish, using the equation for a solid parabola, $I=4\rho b^3 h/15$=3.6E-5kg.m^2, [72] where ρ=2.7E3kg.m^{-3} (assuming aluminium [73]). Therefore, the maximum torque required will be Iω=2pi*I/60=3.77E-6 kg.m^2.s^{-1}. Using a margin of 200%, we can conclude that the required maximum torque is 1E-5 kg.m^2.s^{-1}.
Assuming 85% gearbox efficiency and 30% motor efficiency, the required power is:
P_{req} = 1E-5 * 2pi/60 / 0.85 / 0.3 = 4E-6W. Using the factor of safety of 2, we need to pick a motor with P = 1E-5W. From the trade studies, we decided to use stepper motor for antenna positioning.
For our purposes, ST-PM35-15-11C was chosen, which satisfies the required torque and power requirements (please see Appendix for the datasheet). This requires a gear ratio mg = τ_{output}/ τ_{motor}=1E-5/1E-2=1E-3. With a total approximate volume of 1.25E-4 m^2 and mass of 70g, we meet our mass, power and volume requirements.

Section D Electrical System

1 Overview

The following section provides an overview of electrical requirements for each subsystem within the MSS, which include power requirements, data requirements and communication requirements. All subsystems are listed with their corresponding requirements in Table 2 6 below.

Subsystem	Sub-subsystem	Power Requirements	Data Requirements	Communication Requirements
C&DH		Yes	Yes	No
	Command Handling	Yes	Yes	No
	Data Processing	Yes	Yes	No
	Data Storage	Yes	Yes	No
Chassis & Locomotion		Yes	Yes	No
	Wheels	Yes	No	No
	Frame	No	No	No
	Suspension System	No	No	No
	Local PU	Yes	Yes	No
Power		Yes	Yes	No
	Power Control	Yes	Yes	No
	Power Distribution Unit	Yes	Yes	No
	Solar Panels	Yes	No	No
	Battery & Battery Management System	Yes	No	No
Science		Yes	Yes	No
	Arm	Yes	Yes	No
	Spectrometer	Yes	Yes	No
	Cameras	Yes	Yes	No

	Local PU	Yes	Yes	No
Thermal Control		Yes	Yes	No
	Active Control	Yes	Yes	No
	Passive Control	No	No	No
	Temperature Sensing	Yes	Yes	No
	Local PU	Yes	Yes	No
N&C		Yes	Yes	No
	NavCam	Yes	Yes	No
	HazCams	Yes	Yes	No
	Local PU	Yes	Yes	No
Communication		Yes	Yes	Yes
	Antenna	Yes	Yes	Yes
	Local PU	Yes	Yes	No

Table 26:Overview of Electrical Requirements for each Subsystem

All the subsystems are in need of power to work including power subsystem, which requires a small amount of power for the battery management system. Data are also required for each subsystem as well, since they need to function according to commands from processor. However, only the communication subsystem is used to communicate with the orbiter and the Earth. Other subsystem are free from communication requirements.

2 Requirements

The following section highlights functional and performance requirements for each subsystem of the MSS, taking into account electrical considerations outlined in the previous section. Each requirement includes a rationale statement that serves as justification for why the requirement is relevant, and a suggestion for how the requirement can be verified.

2.1 C&DH Subsystem Requirements

The C&DH module is the central control unit for the rover. The electrical component includes the powering of the controllers and the signal processing components.

2.1.1 Functional Requirements

CD.F.01 The C&DH subsystem shall receive power from the Power subsystem. (Verified by ground testing)
Rationale: power is required for all C&DH operations.

CD.F.02 The C&DH subsystem shall send out commands to all subsystems of the MSS. (Verified by ground testing)
Rationale: the operations of all other subsystems are controlled and monitored by the C&DH subsystem.

CD.F.03 The C&DH subsystem shall receive feedback signals from all subsystems of the MSS. (Verified by ground testing)
Rationale: feedbacks signals from other subsystems need to be received and processed by the C&DH subsystem in order to perform and maintain corresponding operations:

– The C&DH subsystem will receive temperature readings from the Thermal Control subsystem.
– The C&DH subsystem will receive motor angle readings from the Locomotion subsystem.

CD.F.04 The C&DH subsystem shall be capable of data processing by performing mathematical computations. (Verified by ground testing)
Rationale: the system should be capable of analyzing data obtained from other subsystems in order to generate accurate commands:

– The C&DH subsystem will use temperature readings to perform computation to determine if all system components are operating in desired temperatures.
– The C&DH subsystem will use motor angle readings to perform mathematical computation in order to determine travelling distance.

CD.F.05 The C&DH subsystem shall receive and process commands sent from ground control via the Communication subsystem. (Verified by ground testing)
Rationale: commands sent from the ground control will be passed onto the C&DH subsystem via Communication subsystem. These commands are processed by the C&DH subsystem then distributed to the corresponding subsystems.

CD.F.06 The C&DH subsystem shall provide the capability of storage of enough amount of data, which is required for navigation purpose. (Verified by ground testing.)
Rationale: to store data generated from the Navigation & Control subsystem in RAM for map computation, and to store data collected from the Science subsystem in secondary memory (ROM).

CD.F.07 The C&DH subsystem shall have alternative methods for data transmission and reception. (Verified by ground testing)
Rationale: the C&DH is a single point of failure of the system and therefore redundancy is extremely necessary.

2.1.2 Performance Requirements

CD.P.01 The C&DH subsystem shall consume a maximum average electrical power of 200 W. (Verified by ground testing)
Rationale: to ensure proper power allocation, maximum average power value drawn from power budget.

CD.P.02 The C&DH subsystem shall consume a maximum peak electrical power of 500 W. (Verified by ground testing)
Rationale: to ensure proper power allocation, maximum peak power value drawn from power budget.

CD.P.03 The C&DH subsystem shall have a data transfer rate of TBD kbps. (Verified by ground testing)
Rationale: to ensure data is sent back to Earth via the Communication subsystem in a timely manner.

CD.P.04 The C&DH subsystem shall have a data storage capacity of TBD GB. (Verified by ground testing)
Rationale: to guarantee that all results from science experiments are preserved, and there will be space allocated for necessary experiment repetition extra as well as extra science given enough resource.

CD.P.05 The C&DH subsystem shall send new data to the Communication subsystem once DTE signals are detected. (Verified by ground testing)
Rationale: in order to prevent the loss of large amount of data, updated science data should be transferred back to Earth through the Communication subsystem continuously as long as DTE signals can be utilized.

2.1.3 Sub-subsystem Requirements

2.1.3.1 Command Handling Requirements

CD.CH.F.01 The command handling sub-subsystem shall have a data encoding method that is compatible with ground station and the orbiters (verified by ground testing
Rationale: this ensures data send to and from Earth can be decoded and read

CD.CH.F.02 The data handling sub-subsystem shall send necessary data to the data storage sub-subsystem (verified by ground testing)
Rationale: this ensures all data required for operation is maintained

CD.CH.F.03 The data handling sub-subsystem shall send commands to all subsystems within the MSS (verified by ground testing)
Rationale: the C&DH subsystem is the brain of the MSS, thus it must be able to regulate activities of all subsystems

CD.CH.P.01 The command handling sub-subsystem shall send commands to all subsystems at a speed of TBD Hz (verified by ground testing)
Rationale: this allows operations to be executed in an efficient manner

2.1.3.2 Local Data Processing Requirements

CD.DP.F.01 The data processing sub-subsystem shall translate commands from ground station into navigation trajectory (verified by ground testing)
Rationale: the C&DH subsystem must aid the navigation subsystem in path planning

CD.DP.F.02 The data processing sub-subsystem shall update its travel plan based on commands received from ground station (verified by ground testing)
Rationale: the system must follow commands from ground station to ensure it will reach the desired destination in a timely manner

CD.DP.F.03 The data processing sub-subsystem shall calculate all torques necessary for locomotion, robotic arm movement and HGA antenna movement (verified by ground testing)
Rationale: torque data is necessary for controlling motion of the wheels, robotic arm and HGA antenna

CD.DP.P.01 The data processing sub-subsystem shall be able to operate at a speed of TBD Hz (verified by ground testing)
Rationale: some subsystems require fast calibration and the C&DH subsystem must be able to accommodate that

2.1.3.3 Data Storage Requirements

CD.DS.F.01 The data storage subsystem shall save scientific data received from the science subsystem (verified by ground testing)
Rationale: Since there is limited communication between the ground team on Earth and the MSS, the MSS must be able to store scientific data for later transmission when a communication window becomes available.

CD.DS.P.01 The data storage subsystem shall have a data storage capacity of TBD GB (verified by ground testing)
Rationale: to guarantee that all results from science experiments are preserved, and there will be space allocated for necessary experiment repetition extra as well as extra science given enough resource.

2.2 Chassis & Locomotion Subsystem Requirements

This subsystem contains the base and frame of the MSS, as well as a locomotion mechanism (consisting of the suspension system and actuation mechanism for mobility).

2.2.1 Functional Requirements

CF.F.01 The C&L subsystem shall be capable of receiving commands from C&DH subsystem (verified by testing)
Rationale: The C&DH will be controlling the subsystem.

CF.F.02 The C&L subsystem shall be send feedback to C&DH subsystem (verified by testing)
Rationale: The feedback is necessary to ensure the success/failure of the operation.

CF.F.03 The C&L subsystem shall receive power from Power subsystem (verified by testing)
Rationale: Necessary for operation.

CF.F.04 The C&L subsystem shall have redundant means of locomotion (verified by design)
Rationale: To ensure the mobility of the rover. This can be achieved by motors for operating each wheel.

CF.F.05 The C&L subsystem shall hold all the cables of electrical components (verified by ground testing)
Rationale: To ensure the proper connection between the subsystems.

2.2.2 Performance Requirements

CF.P.01 The C&L subsystem shall consume a maximum average power of TBD W. (verified by testing)
Rationale: To ensure appropriate power allocation.

CF.P.02 The C&L subsystem shall consume a maximum peak power of TBD W. (verified by testing)
Rationale: To ensure appropriate power allocation.

CF.P.03 The C&L subsystem shall send the feedback data to C&DH subsystem at a minimum rate of TBD kbps (verified by testing)
Rationale: To ensure the data transmission rate is fast enough, so that C&DH can send commands accordingly.

CF.P.04 The C&L subsystem shall provide the feedback data within TBD% of accuracy (verified by testing)
Rationale: To ensure the accuracy of operation is within acceptable range.

2.2.3 Sub-subsystem Requirements

2.2.3.1 Local Data Processing Requirements

CL.DP.F.01 *The local data processing sub-subsystem shall be capable of receiving commands from C&DH subsystem (verified by ground testing)*
Rationale: to be able to take in commands from the main C&DH and from that send specific commands to the various actuators present in the locomotion subsystem.

2.3 Power Subsystem Requirements

The following section discusses electrical requirements for the power subsystem. Many of the requirements below share similar rationale as previous assignments, and thus are not explained here.

2.3.1 Functional Requirements

PW.F.01 The power subsystem shall distribute power across all other subsystems.
Rationale: to ensure that each subsystem is able operate at their required power.

PW.F.02 The power subsystem shall receive commands from the C&DH subsystem. (Verified by ground testing)
Rationale: the C&DH subsystem will determine which subsystems the power subsystem needs to supply with power at any given time.

PW.F.03 The power subsystem shall send power usage feedback to the C&DH subsystem. (Verified by ground testing)
Rationale: this enables the C&DH subsystem to control which subsystems are powered.

PW.F.04 The power subsystem shall have redundant methods at least one of power distribution. (Verified by ground testing)
Rationale: to reduce system risk. This requirement ensures that requirement PW.F.01 can still be fulfilled in case one method of power generation fails during the mission.

PW.F.05 The power subsystem shall mitigate potential power surges. (Verified by ground testing)
Rationale: to increase system reliability and electrically protect the other subsystems.

2.3.2 Performance Requirements

PW.P.01 The power subsystem shall generate a total of TBD W of average power. (Verified by ground testing)
Rationale: required for operation of all subsystems.

PW.P.02 The power subsystem shall generate a peak power of TBD W. (Verified by ground testing)
Rationale: Required to account for the peak power requirements outlined in the power budget.

PW.P.03 The power subsystem shall consume a maximum average power of TBD W. (Verified by ground testing)
Rationale: required according to the power budget.

PW.P.04 The power subsystem shall consume a maximum peak power of TBD W. (Verified by ground testing)
Rationale: required according to power budget.

PW.P.05 The power subsystem shall transmit data to the C&DH subsystem at a rate of TBD kbps. (Verified by ground testing)
Rationale: to ensure that the C&DH subsystem receives the power usage data in time.

2.3.3 Sub-subsystem Requirements

2.3.3.1 Power Control Requirements

PW.PC.F.01 The power control sub-subsystem shall send power usage feedback to the C&DH subsystem (verified by ground testing)
Rationale: this enables the C&DH subsystem to control which subsystems are powered.

PW.PC.F.02 The power control sub-subsystem shall mitigate potential power surges (verified by ground testing)
Rationale: to increase system reliability and electrically protect the other subsystems.

PW.PC.P.01 The power control sub-subsystem shall transmit data to the C&DH subsystem at a rate of TBD kbps (verified by ground testing)
Rationale: to ensure that the C&DH subsystem receives the power usage data in time.

2.3.3.2 Power Distribution Requirements

PW.PD.F.01 The power distribution sub-subsystem shall have hardware redundancy in case of component failure (verified by ground testing)
Rationale: necessary for operation

PW.PD.F.02 The power distribution sub-subsystem shall feed an appropriate voltage as required by a given subsystem (verified by ground testing)
Rationale: this ensures each subsystem has enough power to operate properly

PW.PD.P.01 The power distribution sub-subsystem shall supply voltage to a given subsystem at a rate of TBD Hz (verified by ground testing)
Rationale: this allows operations to be carried out in a timely manner

2.3.3.3 Solar Panel Requirements

PW.SP.F.01 The solar panel sub-subsystem shall generate power needed for the operation of all other subsystem (verified by ground testing)
Rationale: The solar panels are the primary source of power generation on the MSS, therefore the MSS must be able to generate enough power to remain power positive over a work cycle.

PW.SP.P.01 The solar panel sub-subsystem shall generate a total of TBD W of average power (verified by ground testing)
Rationale: required for operation of all subsystems.

PW.SP.P.02 The solar panel sun-subsystem shall generate a peak power of TBD W (verified by ground testing)
Rationale: Required to account for the peak power requirements outlined in the power budget.

2.3.3.4 Battery Requirements

PW.B.F.01 The battery sub-subsystem shall allow the MSS to operate during periods of negative power gain (verified by ground testing)
Rationale: Required to account for points in the operating cycle where the MSS consumes more power than the solar panels can generate or during the night.

2.4 Science Subsystem Requirements

The science subsystem is responsible for carrying out scientific investigations at the landing site and traverse site B. Only electrical requirements of the science subsystem are discussed here.

2.4.1 Functional Requirements

SC.F.01 The science subsystem shall transmit collected science data to the C&DH subsystem for data storage. (Verified by ground testing)
Rationale: required for the C&DH to send the data to Earth via the communication subsystem.

SC.F.02 The science subsystem shall receive commands from the C&DH subsystem for the actuation of the manipulator arm. (Verified by ground testing)
Rationale: required for the subsystem to operate.

SC.F.03 The science subsystem shall receive electrical power from the power subsystem. (Verified by ground testing)
Rationale: required for the subsystem to operate.

SC.F.04 The science subsystem shall receive updated science objectives from the C&DH subsystem. (Verified by ground testing)
Rationale: to account for the ability to receive updated science objectives from the science team on Earth during the mission.

2.4.2 Performance Requirements

SC.P.01 The science subsystem shall consume a maximum average power of TBD W. (Verifiable by ground testing)
Rationale: required according to the power budget.

SC.P.02 The science subsystem shall consume a maximum peak power of TBD W. (Verifiable by ground testing)
Rationale: required according to the power budget.

SC.P.03 The science subsystem shall transmit data to the C&DH subsystem at a rate of TBD kbps. (Verified by ground testing).
Rationale: to ensure that the C&DH subsystem receives the power usage data in time

2.4.3 Sub-subsystem Requirements

2.4.3.1 Arm Requirements

SC.A.F.01 The arm shall receive movement commands from the system shall be able to control the motion of the robotic manipulator (verified by ground testing)
Rationale: the robotic arm is one of the most important components of the science subsystem as it allows sample collection, thus the science subsystem must be able to control it

SC.A.P.01 The arm shall have a pointing accuracy of TBD mm (verified by ground testing)
Rationale: required for operation

2.4.3.2 Spectrometer Requirements

SC.SP.F.01 The spectrometer sub-subsystem shall transmit collected science data to the C&DH subsystem for data storage (verified by ground testing)
Rationale: to pass on scientific data for analysis.

2.4.3.3 Camera Requirements

SC.C.F.01 The camera subsystem shall transmit collected video data to the local data processing sub-subsystem (verified by ground testing)
Rationale: to provide guidance for experiment.

2.4.3.4 Local Data Processing Requirements

SC.DP.F.01 The local data processing sub-subsystem shall be capable of receiving commands from C&DH subsystem (verified by ground testing)
Rationale: To lessen the computing load on the C&DH

SC.DP.F.01 The local data processing sub-subsystem shall be capable sending commands to the arm (verified by ground testing)
Rationale: To lessen the computing load on the C&DH

SC.DP.F.02 The local data processing sub-subsystem shall be capable sending commands to the spectrometer (verified by ground testing)
Rationale: To lessen the computing load on the C&DH

SC.DP.F.03 The local data processing sub-subsystem shall be capable of sending back science data to the C&DH subsystem to save. (verified by ground testing)
Rationale: Necessary to save the scientific data obtained on site to be transmitted when a communication window is available

2.5 Thermal Control Subsystem Requirements

The thermal control subsystem is responsible for providing thermal protection, by using both active and passive components, to all subsystems of the MSS. The centralized active control unit will be located inside the MSS body to help maintain operational temperatures for all thermally sensitive electronics.

2.5.1 Functional requirements

TC.F.01 The Thermal Control subsystem shall receive power from the Power subsystem. (Verified by ground testing)
Rationale: power is required for all operations in the subsystem.

TC.F.02 The Thermal Control subsystem shall receive commands from the C&DH subsystem. (Verified by ground testing)
Rationale: to receive instruction on temperature adjustments of components as needed.

TC.F.03 The Thermal Control subsystem shall send temperature readings to the C&DH subsystem for processing. (Verified by ground testing)
Rationale: to provide temperature reference for C&DH to determine if system components are operating in desired temperature range.

TC.F.04 The Thermal Control subsystem shall measure temperatures of all thermally sensitive components. (Verified by ground testing)
Rationale: to generate temperature information of all thermally sensitive components to send to C&DH.

TC.F.05 The Thermal Control subsystem shall adjust temperature of all thermally protected components. (Verified by ground testing)
Rationale: based on calculations and commands from C&DH, adjust the temperature of components as needed to accomplish thermal protection.

2.5.2 Performance requirements

TC.P.01 The Thermal Control subsystem shall consume a maximum average electrical power of TBD W. (Verified by ground testing)
Rationale: to ensure proper power allocation, maximum average power value drawn from power budget.

TC.P.02 The Thermal Control subsystem shall consume a maximum peak electrical power of TBD W. (Verified by ground testing)
Rationale: to ensure proper power allocation, maximum peak power value drawn from power budget.

TC.P.03 The Thermal Control subsystem shall send data to C&DH subsystem at a rate of TBD kbps. (Verified by ground testing)
Rationale: to detect any over-heating system components in time to avoid component malfunction.

TC.P.04 The Thermal Control subsystem shall measure the temperatures of system components at a rate of TBD Hz. (Verified by ground testing)
Rationale: to monitor temperature of all thermally sensitive components and generate data for C&DH process in a timely manner.

TC.P.05 The Thermal Control subsystem shall maintain the system temperature from -128◦C to 70◦C. (Verified by ground testing)
Rationale: temperature limit values drawn from Appendix TBD (thermal table)

TC.P.06 The Thermal Control subsystem shall maintain the system temperature from -128◦C to 70◦ C. (Verified by ground testing)
Rationale: temperature limit values drawn from Appendix thermal table.

2.5.3 Sub-subsystem Requirements

2.5.3.1 Active Control Requirements

TC.AC.F.01 The active control sub-subsystem shall adjust temperature of all thermally protected components (verified by ground testing)
Rationale: based on calculations and commands from local data processing sub-subsystem and adjust the temperature of components as needed to accomplish thermal protection.

TC.AC.P.01 The active control sub-subsystem shall maintain the system temperature from -128°C to 70°C (verified by ground testing)
Rationale: necessary to regulate within the extreme operating temperatures

2.5.3.2 Thermal Sensing Requirements

TC.TS.F.01 The thermal sensing sub-subsystem shall measure and send temperature readings of the various subsystems to the local data processing sub-subsystem for processing (verified by ground testing)
Rationale: to provide temperature reference for the local data processing sub-subsystem to determine if system components are operating in desired temperature range.

2.5.3.3 Local Data Processing Requirements

TC.DP.F.01 The local data processing sub-subsystem shall be capable of receiving commands from C&DH subsystem (verified by ground testing)
Rationale: The C&DH will be controlling the subsystem.

TC.DP.F.02 The local data processing sub-subsystem shall send feedback to C&DH subsystem (verified by ground testing)
Rationale: The feedback is necessary to ensure the success/failure of the operation.

2.6 N&C Subsystem Requirements

The navigation and control subsystem contains actuators, sensors and speed control mechanisms that allow the MSS to travel on Mars surface under different surface conditions. In addition, this subsystem is also responsible for guiding the MSS to the landing site and traverse site A.

2.6.1 Functional Requirements

NC.F.01 The N&C subsystem shall be capable of receiving commands from C&DH subsystem (verified by testing)
Rationale: The C&DH will be controlling the subsystem.

NC.F.02 The N&C subsystem shall be send feedback to C&DH subsystem (verified by testing)
Rationale: The feedback is necessary to ensure the success/failure of the operation.

NC.F.03 The N&C subsystem shall receive power from Power subsystem (verified by testing)
Rationale: Power is required for operation.

NC.F.04 The N&C subsystem shall be capable of detecting the hazards while in operation (verified by testing)
Rationale: The subsystem will have to send necessary data (from sensors or cameras) to C&DH subsystem in order to determine the hazards on the way, and navigate the MSS accordingly.

2.6.2 Performance Requirements

NC.P.01 The N&C subsystem shall consume a maximum power of TBD W on average (verified by testing)
Rationale: To ensure appropriate power allocation.

NC.P.02 The N&C subsystem shall consume a maximum peak power of TBD W (verified by testing) *Rationale: To ensure appropriate power allocation.*

NC.P.03 The N&C subsystem shall send feedback to C&DH subsystem at a minimum rate of TBD kbps (verified by testing)
Rationale: To ensure the accuracy of operation is within acceptable range.

2.6.3 Sub-subsystem Requirements

2.6.3.1 NavCam Requirements

NC.NC.P.01 *The N&C subsystem shall scan for navigation reference points with a minimum period of TBD s (verified by design)*
Rationale: To ensure that the MSS can correct its path towards traverse site B within a reasonable amount of time without deviating to far from its original trajectory

2.6.3.2 HazCam Requirements

NC.HC.P.01 *The N&C subsystem shall scan for the hazards with a minimum period of TBD s (verified by design)*
Rationale: To ensure the obstacles are determined within an acceptable time, to give the MSS enough time to overcome it. Very frequent scans can lead to high power usage.

2.6.3.3 Local Data Processing Requirements

NC.DP.F.01 The local data processing sub-subsystem shall be capable of receiving commands from C&DH subsystem (verified by ground testing)
Rationale: The C&DH will be controlling the subsystem.

NC.DP.F.02 The local data processing sub-subsystem shall send feedback to C&DH subsystem (verified by ground testing)
Rationale: The feedback is necessary to ensure the success/failure of the operation.

2.7 Communication Subsystem Requirements

The communication subsystem handles all communications required in the operation, this includes communication with the orbiters as well as interactions with C&DH subsystem. The electrical aspect of this includes the circuits to the actuator of the motors that deploy the antennas along with the signal processing.

2.7.1 Functional Requirements

CM.F.01 The communication subsystem shall be able to receive commands from the C&DH subsystem (verified by ground testing)
Rationale: The C&DH will be controlling the subsystem.

CM.F.02 The communication subsystem shall receive power from Power subsystem (verified by ground testing)
Rationale: The commands from orbiter need to be transmitted to C&DH.

CM.F.03 The communication subsystem shall be able to receive data sent from the orbiter (verified by simulations)
Rationale: Power is required for operation.

CM.F.04 The communication subsystem shall have an IDLE mode during EDL (verified by ground testing)
Rationale: The communication subsystem needs to communicate with orbiter to receive commands.

CM.F.05 The communication subsystem shall have an energy saving mode (verified by design)
Rationale: If the MSS runs low on power, the subsystem will need to go to energy saving mode to make sure that the thermal control and C&DH subsystems can be operational, which can be achieved by minimizing data transfer between the MSS and the orbiter.

CM.F.06 The communication subsystem shall have an emergency mode (verified by design)
Rationale: For fault In case of emergency, the communication system needs to send SOS signal to orbiter and the Earth.

CM.F.07 The communication subsystem shall have redundant methods of communicating

(Verified by design)
Rationale: To reduce system risk, the MSS should have multiple antennas

2.7.2 Performance Requirements

CM.P.01 The communication subsystem shall be able to transfer data to the orbiter up to a maximum distance of 400 km (TBC) (verified by ground testing)
Rationale: Existing Mars rovers such as Spirit, Opportunity and Curiosity all communicate with orbiters up to a maximum distance of 400 km from the surface of Mars [75][76], thus it is safe to assume that this will also be the case for the MSS

CM.P.02 The communication subsystem shall be able to receive up to 500 kB of data from the orbiter per sol (verified by simulations)
Rationale: This is taken directly from the RFP

CM.P.03 The communication subsystem shall be able to transmit a maximum of 2 MB of data to the orbiter per sol (verified by ground testing)
Rationale: This is taken directly from the RFP

CM.P.04 The communication subsystem shall have a maximum power usage of TBD watts per sol (verified by ground testing)

CM.P.05 The communication subsystem shall have a bandwidth of TBD Hz (verified by ground testing)
Rationale: The robotic subsystem must have a frequency range such that it does not interfere with communication from the launch vehicle

CM.P.06 The communication subsystem shall have a maximum power usage of TBD W on average (verified by ground testing)
Rationale: To ensure appropriate power allocation.

CM.P.07 The communication subsystem shall have a maximum peak power usage of TBD W (verified by ground testing)
Rationale: To ensure appropriate power allocation.

2.7.3 Sub-subsystem Requirements

2.7.3.1 Antenna Requirements

CM.A.F.01 The antenna sub-subsystem shall receive power from Power subsystem (verified by ground testing)
Rationale: Power is required for operation.

CM.A.F.02 The antenna sub-subsystem shall be able to receive data sent from the orbiter (verified by simulations)

Rationale: The communication subsystem needs to communicate with the orbiter to receive commands.

2.7.3.2 Local Data Processing Requirements

CM.DP.F.01 The local data processing unit shall be able to receive commands from the C&DH subsystem (verified by ground testing)
Rationale: The local data processing unit

CM.DP.F.02 The local data processing unit shall be able to send commands to the antennae based on commands received by (verified by ground testing)
Rationale: The C&DH will be controlling the subsystem.

3 Trade Studies

This section discusses trade studies for electrical components, including power delivery redundancy, types of batteries, types of antenna etc. Some designs will be compared and the preferred one will be highlighted.

3.1 Types of Battery

The battery is the heart of the electrical system as they store the electricity generated by the solar panels. Their performance is crucial as all of the power for the device comes from the battery and if the battery malfunctions, all systems will go down. A variety of batteries and their functionalities have been compared and they are listed below.

Type	Lead Acid	NMC	Lithium Iron Phosphate	Lithium Titanate	Lithium Nickel Cobalt Aluminium Oxide
Lifespan [79]	500-800 Cycles	400-1200 Cycles	2000 Cycles	20,000 Cycles	500 Cycles
Energy Density [79]	Low	High	Medium	High	High
Safety [79]	High	Medium	High	High	Medium
Temperature Tolerance [80]	-20-50 ^oC	0-45 ^oC	0-45 ^oC	0-45 ^oC	0-45 ^oC
Cost [79]	Low	Medium	Medium	Low	Medium

Table 27:Battery Trade-Off

One of the most important factors of the battery is life span. If it is impossible to charge the battery at all, the device would fail to function. Since it would take many years to reach

Mars, it is crucial for the battery to have a long lifespan such that it would be able to function on Mars.
Energy density is also important as the weight budget is of high importance as it is vital that the device meets the weight budget. A lighter weight for the device means that it can significantly decrease the mass budget and the mass cost could be reallocated to other parts of the subsystem.
Safety is extremely important as batteries may be vulnerable to overheating. Batteries can become volatile and may even explode under circumstances where proper charging or discharging is not done. In this case, the safety of the batteries have been measured primarily from volatility.
Temperature tolerance concerns the operating temperature ranges of the battery. These are further constraints for the thermal control subsystem to maintain the battery in these temperatures. In general, the lead acid batteries will function properly from -20 to 50 degrees Celsius while the Lithium-ion batteries function from 0 to 45 degrees Celsius. In the case of lithium batteries, they can be left below freezing temperatures but any type of charging cannot be conducted in temperatures below freezing.
The cost of lithium batteries are generally double the price of lead acid batteries but hold double the capacity. Due to the huge difference in lifespans, the cost difference being a factor of order 1 and lifespan being a factor of order 10, it is much less important.

3.2 Types of Antenna

Antennas are one of the most important components of the communication subsystem, they are responsible for transmitting as well as receiving data to and from Earth. Referencing past Mars missions, three main types of antennas are considered, High Gain Antenna (HGA), Low Gain Antenna (LGA) and Ultra High Frequency Antenna (UHF), where the HGA and LGA antennas are used for communication directly with the Deep Space Network (DSN) on Earth, and the UHF antenna is used for transmitting data to Mars orbiters, who in turns relay these data to Earth. The benefit of using a UHF antenna is that since the distance between the MSS and the orbiters are much closer compared to ground stations on Earth, the antenna does not require as much power to transmit data to the orbiters [76]. Addition, the orbiters have Earth in their field of vision for much longer periods of time and therefore can transmit more data per sol [76]. Since the CSA already shows intention to purchase communication data from Mars orbiters for this mission [RFP], together with the reasons outlined above, the UHF antenna will be a given component of the communication subsystem and will not be included in the trade study. Electrical considerations for each antenna includes directivity, gain, power required, range and data rate. These characteristics are outlined for both the HGA and LGA antennas as well as their combination in the table below.

Type	High Gain (HGA)	Low Gain(LGA)	Combination of HGA and LGA
Directivity	Directional	Omni-directional	Both
Gain	High	Low	Both
Power Required	High	Medium	Medium
Data Rate	High	Low	Both
Complexity	High	Low	High

Table 28:Antenna Trade-Off

Directivity: the HGA is a directional antenna which means it concentrates a beam of data in a particular direction. This allows more energy to be transmitted in one direction but requires a steering mechanism to align the HGA antenna with the transmitting/receiving antenna on Earth. The LGA antenna is an omni-directional antenna which transmits data in all directions. This means less energy is transmitted in a particular direction as the total power is "spread out" in all directions. Using a combination of both HGA and LGA antennas allows both directional and omni-directional data transfer.

Gain: gain of an antenna is measured as the amount of energy an antenna can transmit in a particular direction compared to the energy transmitted by an isotropic antenna in the same direction, given the same input power [77]. With that being said, the HGA has a higher gain compared to the omni-directional LGA. The combination of both antennas has both high gain and low gain.

Power required: as mentioned above, the HGA needs a steering mechanism which requires additional power to drive, making the LGA slightly more power efficient (without taking into account factors such as amount of data each antenna can transfer per unit time, thermal requirement, etc. This will be discussed later). having both antennas and alternating between them can be more power-efficient. For example, when the orientation of the MSS is unknown, the LGA can be utilised since using the HGA might require lots of steering before the HGA can properly align with the DSN [78]. If the orientation of the MSS is known, however, the HGA would be a better option.

Data rate: since the LGA spreads energy in all directions, it transmits at a much lower data rate in each direction, whereas the HGA transmits data at a higher rate in one particular direction. The combination of both antennas allow data transfer at both low and high rates.

Complexity: from past reference, the HGA uses a two-axis steering mechanism called the

High Gain Antenna Gimbal (HGAG) [79]. The HGAG alone consists of several components, making the HGA system more complex compared to the LGA. The combination of both has the same complexity as the HGA system.

The HGA which facilitates a larger data transfer rate compared to the LGA, at the expense of an additional steering mechanism. In terms of power, the HGA requires more power to operate, however, because it can transfer data at a much higher rate, it will require less time to transmit the same amount of data compared to the LGA, which might result in less power overall. On the other hand, when the orientation of the MSS is unknown, the LGA should be utilised as it transmits data in all directions while the HGA might require a lot of steering in order for it to be properly aligned with the DSN. With these considerations, it is recommended that both a HGA and LGA antenna should be used for the MSS.

3.3 Types of Data Communication

Both wired and wireless networks can be considered as a method of communication between the MSS subsystems. A wired setup achieves data transfer through physical cables, and types of network cables include coaxial cable, optical fiber cable, and twisted pair cables and are used depending on the network's physical topology and size. Wireless network uses infrared or radio frequency signals to transfer and receive data between subsystems. The characteristics of the two network options are elaborates in the table 2 9 .

Characteristics/Type	Wired-based	Wireless-based
Visibility Node to Node on same network	All nodes in the network can hear each other	Many nodes in cannot hear all other wireless nodes in the network
Visibility Network to Network	Invisible to other wired networks, the performance of one wired network is not affected by other networks	Visible to other wireless networks, the performance of one wireless network can be affected by other networks
Reliability	High reliability because of the application of ethernet cables and switches	Medium reliability because the operation the whole network is dependent of functional router, therefore router is a single point of failure

Speed and Bandwidth	High, up to 400mbps	High [106]
Cables	Ethernet, copper and optical fibers	Radio waves and microwaves
Security	High level of security can be achieved using software	High in Martian environment because there is less possibility of interception, and security can be improved by encryption technique
Signal Loss and Fading	Less signal loss and fading because of less interference in wired connections	More signal loss and fading due to more interference, absorption, refraction and reflection
Mass	More mass because of cables	Low-No mass since only radio waves or microwaves are utilized
System Complexity	Network requires cables, connectors, switches, circuit boards and may add on to mechanical system complexity	Network requires higher level of computing complexity

Table 29:Types of Data Communication

Based on the comparisons above, we recommend to use wired-based network as the main method for data transmission, since wire-based network is a more reliable option and the mass of cables will fit into the allocation in mass budget.

3.4 Types of Heaters

Several heating methods are considered:

Radioisotope Heating Unit (RHU): heat is generated by decay of radioactive isotope of plutonium (Pu-238). Although the radioactive elements are not permitted in this mission, NASA's preferred heat generation method is used as a reference design to compare other design candidates.

Patch Heater: electrical-resistance element placed between two electrical insulators. This is a popular and reliable heating method for space missions.

Heat Dissipation from Electronics: no specific heating mechanism will be used. The system will rely on the dissipated heat from other electrical components of the system, such as battery, CPU and scientific electronics.

Heat pump: a device that moves heat from one environment to another by doing external mechanical work. This system can act as a refrigerator or heater, by reversing its cycle.

Heat pipe: heats the system by moving a hot vapour/liquid through the pipes.

Criteria	Radioisotope Heating Unit	Patch Heater	Heat Dissipation from Electronics	Heat Pump	Heat Pipe
Reliability	High	Medium	Low	High	Medium
Lifetime	High	Medium	High	Medium	Low
Safety	High	Medium	High	Low	Low
Mass	Low	Medium	No mass	Heavy	Heavy
Effectiveness	High	High	Low	Medium	Medium
Complexity	Medium	Medium	Low	Medium	High
Power Usage	No	Medium	No	High	High

Table 30:Types of Heaters

Reliability: Judging from the reference designs (Opportunity and Curiosity rover, spacecraft applications), RHUs and heating patches have proven to be reliable means of heating. [18, 17] Lack of a designated heating system can be fatal in a Martian mission, due to harsh environmental conditions. Heating pipes are one of the traditional systems for residential or public buildings, but their performance in an exploration mission is not well understood, as they rely on a frequent shifts in the state of matter of the fluid.

Lifetime: RHUs usually last more than a decade [97]. Heat will be dissipated from the electrical components as long as they are functional, and assuming that this heat will be sufficient for survival of the electronics, the lifetime will be identical to that of electrical components. Heat pipes need frequent maintenance, and the low temperatures on Mars will decrease the usual lifetime of the system [R3]. Patch heaters and heat pumps on the other hand, perform for much longer. The patch heaters are especially designed for long space applications. [94] And heat pumps can last up to 15 years. [100]

Safety: RHUs are considered to be safe options for heating. [93] Heat dissipation doesn't involve any safety concerns, whereas heat pipe and heat pumps involve hot fluids and heaters, which decrease the safety of the system. [21, 27] And the patch heaters are designed for safety, due to their application in space missions. [94]

Mass: RHUs and Patch Heaters are very light heating options. RHU weigh around 40g, including the safety coating, whereas the patch heaters involve several small electrical circuits. [28, 24]. Heat pumps and heat pipes, on the other hand, involve refrigerants, heaters and vessels, which add to overall mass.

Effectiveness: The reason RHUs and patch heaters are popular in the space missions is their effectiveness in harsh environments. Heat pipes and pumps are reliable heating systems for buildings and cars, but they aren't used in spacecrafts or rovers due to the concerns of their effectiveness, as they involve frequent shifts in state of matter.

Complexity: Although the RHU involves a radioactive element, its working principle is simple, and it involves a small coated cylindrical unit. [93] Heater patches use simple electrical circuits. Heat pipes and pumps use highly complex systems, involving heaters, refrigerators and fluid vessels.

Power Usage: The RHUs generate the heat by radioactive decay of the Pu-238, so it doesn't involve any power usage. [93] The heat patches have electrical circuits, which don't involve significant power usage. [98] Heat pipes and pumps continuously heat and cool down the fluids, which requires a significant power usage. [29, 30]

Preference: The best design candidate, which is comparable to RHUs, are Patch Heaters. Relying on the heat dissipation would be unacceptable in such a mission, and the heat pumps and pipes are too heavy and complex, and involve high power usage, which push against the requirements of the mission.

3.5 Computing Architecture

There are three computing architectures to consider for the MSS: centralized, semi-distributed and distributed computing.[107] Centralized computing is the most common computing architecture due to its simplicity and ease relative ease of programming, testing and debugging. The main drawback of centralized computing is that fault tolerance is low, since all computing is done in one location.[107] Semi-distributed computing has increased fault tolerance over centralized computing and allows time critical functions to be off-loaded to micro controllers governing a particular subsystem. The main tradeoffs compared to a centralized architecture is increased design complexity and the need for additional requirements for each subsystem.[107] In addition, since the main CPU must communicate with multiple different processing units in each subsystem, there is increased communication time between subsystems which may counteract the time gained by task division. Distributed computing is the computing architecture with the highest complexity [M1]. The key difference between a semi-distributed architecture and a distributed architecture is that there is no master processing unit in the system; each processing unit is connected in a network, which results in increased fault tolerance. A distributed computing architecture requires increased coordination between each computing element in the network, which contributes to the overall complexity of the system. The tradeoff between fault tolerance and system complexity is summarized in the table below, where each option is rated on a scale of 1 to 3, where 1 denotes the least quantity and 3 denotes the highest quantity.

	Centralized	**Semi-distributed**	**Fully-distributed**
System Reliability	Low, one crash may lead to whole system failure.	Medium, some problems will influence part of the system.	High, each part is highly independent of each other. Failure will not be spread or inhere.
System Complexity	Easy to implement, High Computational Cost, Low mechanical complexity, since everything at single location	Medium complexity for both implementation, computational cost, and mechanical	Simpler computation process, High mechanical complexity
Communication Delay	High Delay, local computation is prohibited, data transmission may take long time	Medium, some local computing are supported, while others need data transmission	Delay free for locally transmission
System Mass	Low, since only one central controller	Medium, the number of controllers required is less than fully-distributed computing	High, multiple controllers are required

Table 31 Computer Architecture

A fully distributed computing architecture will not be considered for the MSS due to the significantly increased complexity that would be added to the overall system compared to the other two options. The main trade trade to consider is between a centralized architecture and a semi-distributed architecture. The preferred architecture is a semi-distributed architecture, due to its increased fault tolerance over a centralized system. This increase in fault tolerance outweighs the increased complexity of the system, since a master-slave architecture can be used to reduce computational load on the C&DH subsystem by relegating specific tasks to micro controllers in each subsystem.[108] Further computing architecture analysis will be conducted during the control phase of the design.

3.6 Power Delivery Redundancy

As with any space missions, redundancies are very critical in order to deal with unexpected failures. One of the major redundancy consideration is with its power systems. If the power fails on the rover, the entire mission will fail. Four competing methods are considered. There are pros and cons for each method, and the following section will talk in more detail about the trade off between them.

Firstly, the most direct way to feed power to the system is to have power coming off the batteries via two identical common power rail. The power will be delivered to voltage converters locally just before getting to each subsystem, where voltage will be converted to the respective ranges. This method is simple to implement, and saves space on the already confined working volume on the rover. However, by having the power on a common rail, if the rail malfunctions, all subsystems on the rail will lose power. The only backup is the secondary power rail, which serves as redundancy for all components. In addition, if the battery itself fails, all power will be lost.

Second method is to have separate power rails providing power, and each voltage will get their own rail. This way, if one power rail fails, other subsystems would be unaffected. This method also cuts down on the requirement for voltage converters at the subsystem end, as power coming out of the power supply unit would already be in the correct voltage. This method still runs into the problem of partial system shut down if one part fails. Even if other subsystems remains functional, the mission could still be jeopardized. This method is also prone to battery failures, as this will cut power all together.

The third method is similar to method number 1, except the power is fed to each of the subsystems from both the battery AND the solar panel. Power will first be drawn from the solar panel, and any surplus or deficit will be routed to the battery. This way, if failure occurs on the battery, the rover could still operate on solar panel power alone, at a reduced efficiency. Like method 1, a single power rails will come from the battery and another single power rail will come from the solar panel, and voltage converters will be placed locally at each subsystem.

The last method combines both method 2 and method 3, where both the battery and solar panels are used, and each will provide multiple voltage power rails to the subsystems. This method provides the most reliability, as failure of both the power source and the power delivery rail are covered. However, this introduces tremendous complication, and the extra components could lead to larger volume and size. It is important to note that the solar panel cannot provide power of different voltages, therefore individual voltage converters will be required locally.

Category	**Common Rail + Battery Only**	**Multiple Rail + Battery Only**	**Common Rail + Battery and Solar Panel**	**Multiple Rail + Battery and Solar Panel**

Physical Space	2 power rail + 6x Voltage converter	1x6 Sets of power rail	2 power rail + 6x Voltage converter	2x6 Sets of power rail + 6x voltage converters
Power Redundancy Coverage	one common rail failure	all components isolated, not affected by other failures	· battery failure · one common rail failure	Both power source and power rail failure
Failure Mode not covered	Battery failure Common rail failure leads to all components fail	Battery failure	Common rail failure leads to all components fail	none
Wiring	Bundled	Bundled	Separate	Separate
Complexity*	1	2	3	4

Table 32:Power Delivery Redundancy

** From 1 to 4, the complexity goes from the simplest to the most complex*

From the above discussion, it can be seen that by using both solar panel and battery on multiple power rails, the most coverage is achieved. However, from past space missions, the likelihood of both common power rails failing is extremely low, and separate power rails for each subsystem is likely to be over designed. The chosen solution from this trade study is the common rail with both battery and solar panel method, as it offers the widest redundancy at the same time keeping the physical space and complexity at a minimal. This design will protect from a both a battery failure and a single rail failure, as the possibility of both common rail failing is deemed insignificant and not worth the extra space and complexity.

4. Architecture

4.1 Legends

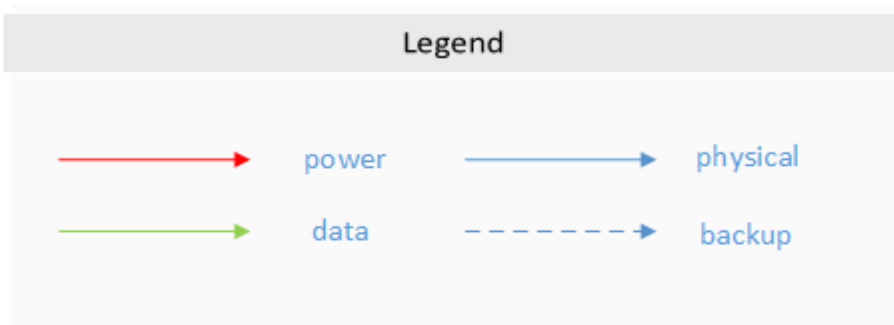

Figure 18 Legend

The red and green arrows indicate the power and data/commands transmission direction. The blue lines are for connections in a physical sense. The dashed lines indicate a back-up (redundancy) solution.

4.2 C&DH

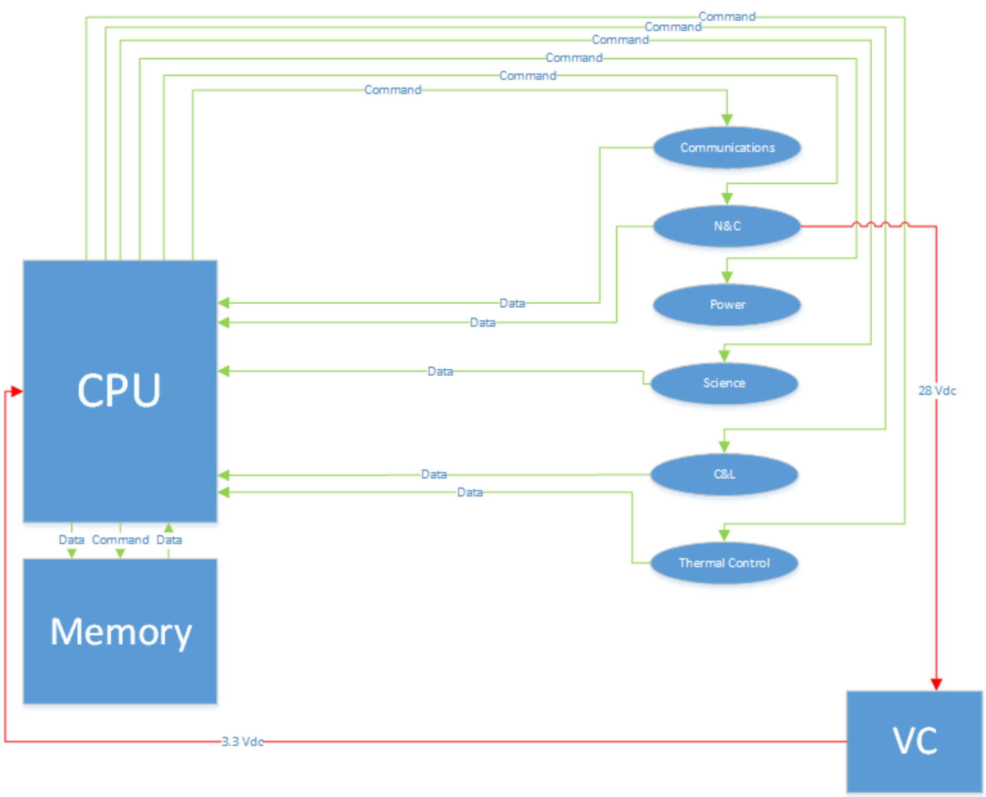

Figure 19 C&DH Subsystem Architecture

The red and green arrows indicate the power and data/commands transmission direction. The blue lines are for connections in a physical sense. The dashed lines indicate a back-up (redundancy) solution.

4.3 Power

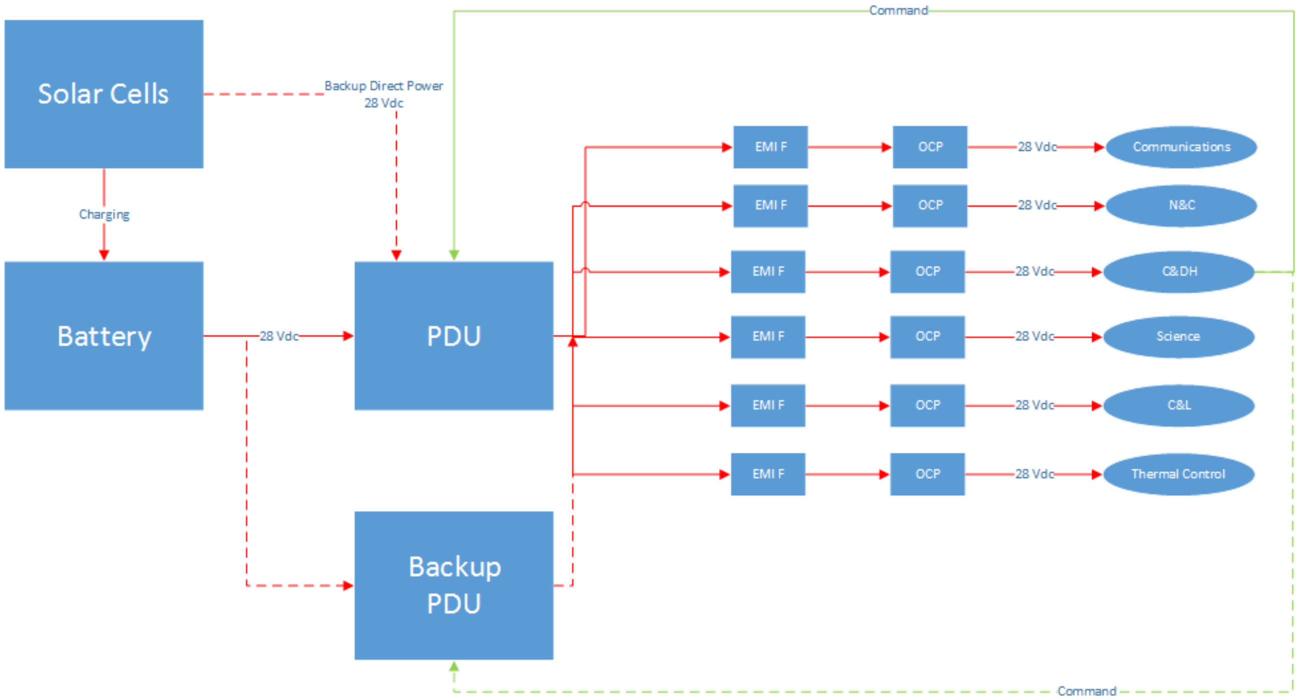

Figure 20 Power Subsystem Architecture

The dotted lines denote back-up power methods.

4.4 Locomotion

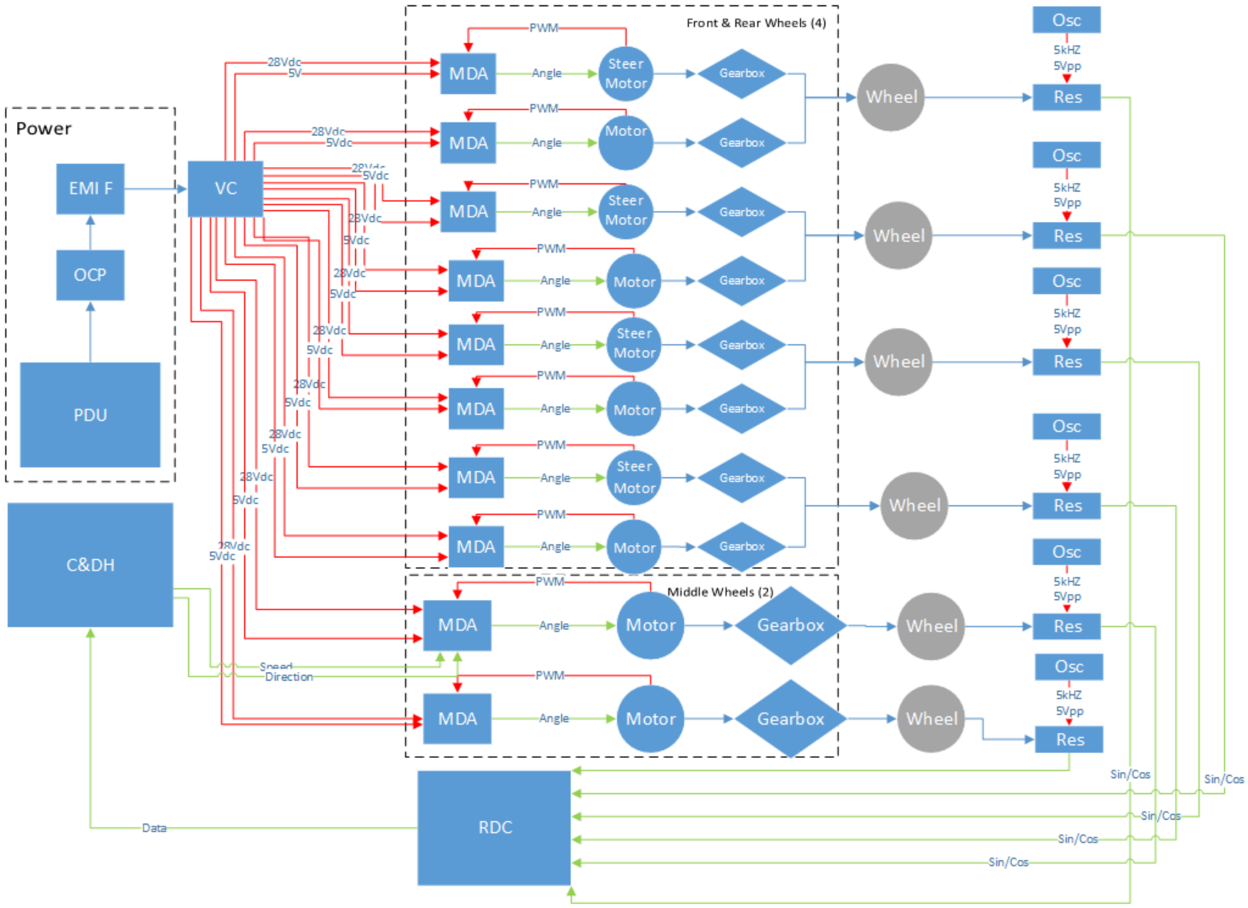

Figure 21 Locomotion Subsystem Architecture

The speed and direction information transferring into MDA from C&DH are only drawn on one set, the pattern is repetitive so not drawn on all MDA components. Also, the oscillator's signal is 5kHz and 5Vpp.

4.5 Thermal Control

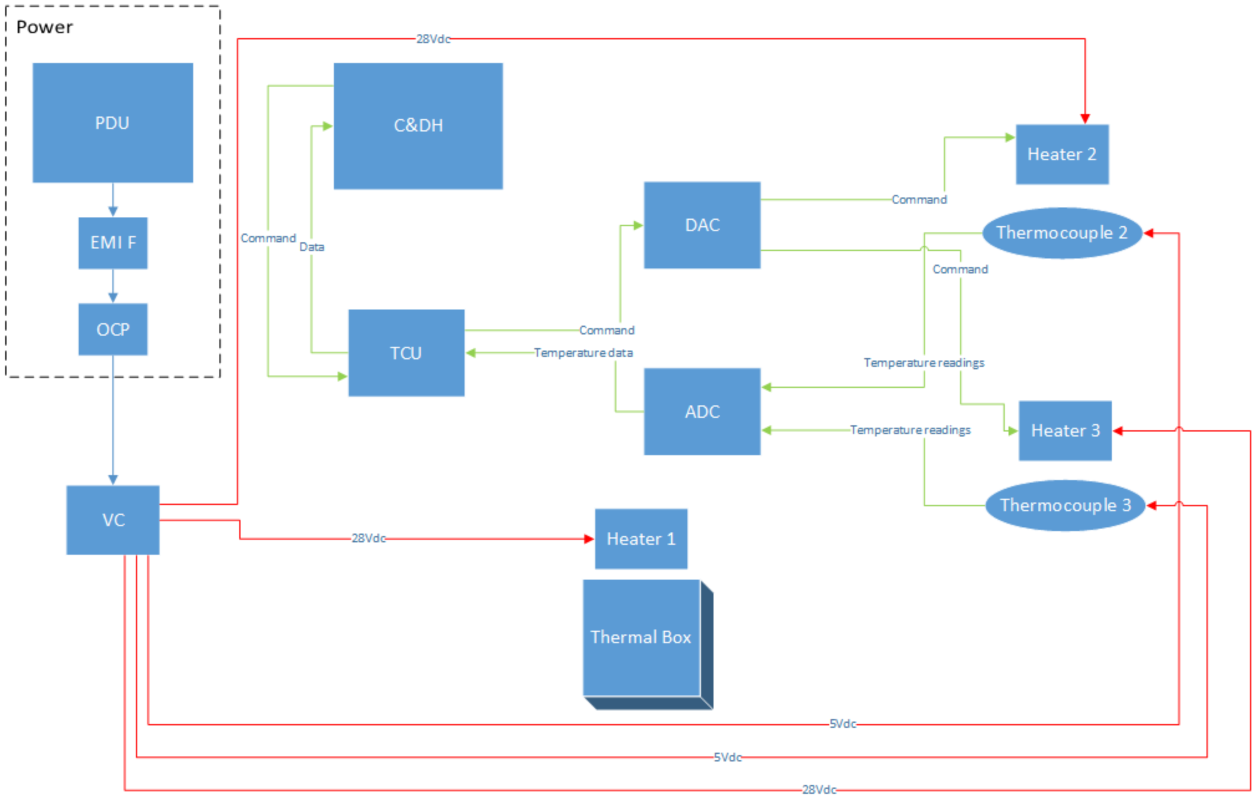

Figure 22 Thermal Control Subsystem Architecture

The Thermal Box block in the figure is the representation of the assembly of all thermally sensitive electronic components, as part of centralized thermal control architecture.

4.6 Science

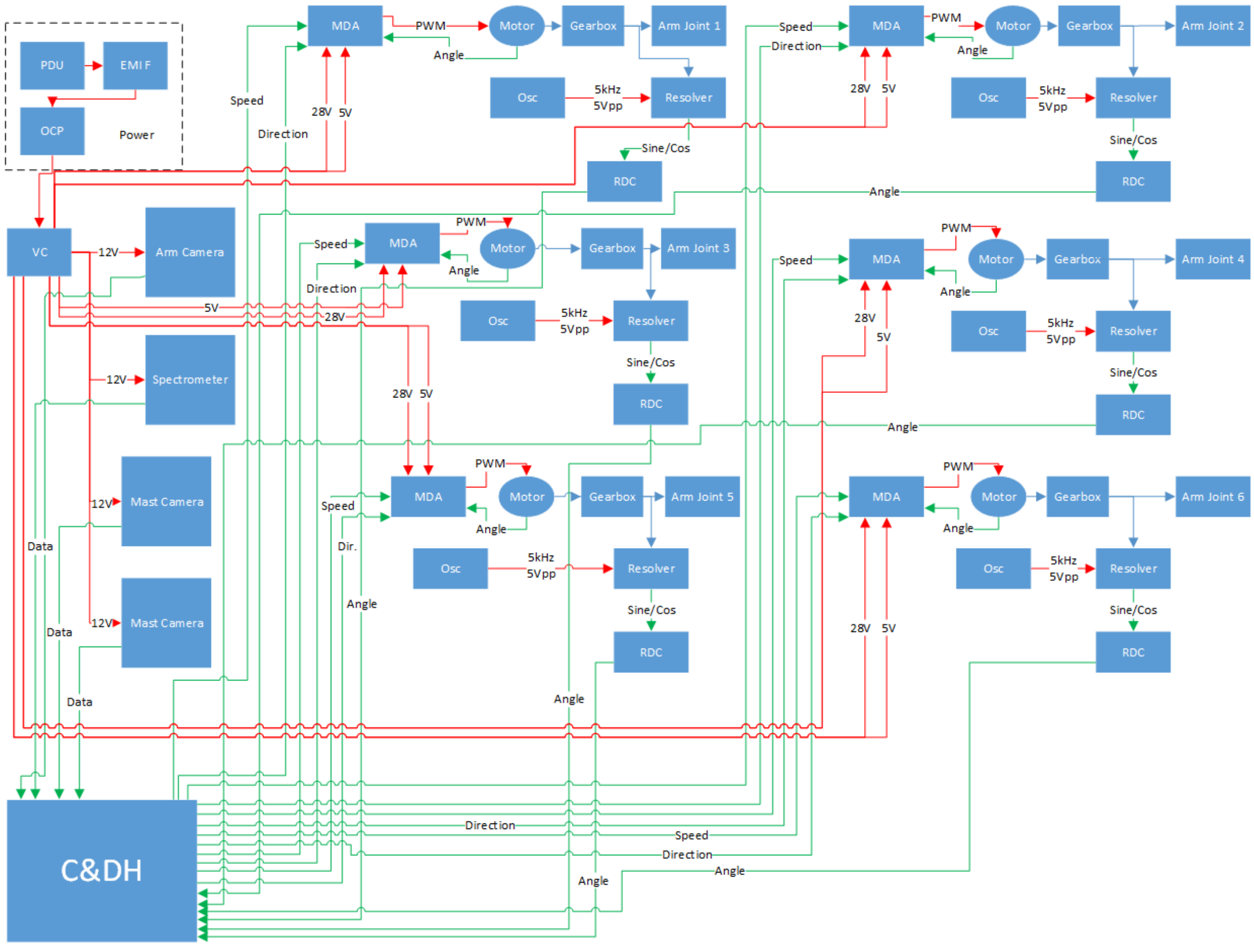

Figure 23 Science Subsystem Architecture

4.7 Navigation and Control

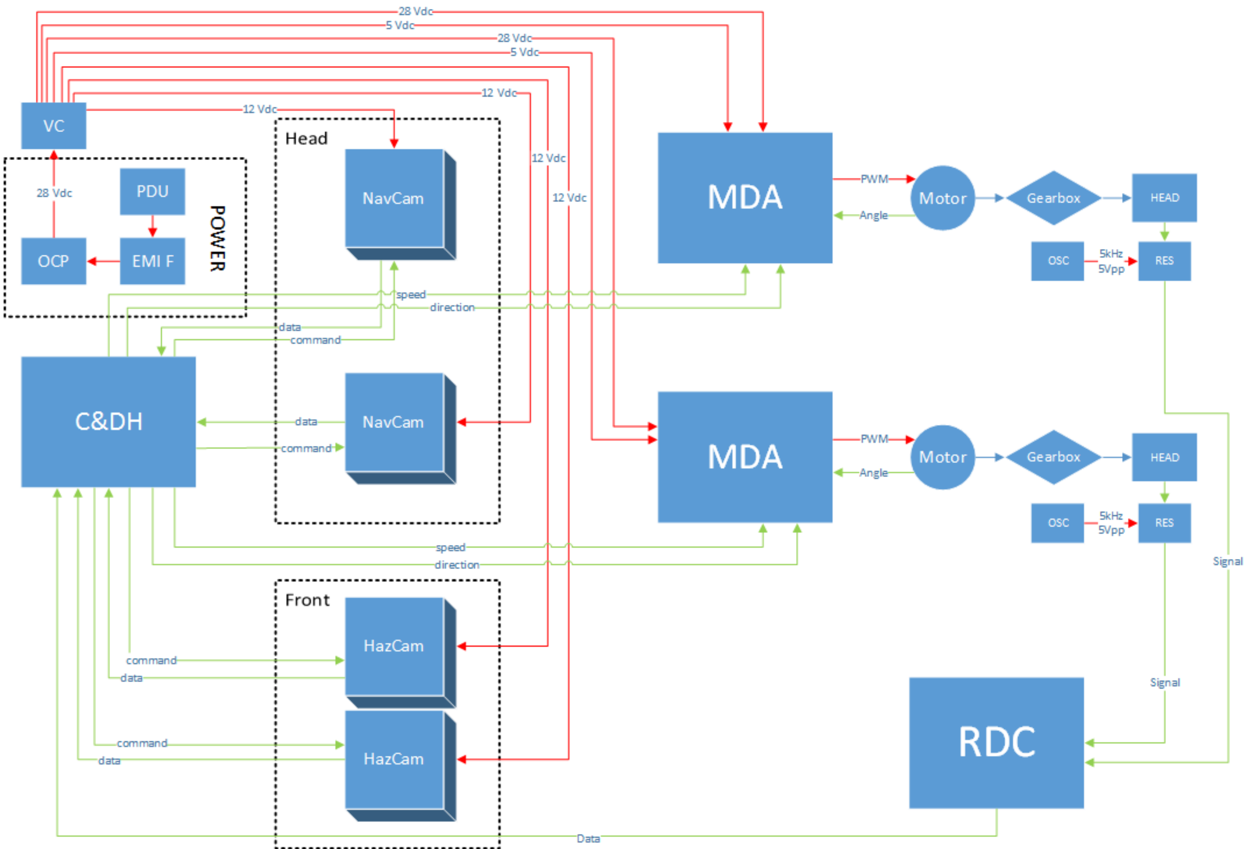

Figure 24 N&C Subsystem Architecture

4.8 Communication

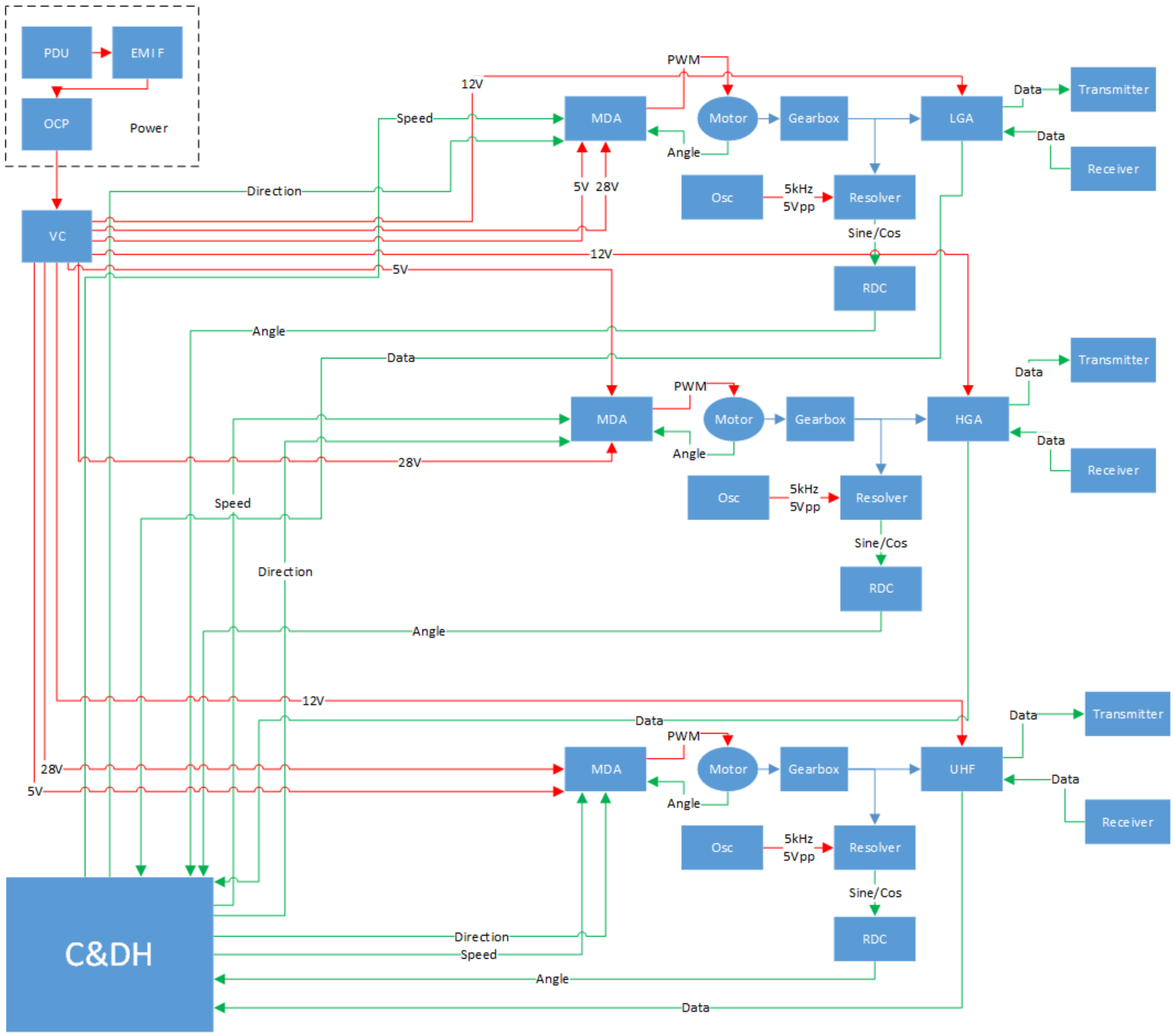

Figure 25 Communication Subsystem Architecture

4.9 Physical Architecture

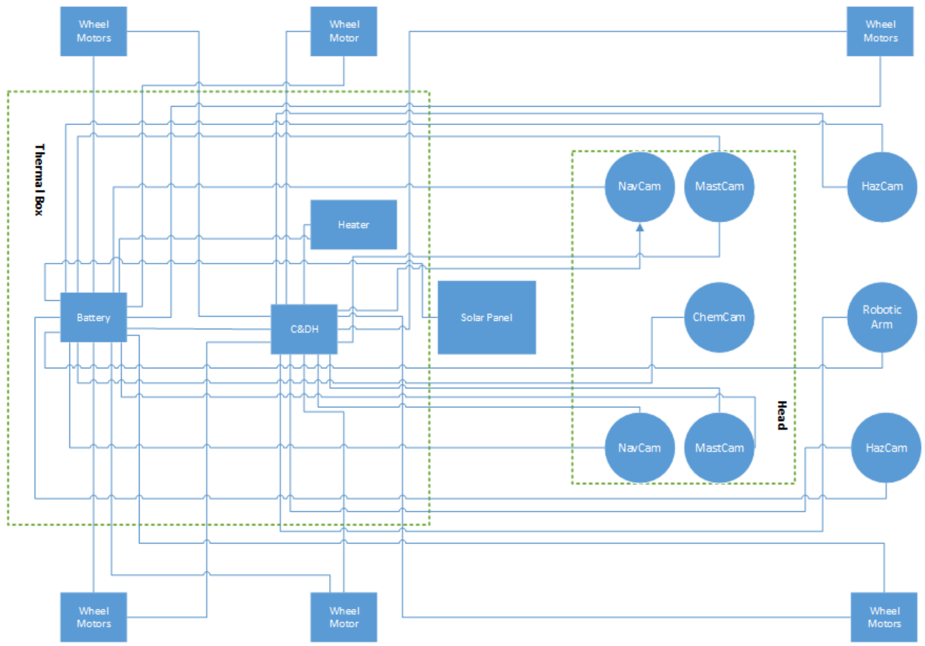

Figure 26 Physical Architecture

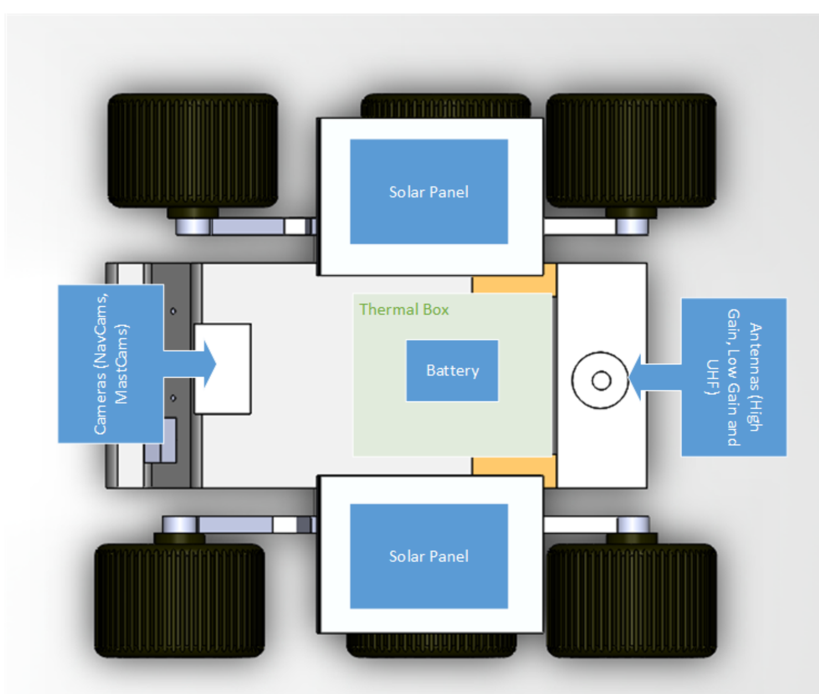

Figure 27 Physical Architecture CAD

The diagram is broken down to:
– Thermal box: which contains the electrical components
– Front: where HazCams are located
– Top: The solar panel and robotic arm is located
– Head: 5 cameras are places here, 2 MastCams, 2 NavCams and 1 ChemCam.
The front and rear wheels have steering motors, all wheels have turning motors
The antennas and motors for moving the head (rotation and up/down movement) were omitted from the physical architecture to simplify the diagram. The antennas will be located on top of the thermal box, and will have cable connections to and from C&DH and battery.

5 Detailed Design

5.1 Force and Torque Sensors Selection:

Force and torque sensors need to be selected for Locomotion and Science (Arm) Subsystem. Capacitive F/T Transducer Model 200 by ATI have been selected, which can measure the six components of force and torque. [110]

5.2 Failure Modes:

Each subsystem has the tendency to fail. Failures that could result in either loss of equipment or mission failure are presented below. Solutions on detecting failures and mitigating them are indicated in Table as well. The system is designed to have single fault tolerance under all operations.

Subsystem	**Description(Detection Plan)**	**Mitigation Plan**	**Risk Level**
Power	Cannot draw power from the batteries	The system can be powered by solar panel directly. However, it has no source and cannot be operated other than daytime	High
Power	Power distribution unit fails	Switch to backup PDU	Medium
Locomotion	Failure of one motor or brakes	The system still has 5 motors working. Recalculation of torques required for each motor may be in need and the performance shall not be as good as before. If one brake fails, the operation of halt can rely on other brakes and the wheel with broken brake will be halted passively.	Low

Locomotion	Failure of one steering motor	The system still has 3 steering motors working, though the performance shall not be as good as before.	Low
Thermal Control	Temperature of subsystems reach outside the survival temperature range. (Check temperature of the subsystems)	The subsystem will turn on or turn off heaters to keep the temperatures back to survival range.	High
Thermal Control	Heater or thermocouple failure	Switch to backup thermal control unit	Medium
C&DH	No data transmission from subsystems	Switch to backup C&DH unit	High
C&DH	Failure of processor	Switch to backup processor	High
C&DH	The rover fails to be deployed	Communicate with the orbiter and the Earth. Failing to be deployed results in failure of the whole mission since the rover cannot move and the science subsystem cannot function as desired either.	High
N&C	Loss of the path	Communicate with the orbiter and the Earth	High
N&C	Failure of one NavCamera	The system is then navigated fully depending on the rest one	Medium
N&C	Failure of both NavCameras	Communicate with the orbiter and the Earth. If the rover already arrived at traverse site B, this failure is not quite essential; otherwise, it leads to failure of the mission	High
N&C	Failure of HazCamera	The system is then lack of capability to detecting hazards on its way. It is possible that the rover gets stuck before arrival of traverse site	High
Science	Failure of Arm Camera	Failure of arm camera may affect the accuracy of arm performance. However, the arm can be manipulated by force/torque	Medium

		sensors and the calculation of kinematics and dynamics model.	
Science	Failure of Spectrometer	The failure of spectrometer functionality affects the achievements of some scientific goals, but rest of goals can be accomplished as planned.	Medium

Table 33 Detailed Design

6. Power Budget

6.1 Average and Peak Power Budget

The table below outlines the estimated average and peak power budgets for subsystems and sub-subsystems. The estimates are justified below.

Subsystem	Sub-subsystem	Margin	Average Power (W)	Average with Margin (W)	Peak Power (W)	Peak Power with Margin (W)
C&DH		0.3	8	10.4	20	26
Chassis & Locomotion		0.5	10	15	35	52.5
	Gear Box	0.5	10	15	35	52.5
Power		0.3	0.25	0.325		0
	Power Distribution Unit	0.3	0	0		0
	Solar Panels	0.3	0	0	0	0
	Battery & Battery Management System	0.3	0.25	0.325	0.25	0.325
Science		0.3	8	10.4	20	26
	Arm	0.3	8	10.4	12	15.6
	Spectrometer	0.3	5	6.5	5	6.5
	Camera	0.3	5	6.5	5	6.5
Thermal Control		0.5	20	30	60	90
	Heater Box	0.5	15	22.5	15	22.5
	Heaters	0.5	0	0	40	60
	Temperature Sensing	0.5	5	7.5	5	7.5

N&C		0.3	12	15.6	20	26
	NavCam	0.3	12	15.6	12	15.6
	HazCams	0.3	8	10.4	8	10.4
Communication		0.3	72	93.6	120	156
	SDST & SSPA	0.3	72	93.6	72	93.6
	Antenna	0.3	0	0	48	62.4
Total			**140**	**200**	**265**	**470**

Table 34 Power Budget

Justification:

C&DH: The processor used in Spirit and Opportunity rovers is the RAD6000 processor [89], which has an average power usage of 8W and a peak power usage of 11.9W [90]. The processor is responsible for command handling, data processing and storing data into memory chip. We will account for its power consumption as a whole.

Chassis & Locomotion: The locomotion subsystem contains 6 driving motors and 4 steering motors. Similar locomotion found on the MER have a power consumption of 10W average power [109], where only a portion of the motors will be running (ie. Moving in a straight line and no steering required). Peak power will be achieved when all motors are activated, likely in tight turns or difficult terrain. The peak power accounting for motors and servos are expected to be 35W [111].

Power: The power consumption of a typical BMS system has been observed, as a lithium battery requires a battery management system [82]. This is the only component of the power system that will consume electricity, which consumes 0.25W constantly.

Science: the entire system consists of a spectrometer and a camera. The Mossbauer spectrometer used for two of the Mars rovers have been referenced and power consumption has been drawn from the references. Meanwhile, the power consumption of a common store bought camera with wireless functionalities have been used to estimate the power consumption of the camera.

Thermal Control: Thermal control subsystems requires 20W in average and 60W in peak [88]. The heater in the thermal box is always in operation and it consumes 15W in average. Two thermocouples to measure the temperatures for outside components, namely one for wheels and one for cameras on arm requires 5W. When the thermocouples report the surrounding temperature cannot meet components' operation temperatures, extra heaters will be turned on, which requires 20W for each and 40W in total. Under that circumstances, the peak power is 20+40=60W.

N&C: Navigation subsystem mainly uses four cameras for detecting the surroundings, two for navigation purposes and two for hazard detection purposes. Similar NavCams were used in MER missions, and the power consumption for these cameras are around 6W. HazCams used in our design is similar to which was used in MER missions as well, and it consumes 4W each in average [109]. Those four cameras are always in working mode, so the peak power consumption is the same as average counterpart.

Communication: Based on information from Spirit and Opportunity rovers, which have similar mass and dimensions as the MSS, the communication subsystem consists of a Small Deep Space Transponder (SDST), a Solid State Power Amplifier (SSPA) and a UHF Transceiver apart from the HGA, LGA and UHF antennas. According to [88], the SDST and SSPA are operational at all times. The average power is thus the combined power requirement of the SDST and the SSPA. The SDST has three operating modes, Receiver, Receiver + Exciter (coherent) and Receiver + Exciter (aux osc), with input powers 11W, 13.3W and 13.8W, respectively [88] . Thus the maximum average power of the communication subsystem is 13.8W + 58W = 71.8W.
The peak power requirement arises when the UHF antenna communicates with the orbiters, which utilises the UHF transceiver, and the HGA sends data to the DSN at the same time. The UHF transceiver has two input power values, 6W for receiving only and 43W for transmitting and receiving. The HGAG system has two Maxon RE-20 motors [79], each requiring about 5W of power. Thus the maximum peak power consumption of the communication is 43W + 5W + 71.8W = 119.8W.

6.2 Design Reference Mission

Energy Balance Power generated from solar arrays will be around 15W peak per 0.3m2 [111], which will taper off the rest of the day. Solar panel efficiencies drop throughout the day, and it is equivalent to having 4 hours of full solar coverage per day. It is expected that the power produced by the solar panels to be around 800W each day. This is estimated from the peak value above multiplied by the estimated area of 4.5m2 for the solar panels. 4.5m2 ∗ 15W power generation/0.3m2 ∗ 4hours = 900W hr It can be assumed that the power can be evenly distributed to the subsystems throughout the day, as the battery will absorb extra power during peak generation, and release power during blackouts. To conserve power, subsystems not immediately relevant to an action will not be operating. For example, when traversing, only locomotion subsystem, navigation and C&DH will be powered, while communications and sciences will be turned off.

In this section, the operation of each day will be analyzed. Prior to reaching the destination, each day will begin with the rover in traversal mode, where the locomotion, navigation, and C&DH subsystems will be powered. From the above table, locomotion is estimated to be 10W average, while navigation is estimated to be 13W for the cameras. The C&DH processors will also be powered, using around 8W. In total, 31W will be drawn during traversal.

Communication will be done three times day, and this will occur when the rover has stopped moving. This means, the power for the locomotion can be freed up. In this mode, only the C&DH and communication subsystems will be active, drawing 8W plus 71.8W respectively. It is assumed that each communication block is 15min, and in total half an hour each day will be designated for communication.

Thermal subsystem will be the always on to protect the electronics. This subsystem draws 100W of power at its peak, and 20W when moderating temperature (PWM mode). For this estimation, the average 20W will be used around the clock.

Lastly, once the destinations are reached, science subsystems will be turned on. This subsystem draws 8W of power peak. While the science equipment are on, the locomotion will not be active, and thus full power (besides thermal control) is routed to the science equipment.
Therefore, for each cycle, the power breakdown can be shown as follows:

	Thermal	**C&DH**	**Communications**	**Locomotion**	**N&C**	**Science**	**Total**
Prior to reaching destination	20W*24 hr	8W * 24hr	71.8W * 0.5hr	10W * 7.4hr	13W *7.4hr	NA	900Whr
At destination	20W*24 hr	8W * 24hr	71.8W * 0.5hr	NA	NA	8W * 24hr	900Whr

Table 35 Design Reference Mission

From this table, it can be seen that the power produced by the solar panels will power for entire day in science mode, and will operate for 7.4hours travelling before it needs to wait for the next day.

Section E Controls System

1 Overview

The following section provides an overview of control requirements for each subsystem within the MSS, which include command and data handling requirements and autonomous behaviour requirements. All subsystems are listed with their corresponding requirements in Table 1 below.

Subsystems	Sub-subsystems	Command and Data Handling Requirements	Autonomous Behaviour Requirements
Thermal		Yes	Yes
	Active Control	Yes	Yes
	Local PU	Yes	Yes
	Temperature Sensing	Yes	Yes
	Passive Control	No	No
Chassis & Locomotion		Yes	Yes
	Wheels	No	No
	Frame	No	No
	Suspension System	No	No
	Local PU	Yes	Yes
Power		Yes	Yes
	Battery	No	No
	Power Control	Yes	Yes
	Power Distribution	Yes	Yes
	Solar Panels	No	No
C&DH		Yes	Yes
	Command Handling	Yes	Yes
	Data Processing	Yes	Yes
	Data Storage	Yes	Yes

Science		Yes	Yes
	Arm	No	No
	Spectrometer	Yes	Yes
	Cameras	Yes	Yes
	Local PU	Yes	Yes
Communication		Yes	Yes
	Antennas	No	No
	Local PU	Yes	Yes
Navigation & Control		Yes	Yes
	NavCam	Yes	Yes
	HazCams	Yes	Yes
	Local PU	Yes	Yes

Table 36: Overview of control requirements for each subsystem

2 Requirements

The following section discusses the requirements for each subsystem from a controls perspective.

2.1 C&DH Subsystem Requirements

This subsystem behaves like a brain of the MSS, and is responsible for data processing and storage, as well as commands to all other subsystems.

2.1.1 Functional Requirements

CD.F.01 The C&DH subsystem shall send out commands to all subsystems of the MSS (verified by ground testing)
Rationale: the operations of all other subsystems are controlled and monitored by the C&DH subsystem.

CD.F.02 The C&DH subsystem shall receive feedback signals from all subsystems of the MSS (verified by ground testing)
Rationale: feedbacks signals from other subsystems need to be received and processed by the C&DH subsystem in order to perform and maintain corresponding operations:
The C&DH subsystem will receive temperature readings from the Thermal Control subsystem.

The C&DH subsystem will receive motor angle readings from the Locomotion subsystem.

CD.F.03 The C&DH subsystem shall be capable of data processing by performing mathematical computations (verified by ground testing)
Rationale: the system should be capable of analyzing data obtained from other subsystems in order to generate accurate commands:
The C&DH subsystem will use temperature readings to perform the computation to determine if all system components are operating at desired temperatures.
The C&DH subsystem will use motor angle readings to perform the mathematical computation in order to determine traveling distance.

CD.F.04 The C&DH subsystem shall receive and process commands sent from ground control via the Communication subsystem (verified by ground testing)
Rationale: commands sent from the ground control will be passed to the C&DH subsystem via Communication subsystem. These commands are processed by the C&DH subsystem then distributed to the corresponding subsystems.

CD.F.05 The C&DH subsystem shall send new data to the Communication subsystem once DTE signals are detected (verified by ground testing)
Rationale: in order to prevent the loss of a large amount of data, updated science data should be transferred back to Earth through the Communication subsystem continuously as long as DTE signals can be utilized.

CD.F.06 The C&DH subsystem shall have alternative methods for data transmission and reception (verified by ground testing)
Rationale: the C&DH is a single point of failure of the system and therefore redundancy is extremely necessary.

2.1.2 Performance Requirements

CD.P.01 The C&DH subsystem shall have a data transfer rate of TBD kbps (verified by ground testing)
Rationale: to ensure data is sent back to Earth via the Communication subsystem in a timely manner.

CD.P.02 The C&DH subsystem shall have a data storage capacity of TBD GB (verified by ground testing)
Rationale: to guarantee that all results from science experiments are preserved, and there will be space allocated for necessary experiment repetition extra as well as extra science given enough resource.

CD.P.03 The C&DH subsystem shall send out commands and receive data with TBD % accuracy. (verified by ground testing)
Rationale: to enhance system integrity.

2.1.3 Sub-subsystem Requirements

2.1.3.1 Command Handling Requirements

CD.CH.F.01 The command handling sub-subsystem shall have a data encoding method that is compatible with ground station and the orbiters (verified by ground testing
Rationale: this ensures data send to and from Earth can be decoded and read

CD.CH.F.02 The data handling sub-subsystem shall send necessary data to the data storage sub-subsystem (verified by ground testing)
Rationale: this ensures all data required for operation is maintained

CD.CH.F.03 The data handling sub-subsystem shall send commands to all subsystems within the MSS (verified by ground testing)
Rationale: the C&DH subsystem is the brain of the MSS, thus it must be able to regulate activities of all subsystems

CD.CH.P.01 The command handling sub-subsystem shall send commands to all subsystems at a speed of TBD Hz (verified by ground testing)
Rationale: this allows operations to be executed in an efficient manner

2.1.3.2 Data Processing Requirements

CD.DP.F.01 The data processing sub-subsystem shall translate commands from ground station into navigation trajectory (verified by ground testing)
Rationale: the C&DH subsystem must aid the navigation subsystem in path planning

CD.DP.F.02 The data processing sub-subsystem shall update its travel plan based on commands received from ground station (verified by ground testing)
Rationale: the system must follow commands from ground station to ensure it will reach the desired destination in a timely manner

CD.DP.F.03 The data processing sub-subsystem shall calculate all torques necessary for locomotion, robotic arm movement and HGA antenna movement (verified by ground testing)
Rationale: torque data is necessary for controlling motion of the wheels, robotic arm and HGA antenna

CD.DP.P.01 The data processing sub-subsystem shall be able to operate at a speed of TBD Hz (verified by ground testing)
Rationale: some subsystems require fast calibration and the C&DH subsystem must be able to accommodate that

2.1.3.3 Data Storage Requirements

CD.DS.F.01 The data storage sub-subsystem shall have a minimum capacity of TBD GB (verified by design)
Rationale: this is necessary to ensure there is enough storage space for all necessary data

2.2 Thermal Control Subsystem Requirements

This subsystem monitors and adjusts the temperature of all components on the MSS, and contains both active and passive systems components.

2.2.1 Functional Requirements

TC.F.01 The Thermal Control subsystem shall receive commands from the C&DH subsystem (verified by ground testing)
Rationale: to receive instruction on temperature adjustments of components as needed.

TC.F.02 The Thermal Control subsystem shall send temperature readings to the C&DH subsystem for processing (verified by ground testing)
Rationale: to provide temperature reference for C&DH to determine if system components are operating in desired temperature range.

TC.F.03 The Thermal Control subsystem shall measure temperatures of all thermally sensitive components (verified by ground testing)
Rationale: to generate temperature information of all thermally sensitive components to send to C&DH.

TC.F.04 The Thermal Control subsystem shall adjust temperature of all thermally protected components (verified by ground testing)
Rationale: based on calculations and commands from C&DH and adjust the temperature of components as needed to accomplish thermal protection.

2.2.2 Performance Requirements

TC.P.01 The Thermal Control subsystem shall send data to C&DH subsystem at a rate of TBD kbps (verified by ground testing)
Rationale: to detect any over-heating system components in time to avoid component malfunction.

TC.P.02 The Thermal Control subsystem shall measure the temperatures of system components at a rate of TBD Hz (verified by ground testing)
Rationale: to monitor temperature of all thermally sensitive components and generate data for C&DH process in a timely manner.

TC.P.03 The Thermal Control subsystem shall maintain the system temperature from -128°C to 70°C (verified by ground testing)
Rationale: temperature limit values drawn from Appendix TBD (thermal table)

2.2.3 Sub-subsystem Requirements

2.2.3.1 Active Thermal Control Requirements

TC.AC.F.01 The active thermal control sub-subsystem shall process command from the C&DH subsystem to turn on/off heaters (verified by ground testing)
Rationale: this is required for operation
TC.AC.P.01 The active thermal control sub-subsystem shall increase the temperature of a given subsystem by TBD degrees per second (verified by ground testing)
Rationale: this ensures the subsystems are maintained within their operational temperature range

2.2.3.2 Temperature Sensing Requirements

TC.TS.F.01 The temperature sensing sub-subsystem shall measure temperature of all thermally sensitive components (verified by ground testing)
Rationale: required for operation

TC.TS.F.02 The temperature sensing sub-subsystem shall communicate temperature readings with the local data processing sub-subsystem (verified by ground testing)
Rationale: necessary for operation

TC.TS.P.01 The temperature sensing sub-subsystem shall communicate with the local data processing sub-subsystem at a rate of TBD kbps (verified by ground testing)
Rationale: this ensures temperature data is received and processed in a timely manner

TC.TS.P.02 The temperature sensing sub-subsystem shall measure temperature of each subsystem with an accuracy of TBD degrees (verified by ground testing)
Rationale: this allows temperature of each subsystem to be properly maintained

TC.TS.P.03 The temperature sensing sub-subsystem shall measure the temperature of a given subsystem at a rate of 35 Hz (see Appendix) (verified by ground testing)
Rationale: this ensures temperatures of thermally sensitive components are regulated at all times

2.2.3.3 Local Data Processing Requirements

TC.DP.F.01 The local data processing sub-subsystem shall send temperature data to the C&DH subsystem (verified by ground testing)
Rationale: required for operation

TC.DP.F.02 The local data processing sub-subsystem shall send commands to other sub-subsystems of the thermal control subsystem (verified by ground testing)
Rationale: required for operation

TC.DP.P.01 The local data processing sub-subsystem shall transmit data to the C&DH subsystem at a rate of TBD Hz (verified by ground testing)
Rationale: this ensures the C&DH always knows the current thermal condition of each subsystem

2.3 Power Subsystem Requirements

This subsystem is responsible for generating, storing and distributing power to all other subsystems.

2.3.1 Functional Requirements

PW.F.01 The power subsystem shall distribute power across all other subsystems (verified by ground testing)
Rationale: to ensure that each subsystem is able to operate at their required power.

PW.F.02 The power subsystem shall receive commands from the C&DH subsystem (verified by ground testing)
Rationale: the C&DH subsystem will determine which subsystems the power subsystem needs to supply with power at any given time.

PW.F.03 The power subsystem shall send power usage feedback to the C&DH subsystem (verified by ground testing)
Rationale: this enables the C&DH subsystem to control which subsystems are powered.

PW.F.04 The power subsystem shall have redundant methods of power distribution (verified by ground testing)
Rationale: to reduce system risk. This requirement ensures that requirement PW.F.01 can still be fulfilled in case one method of power generation fails during the mission.

PW.F.05 The power subsystem shall mitigate potential power surges (verified by ground testing)
Rationale: to increase system reliability and electrically protect the other subsystems.

2.3.2 Performance Requirements

PW.P.01 The power subsystem shall transmit data to the C&DH subsystem at a rate of TBD kbps (verified by ground testing)
Rationale: to ensure that the C&DH subsystem receives the power usage data in time

PW.P.02 The power subsystem shall transmit data to the C&DH subsystem with TBD % accuracy (verified by ground testing)
Rationale: to ensure system reliability

PW.P.03 The power subsystem shall transmit data to the C&DH subsystem at a frequency of TBD Hz (verified by ground testing)
Rationale: to ensure that the C&DH subsystem receives the power usage data regularly

PW.P.04 The power subsystem shall provide output voltages to each subsystem within a tolerance of +- TBD V (verified by ground testing)
Rationale: to ensure that each subsystem receives the correct voltage necessary to operate

PW.P.05 The power subsystem shall execute commands after TBD min of receiving a command from the C&DH (verified by ground testing)
Rationale: necessary for system responsiveness

2.3.3 Sub-subsystem Requirements

2.3.3.1 Power Control Requirements

PW.PC.F.01 The power control sub-subsystems shall draw power from the power supply (verified by ground testing)
Rationale: necessary for operation

2.3.3.2 Power Distribution Requirements

PW.PD.F.01 The power distribution sub-subsystems shall have hardware redundancy in case of component failure (verified by ground testing)
Rationale: necessary for operation

PW.PD.F.02 The power distribution sub-subsystems shall feed an appropriate voltage as required by a given subsystem (verified by ground testing)
Rationale: this ensures each subsystem has enough power to operate properly

PW.PD.P.01 The power distribution sub-subsystem shall supply voltage to a given subsystem at a rate of TBD Hz (verified by ground testing)
Rationale: this allows operations to be carried out in a timely manner

2.3.3.3 Local Data Processing Requirements

PW.DP.F.01 The local data processing sub-subsystem shall send data to the C&DH subsystem (verified by ground testing)
Rationale: required for operation

PW.DP.F.02 The local data processing sub-subsystem shall send commands to other sub-subsystems of the power subsystem (verified by ground testing)
Rationale: required for operation

PW.DP.P.01 The local data processing sub-subsystem shall transmit data to the C&DH subsystem at a rate of TBD Hz (verified by ground testing)
Rationale: this allows the C&DH subsystem to regulate power in a timely manner

PW.DP.P.02 The local data processing sub-subsystem shall keep a log of how much voltage was supplied to each subsystem (verified by ground testing)
Rationale: this allows the system to effectively regulate the system's power distribution

2.4 Science Subsystem Requirements

This subsystem contains experimental equipment, manipulators, sensors and detectors as well as tools needed to perform scientific tasks.

2.4.1 Functional Requirements

SC.F.01 The science subsystem shall transmit collected science data to the C&DH subsystem for data storage (verified by ground testing)
Rationale: required for the C&DH to send the data to Earth via the communication subsystem.

SC.F.02 The science subsystem shall receive commands from the C&DH subsystem for the actuation of the manipulator's arm (verified by ground testing)
Rationale: required for the subsystem to operate.

SC.F.03 The science subsystem shall receive updated science objectives from the C&DH subsystem (verified by ground testing)
Rationale: to account for the ability to receive updated science objectives from the science team on Earth during the mission.

SC.F.04 The science subsystem shall collect mass spectrometry data to achieve science goal AB-5 (verified by ground testing)
Rationale: AB-5 was identified as the highest priority science objective, therefore the science subsystem must be to collect data related to this science goal.

SC.F.05 The science subsystem shall record video data of the Martian surface (verified by ground testing)
Rationale: the ability to provide a video feed of the Martian environment is needed to work on science goal PG-M-2

SC.F.06 The science subsystem shall be able to control the motion of the robotic manipulator (verified by ground testing)
Rationale: the robotic arm is one of the most important components of the science subsystem as it allows sample collection, thus the science subsystem must be able to control it

2.4.2 Performance Requirements

SC.P.01 The science subsystem shall transmit data to the C&DH subsystem at a rate of TBD kbps (verified by ground testing)
Rationale: to ensure that the C&DH subsystem receives the power usage data in time

SC.P.02 The science subsystem shall transmit data to the C&DH subsystem at a frequency of TBD Hz (verified by ground testing)
Rationale: to ensure that science data is saved regularly

SC.P.03 The science subsystem shall update its current objective after TBD min of receiving new science objectives (verified by ground testing)

Rationale: to ensure system responsiveness

SC.P.04 The science subsystem shall transmit data to the C&DH with TBD % accuracy (verified by ground testing)
Rationale: necessary to ensure the integrity of the science data being sent back to Earth

SC.P.05 The science subsystem's manipulator arm shall have a pointing accuracy of TBD mm (verified by ground testing)
Rationale: required for operation

2.4.3 Sub-subsystem Requirements

2.4.3.1 Spectrometer Requirements

SC.S.F.01 The spectrometer shall send all scientific data collected to the local data processing sub-subsystem (verified by ground control)
Rationale: required for operation

SC.S.P.01 The spectrometer shall send data to the local data processing sub-subsystem at a rate of TBD Hz (verified by ground testing)
Rationale: this ensures enough data is collected to be transmitted to Earth

2.4.3.2 Camera Requirements

SC.C.F.01 The camera shall send images to the local data processing sub-subsystem (verified by ground testing)
Rationale: this allows the C&DH subsystem to determine the appropriate samples to collect

2.4.3.3 Local Data Processing Requirements

SC.DP.F.01 The local data processing sub-subsystem shall send data to the C&DH subsystem (verified by ground testing)
Rationale: required for operation

SC.DP.F.02 The local data processing sub-subsystem shall send commands to other sub-subsystems of the power subsystem (verified by ground testing)
Rationale: required for operation

SC.DP.P.01 The local data processing sub-subsystem shall transmit data to the C&DH subsystem at a rate of TBD Hz (verified by ground testing)
Rationale: this allows the C&DH subsystem to collect enough data to be sent to Earth

2.5 Chassis and Locomotion Subsystem Requirements

This subsystem contains the base and frame of the MSS, as well as a locomotion mechanism to allow mobility of the MSS.

2.5.1 Functional Requirements

CL.F.01 The C&L subsystem shall be capable of receiving commands from C&DH subsystem for adjusting the speed of motion of the MSS (verified by ground testing)
Rationale: the C&DH will be controlling the subsystem.

CL.F.02 The C&L subsystem shall be capable of receiving commands from C&DH subsystem for adjusting the direction of motion of the MSS (verified by ground testing)
Rationale: the C&DH will be controlling the subsystem.

CL.F.03 The C&L subsystem shall send feedback to C&DH subsystem about the actual speed and direction (verified by ground testing)
Rationale: the feedback is necessary to ensure the success/failure of the operation.

CL.F.04 The C&L subsystem shall have redundant means of facilitating the system's locomotion (verified by design)
Rationale: to ensure the mobility of the rover. This can be achieved by motors for operating each wheel

2.5.2 Performance Requirements

CL.P.01 The C&L subsystem shall provide the feedback data within TBD% of accuracy (verified by ground testing)
Rationale: to ensure the accuracy of operation is within an acceptable range.

CL.P.02 The C&L subsystem shall send feedback to C&DH subsystem at a minimum rate of TBD kbps (verified by ground testing)
Rationale: to ensure the operation can be regulated within an acceptable range of time.

CL.P.03 The C&L subsystem shall be able to move at a minimum speed of 0.1 km/hr (verified by ground testing)
Rationale: this requirement was established by using Opportunity rover as the reference design [117] and can be verified by ground testing.

CL.P.04 The C&L subsystem shall be able to overcome torques of TBD N*m (verified by ground testing)
Rationale: to ensure it is capable of moving the MSS on Martian surface.

CL.P.05 The C&L subsystem shall be able to reject disturbance torques of at least TBD N*m (verified by ground testing)
Rationale: to ensure it is capable of moving accurately on the MSS on Martian surface.

CL.P.06 The C&L subsystem shall be able to move the system with a maximum rise time of TBD s. (verified by ground testing)
Rationale: to ensure the subsystem is sufficiently responsive.

CL.P.07 The C&L subsystem shall be able to move the system with a maximum accuracy of TBD %. (verified by ground testing)
Rationale: to ensure the desired movement is accurate enough.

CL.P.08 The C&L subsystem shall be able to move the system with a maximum settling time of TBD s. (verified by ground testing)
Rationale: To ensure the desired movement can stabilize sufficiently fast, can help save power by requiring a uniform torque from the motors

CL.P.9 The C&L subsystem shall be able to steer the system with a maximum accuracy of TBD %. (verified by ground testing)
Rationale: To ensure the desired movement is achieved.

CL.P.10 The C&L subsystem shall have maximum latency of TBD s (verified by design)
Rationale: To ensure the MSS is reacting fast enough to the commands.

2.5.3 Sub-subsystem Requirements

2.5.3.1 Local Data Processing Requirements

CL.DP.F.01 The local data processing sub-subsystem shall send data to the C&DH subsystem (verified by ground testing)
Rationale: required for operation

CL.DP.F.02 The local data processing sub-subsystem shall send commands to other sub-subsystems of the chassis and locomotion subsystem (verified by ground testing)
Rationale: required for operation

CL.DP.P.01 The local data processing sub-subsystem shall transmit data to the C&DH subsystem at a rate of TBD Hz (verified by ground testing)
Rationale: this ensures the C&DH subsystem receives enough data to send back to Earth

CL.DP.P.02 The local data processing sub-subsystem shall keep a log of how much the system has moved (verified by ground testing)
Rationale: this information is required to help the N&C subsystem navigate the MSS

2.6 N&C Subsystem Requirements

This subsystem is responsible for guiding the MSS to different traverse sites and landing site.

2.6.1 Functional Requirements

NC.F.01 The N&C subsystem shall be capable of receiving commands from C&DH subsystem for navigating the MSS (verified by ground testing)
Rationale: The C&DH will be controlling the subsystem.

NC.F.02 The N&C subsystem shall send feedback from camera sensors and the inertial measurement unit to the C&DH subsystem (verified by ground testing)

Rationale: The feedback is necessary to ensure the success/failure of the operation.

NC.F.03 The N&C subsystem shall be capable of detecting the hazards while in operation (verified by ground testing)
Rationale: The subsystem will have to send necessary data (from sensors or cameras) to C&DH subsystem in order to determine the hazards on the way, and navigate or terminate navigation of the MSS accordingly.

NC.F.04 The N&C subsystem shall be able to perform path planning based on commands received from the C&DH subsystem (verified by ground testing)
Rationale: This is one of the basic functions of a navigation subsystem

2.6.2 Performance Requirements

NC.P.01 The N&C subsystem shall send feedback to C&DH subsystem at a minimum rate of TBD kbps (verified by ground testing)
Rationale: To ensure the accuracy of operation is within an acceptable range.

NC.P.02 The N&C subsystem shall navigate the MSS within TBD% accuracy (verified by ground testing)
Rationale: To ensure that the system reaches the traverse site within an acceptable radius, and uses the optimal path to save time and power.

NC.P.03 The N&C subsystem shall scan for the hazards with a minimum period of TBD s (verified by design)
Rationale: To ensure the obstacles are determined within an acceptable time, to give the MSS enough time to overcome it. Very frequent scans can lead to high power usage.

NC.P.04 The N&C subsystem shall have maximum latency of TBD s (verified by design)
Rationale: To ensure the MSS is reacting fast enough to the commands.

2.6.3 Sub-subsystem Requirements

2.6.3.1 Camera Requirements

NC.C.F.01 The cameras shall send images and video captures to the local data processing sub-subsystem (verified by ground testing)
Rationale: this data allows the system to navigate to different sites of interest

NC.C.P.01 The cameras shall send data to the local data processing sub-subsystem at a rate of TBD Hz (verified by ground testing)
Rationale: this ensures enough data is collected to be sent to Earth

2.6.3.2 Local Data Processing Requirements

NC.DP.F.01 The local data processing sub-subsystem shall send data to the C&DH subsystem (verified by ground testing)
Rationale: required for operation

NC.DP.F.02 The local data processing sub-subsystem shall receive data from the C&DH subsystem (verified by ground testing)
Rationale: required for operation

NC.DP.F.03 The local data processing sub-subsystem shall send commands to other sub-subsystems of the N&C subsystem (verified by ground testing)
Rationale: required for operation

NC.DP.P.01 The local data processing sub-subsystem shall transmit data to the C&DH subsystem at a rate of TBD Hz (verified by ground testing)
Rationale: this ensures the C&DH subsystem receives enough data to send back to Earth

2.7 Communication Subsystem Requirements

This subsystem handles all communications required in the operation, which includes communication with the orbiter and the Earth.

2.7.1 Functional Requirements

CM.F.01 The communication subsystem shall be able to receive commands from the C&DH subsystem (verified by ground testing)
Rationale: The C&DH will be controlling the subsystem.

CM.F.02 The communication subsystem shall be able to send data to the C&DH subsystem (verified by ground testing)
Rationale: The commands from orbiter need to be transmitted to C&DH.

CM.F.03 The communication subsystem shall be able to receive data/commands sent from the orbiter (verified by simulations)
Rationale: The communication subsystem needs to communicate with the orbiter to receive commands.

CM.F.04 The communication subsystem shall be able to send data/mission status to the orbiter (verified by simulations)
Rationale: The communication subsystem needs to communicate with the orbiter to send commands, scientific data and mission report.

CM.F.05 The communication subsystem shall be able to receive commands sent from the Earth (verified by simulations)
Rationale: The communication subsystem needs to communicate with the Earth to receive commands.

CM.F.06 The communication subsystem shall be able to send mission status to the Earth, if requested (verified by simulations)

Rationale: The communication subsystem needs to communicate with the Earth for mission report, if it receives such commands from the orbiter or the Earth.

CM.F.07 The communication subsystem shall have an IDLE mode during EDL (verified by ground testing)
Rationale: The subsystem needs to be ready for operation on Mars.

CM.F.08 The communication subsystem shall have an energy saving mode (verified by design)
Rationale: If the MSS runs low on power, the subsystem will need to go to energy saving mode to make sure that the thermal control and C&DH subsystems can be operational, which can be achieved by minimizing data transfer between the MSS and the orbiter.

CM.F.09 The communication subsystem shall have an emergency mode (verified by design)
Rationale: In case of emergency, the communication system needs to send SOS signal to the orbiter and the Earth
.
CM.F.10 The communication subsystem shall have redundant methods of communicating (Verified by design)
Rationale: To reduce system risk, the MSS should have multiple antennas.

2.7.2 Performance Requirements

CM.P.01 The communication subsystem shall be able to transfer data to the orbiter with a minimum speed of TBD kbps (TBC) (verified by ground testing)
Rationale: the communication subsystem must be able to establish an effective communication link with the orbiter, thus a minimum data transfer speed is necessary to make sure this will be achieved

CM.P.02 The communication subsystem shall be able to receive commands from the orbiter with a minimum speed of TBD kbps (TBC) (verified by ground testing)
Rationale: the communication subsystem must be able to establish an effective communication link with the orbiter, thus a minimum data receiving speed is necessary to make sure this will be achieved

CM.P.03 The communication subsystem shall be able to receive commands from ground control with a minimum speed of TBD kbps (TBC) (verified by ground testing)
Rationale: the communication subsystem must be able to establish an effective communication link with the Deep Space Network

2.7.3 Sub-subsystem Requirements

2.7.3.1 Local Data Processing Requirements

CM.DP.F.01 The local data processing sub-subsystem send data to the C&DH subsystem (verified by ground testing)
Rationale: required for operation

CM.DP.F.02 The local data processing sub-subsystem shall receive data from the C&DH subsystem (verified by ground testing)
Rationale: required for operation

CM.DP.F.03 The local data processing sub-subsystem shall send commands to other sub-subsystems of the communication subsystem (verified by ground testing)
Rationale: required for operation

CM.DP.P.01 The local data processing sub-subsystem shall transmit data to the C&DH subsystem at a rate of TBD Hz (verified by ground testing)
Rationale: this ensures the C&DH subsystem receives enough data to send back to Earth

3 Trade Studies

This section discusses trade studies for controls components of the robotic system, which include type of processor, level of autonomy and computer architecture. For each, different options are compared against each other and the final design choice is highlighted.

3.1 Level of Autonomy

Deciding the level of autonomy is a crucial part in the design of the robotic system. This determines the amount of work that the system will perform on its own versus the amount of work that needs to be done by ground station on Earth. There are three levels of autonomy, non-autonomous, semi-autonomous and fully-autonomous. Non-autonomous systems rely completely on human inputs from ground station, semi-autonomous systems can perform some tasks autonomously using predefined algorithms, which are typically simpler tasks, while more complex tasks are done based on human inputs, and fully-autonomous systems perform every task without human interference. Table 2 below compares the three levels of autonomy.

	Non-autonomous	Semi-autonomous	Fully-autonomous
Complexity	Low	Medium	High
Human Workload	Requires monitoring and control from ground station for all operations	Only requires interference from ground station for more complex tasks	Does not require any commands from ground station
Operational Time	Long	Medium	Short
Operational Risks	Mainly subjected to human errors	Risk from hardware and software malfunctions/failure	Risk from hardware and software malfunctions/failure

		as well as human errors	

Table 37 Comparison of levels of autonomy

System complexity: as non-autonomous systems perform solely from human inputs, they do not require complex hardware and software to operate. On the other hand, semi-autonomous systems require pre-programmed algorithms to perform simple tasks automatically, which requires higher computational ability. As a result, fully-autonomous systems will be even more complex, as all operations must be performed autonomously, requiring higher computational ability, more data storage and advanced software.

Human workload: it can be expected that non-autonomous systems require a high amount of work to be done by scientists and engineers on Earth, while for semi-autonomous systems, only complex tasks must require control from Earth. Fully-autonomous systems only need to be monitored from ground station, however operations do not need to be controlled.

Operational time: one of the challenges that comes with controlling the robotic system from ground station is the time delay, which is about 20 minutes on average [118]. In case of an emergency, such as when the robotic system encounters an obstacle on the road, a non-autonomous system must wait for communication from Earth before it can proceed. For a semi-autonomous system, the time required to complete a task depends on whether that task is done autonomously, in which case the time required is subjected to the speed of the processor and computational algorithms, or if it requires human inputs. A fully-autonomous system is only subjected to the speed of the processor and the computational algorithms.

Operational risks: non-autonomous systems are subjected to risks due to human errors, which are typically low-level compared to risks experienced by semi-autonomous and fully-autonomous systems. If there is a hardware malfunction/failure (when the processor stops working for example), or if the robotic system encounters a situation that has not been accounted for within the software, it will not be able to proceed. However, these risks can be mitigated by having hardware and software redundancies.

The sub-section below discusses the level of autonomy that should be used in each subsystem.

3.1.1 Power Subsystem

The power subsystem has to be completely autonomous, as this is the main subsystem which keeps the MSS alive. Having a non-autonomous power subsystem would not be feasible in this mission, due to the delay between the commands sent from the Earth to the MSS or orbiter.

3.1.2 N&C Subsystem

The navigation and control subsystem is semi-autonomous. For each location sent from operations, it is received from the communications subsystem which is relayed to the central C&DH and then to the N&C subsystem. The N&C subsystem will try to autonomously direct the system to move towards the given location. The task will either be completed or failed. In the case of detecting a hazard, the system will abort the command and measure whatever position and orientation it is at and send it to C&DH to be sent back to earth.

3.1.3 Communications Subsystem

The main function of the communication subsystem is to transmit and receive data/command to and from Earth using three antennas, the High Gain Antenna (HGA), Low Gain Antenna (LGA) and Ultra High Frequency Antenna (UHF). The LGA and UHF antennas are omnidirectional and require no steering, thus the only control that needs to be implemented is when to activate each one, which can be done using a preset program. As well, positioning the HGA antenna can be done using a predetermined procedure and the sun as reference [119]. Thus the communication subsystem will be fully autonomous.

3.1.4 C&L Subsystem

The Chassis and Locomotion subsystem will be completely autonomous considering about the time delay of transmission of data. It is quite time-consuming even if it is semi-autonomous, since it takes around 20 minutes for communication with Earth. The rover should be able to deal with upcoming hazards itself, since the rover only communicates with the Earth three times per day, which is infeasible to solve hazards manually in a timely manner.

3.1.5 Thermal Control Subsystem

The thermal control subsystem will be completely autonomous, since all temperature readings will be automatically fed to C&DH during operation in order to properly regulate system temperatures. Thermal diagnosis will be pre-scripted and loaded to C&DH prior to mission and will also be completely autonomous.

3.1.6 Science Subsystem

The science subsystem shall accommodate both autonomous and human-in-the-loop control. Since there are limited windows available for communication to Earth and the communication delay between Earth and Mars, autonomy is necessary to gather science data. Elements of human-in-the-loop control can be implemented via the camera system within the science subsystem to provide potential sites of interest for the rover to examine. Autonomous control is necessary to correct the pointing accuracy of the manipulator arm and to save spectroscopy emission data to the C&DH for transmission back to Earth.

3.2 Computer Architecture

There are three types of computing architectures to consider for the MSS: centralized, semi-distributed and distributed computing. Table 3 below compares characteristics of these three computer architectures.

	Centralized	Semi-distributed	Fully-distributed
System Reliability	Low, one crash may lead to whole system failure.	Medium, some problems will influence part of the system.	High, each part is highly independent of each other. Failure will not be spread or inhere.
System Complexity	Easy to implement, High Computational Cost, Low mechanical complexity, since everything at single location	Medium complexity for both implementation, computational cost, and mechanical	Simpler computation process, High mechanical complexity
Communication Delay	High Delay, local computation is prohibited, data transmission may take long time	Medium, some local computing are supported, while others need data transmission	Delay free for locally transmission
System Mass	Low, since only one central controller	Medium, the number of controllers required is less than fully-distributed computing	High, multiple controllers are required

Table 38 Comparison of computer architecture

Centralized computing is the most common computing architecture due to its simplicity and relative ease of programming, testing and debugging. The main drawback of centralized computing is that fault tolerance is low, since all computing is done in one location. One crash may lead to failure of the whole system [120]; however this can be mitigated by using parallel channels. Another ineligible weakness is the time cost during data transmission. Centralized computing prohibits local computation and analysis, all data must be transmitted to the CPU. Semi-distributed computing has increased fault tolerance over centralized computing and allows time critical functions to be off-loaded to micro-controllers governing a particular sub-system. The main tradeoffs compared to a centralized architecture is increased design complexity and the need for additional requirements for each subsystem as well as a larger subsystem mass. [120] In addition, since the main CPU must communicate with multiple different processing units in each subsystem, there is increased communication time between subsystems which may counteract the time gained by task division. Distributed computing is the computing architecture with the highest complexity. The key difference between a semi-distributed architecture and a distributed architecture is that there is no master processing unit in the system; each processing unit is connected in a network, which results in increased fault tolerance. A distributed computing architecture requires increased coordination between each computing element in the network, which contributes to the overall complexity of the system.

In conclusion, the preferred architecture is a semi-distributed architecture, due to its increased fault tolerance over a centralized system, and reduced complexity compared to a fully-distributed system. This increase in fault tolerance outweighs the increased complexity of the system (compared to a centralized system), since a master-slave architecture can be used to reduce computational load on the C&DH subsystem by relegating specific tasks to micro-controllers in each subsystem. [121] Further computing architecture analysis will be conducted during the control phase of the design.

3.3 Redundancy

Redundancy in the system is essential as it is impossible to send personnel to the device for repairs if a system malfunctions. Since ensuring continuous operation of the system despite a minor failure is important, we must discuss the different types of redundancies and how they may impact the entire device.

	Hardware Redundancies	Software Redundancies
Mass	Greater mass due to more equipment added to the device [122]	Does not add more weight to the device
Power Consumption	More power required to run additional equipment. However, backup equipment not required to be powered on but preferred to compare results. [122]	Less equipment to power but more power is required
Reliability	Cannot detect faults in software [123]	Can detect most faults in software and hardware.
Complexity	Requires double or triple the equipment needed.	Requires more complexity in software to process and identify errors.

Table 39 Comparison of types of redundancy

The system should not rely on only hardware redundancy or only software redundancy but a combination of the two types of redundancies. Further redundancies of each subsystem will be shown later in Section 4.

An example of hardware redundancy would be to implement a standby system of a specific subsystem. A choice of keeping the system active to become a dual modular redundancy would assist in detecting preliminary failures of hardware and immediately turning a subsystem onto maintenance mode. However, if the power budget cannot afford to power the redundant hardware, a cold standby system can be used as a redundancy system.

As for software redundancy, the Triple Modular Redundant system runs on three separate codes that are ideally developed by three different teams for each type of operation. The codes are to run parallel, and the output from the code is only accepted if at least two of the codes give identical input. If there is a discrepancy, the third code is taken in and the majority vote becomes the output. [124] If all three codes produce different output, the output is rejected and the subsystem is switched into standby state to prevent damage. It is important to have three different types of code as the system can continue to operate even if one of the software system fails, the majority vote can determine what is the appropriate output. This system is implemented into modern airliner aircraft for redundancy.

4 Architecture

4.1 Legend

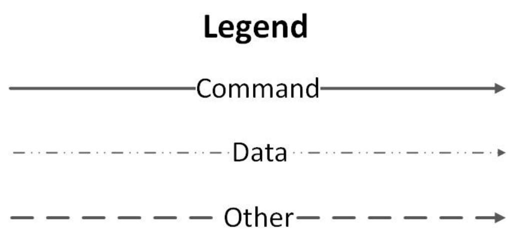

Table 40 Legend

4.2 Science Subsystem

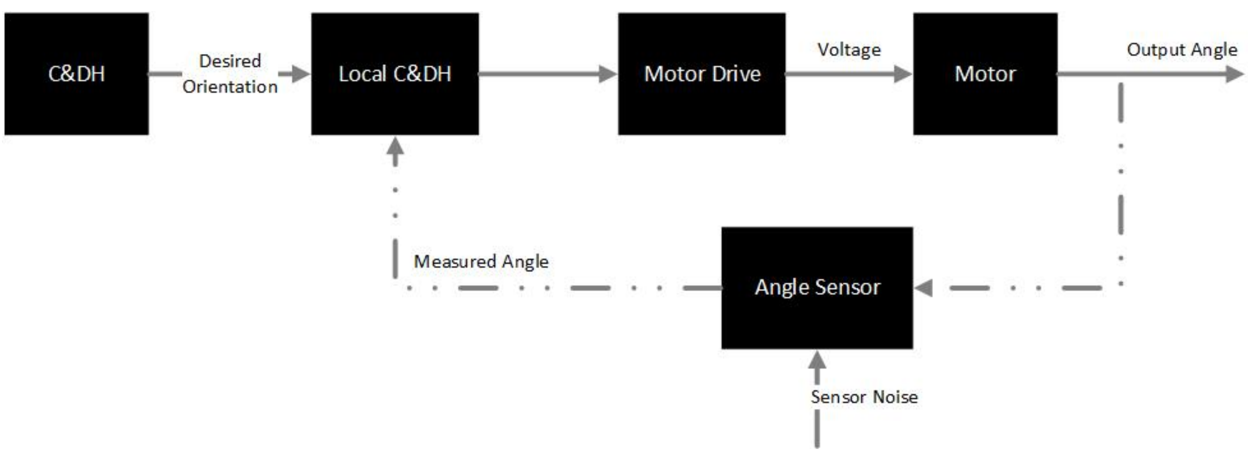

Table 41 Arm

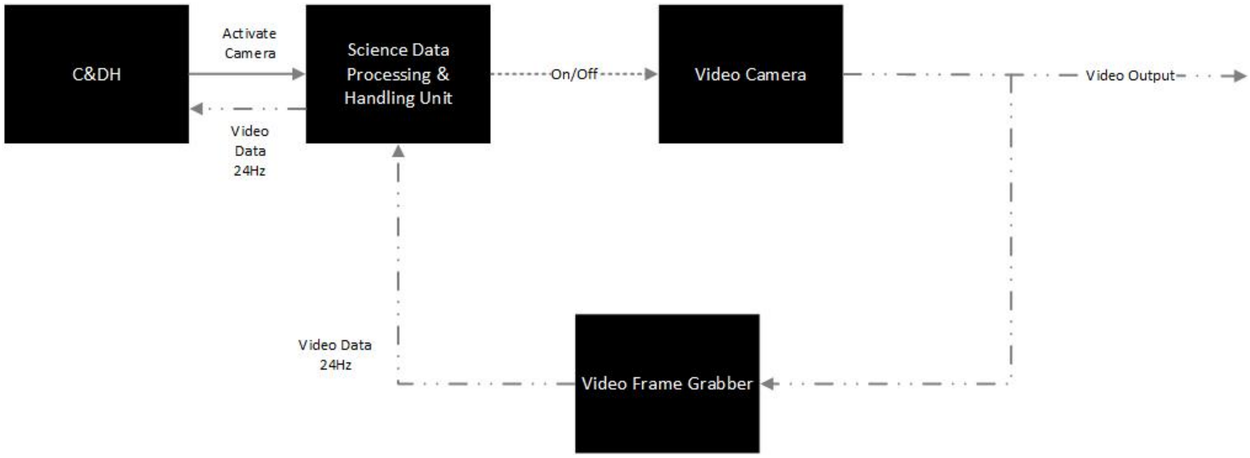

Table 42 Camera

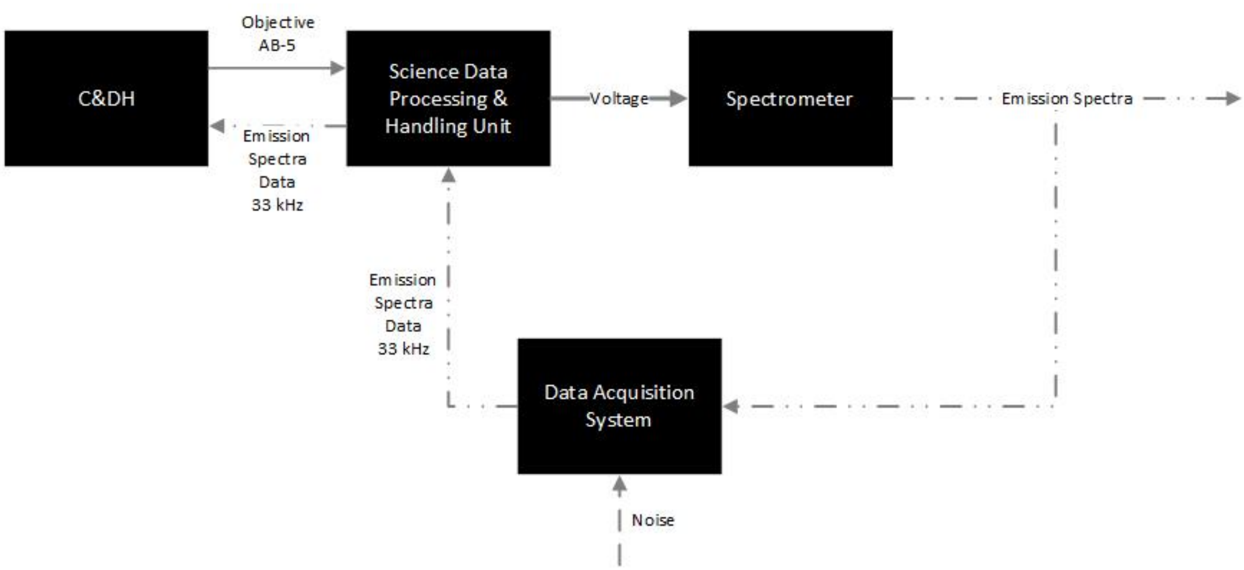

Table 43 Spectrometer

4.3 Communication Subsystem

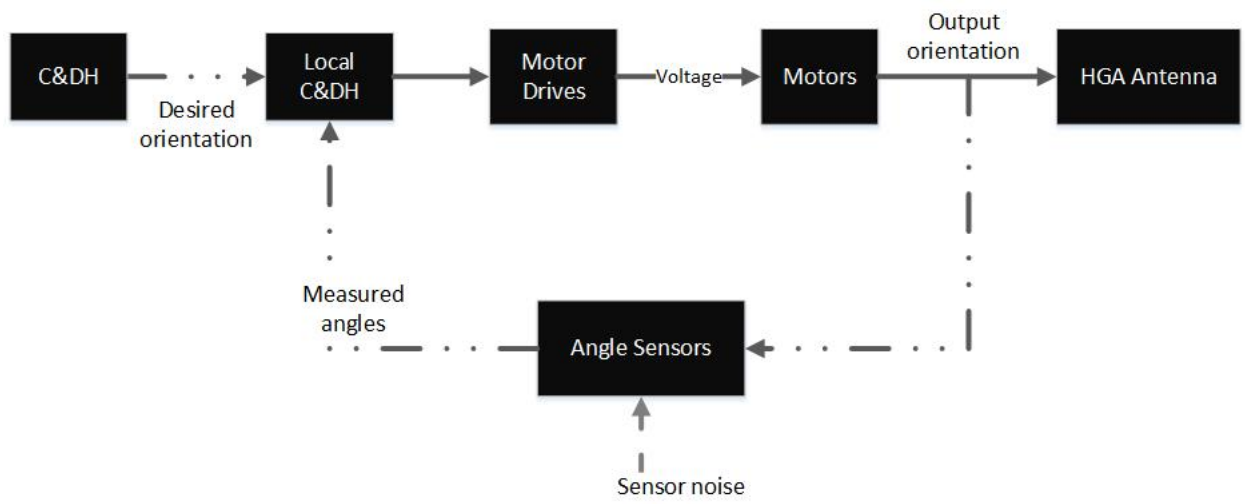

Figure 28 HGA Antenna

4.4 Locomotion Subsystem

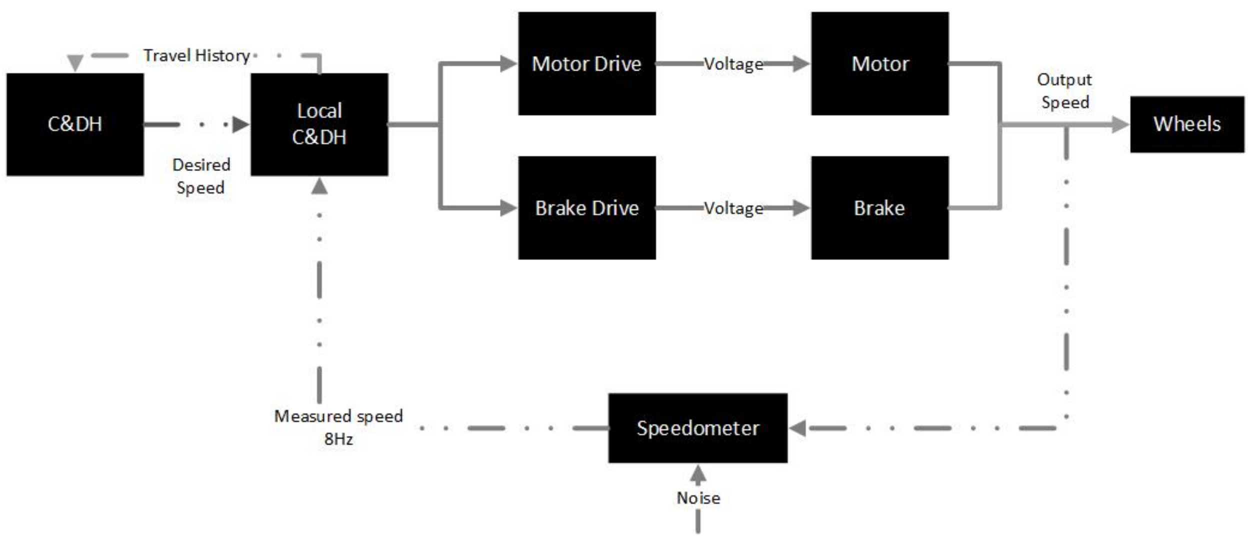

Figure 29 Locomotion

4.5 Thermal Control Subsystem

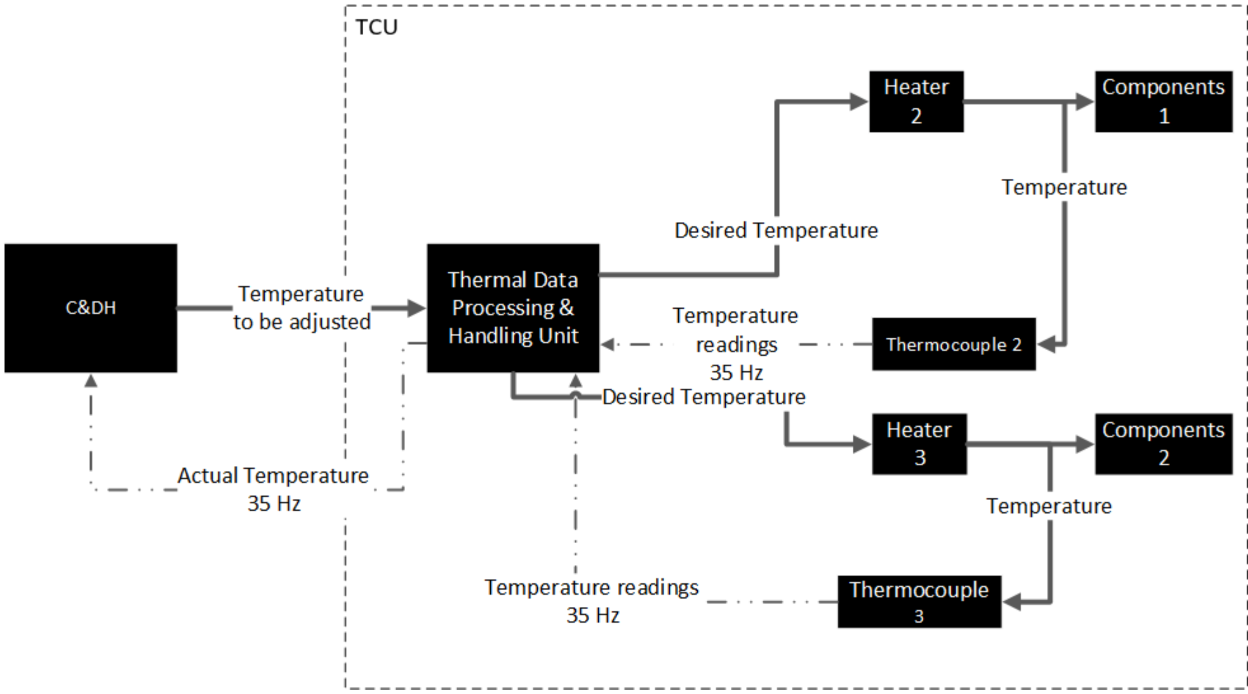

Figure 30 Thermal Control

4.6 Navigation Subsystem

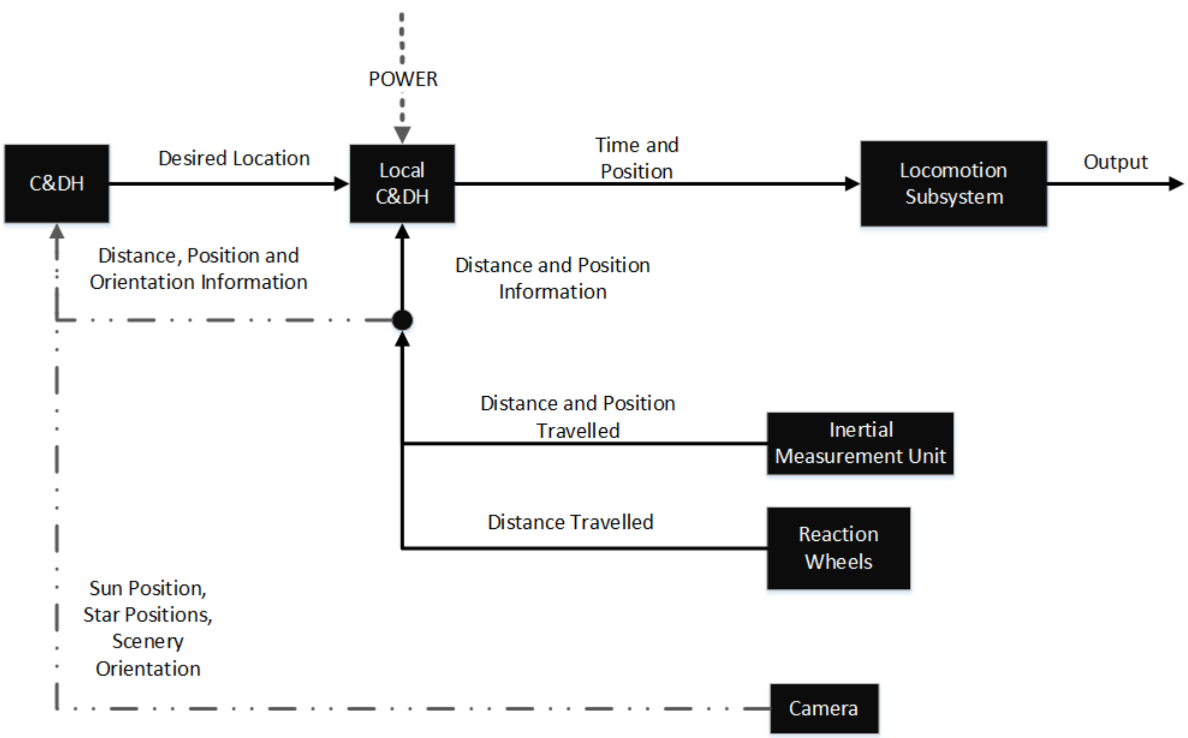

Figure 31 Navigation

4.7 Power Subsystem

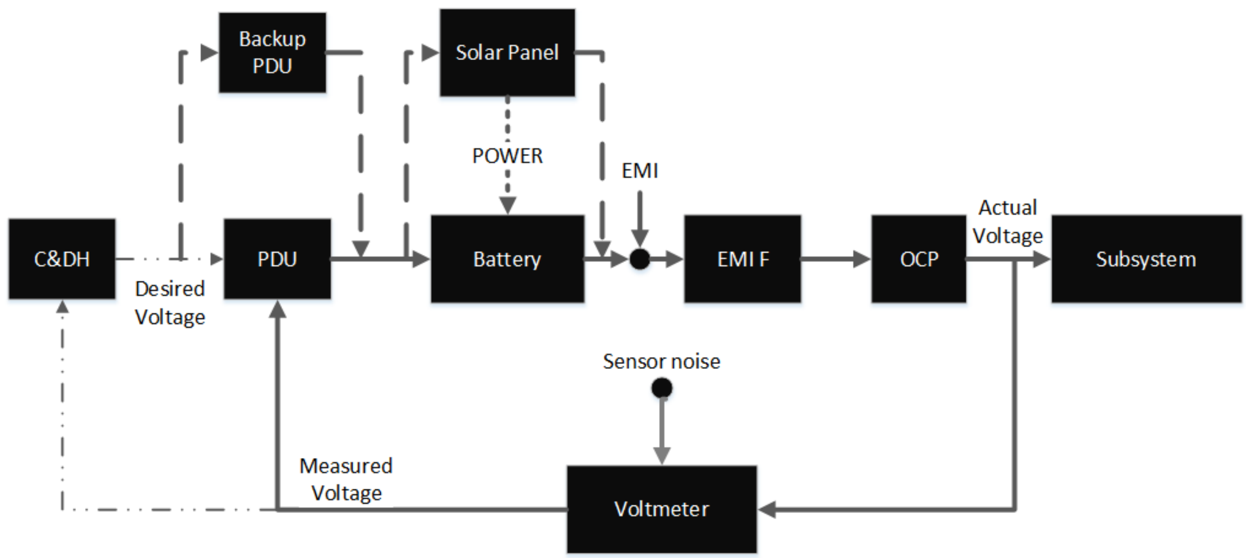

Figure 32 Power

4.8 C&DH Subsystem

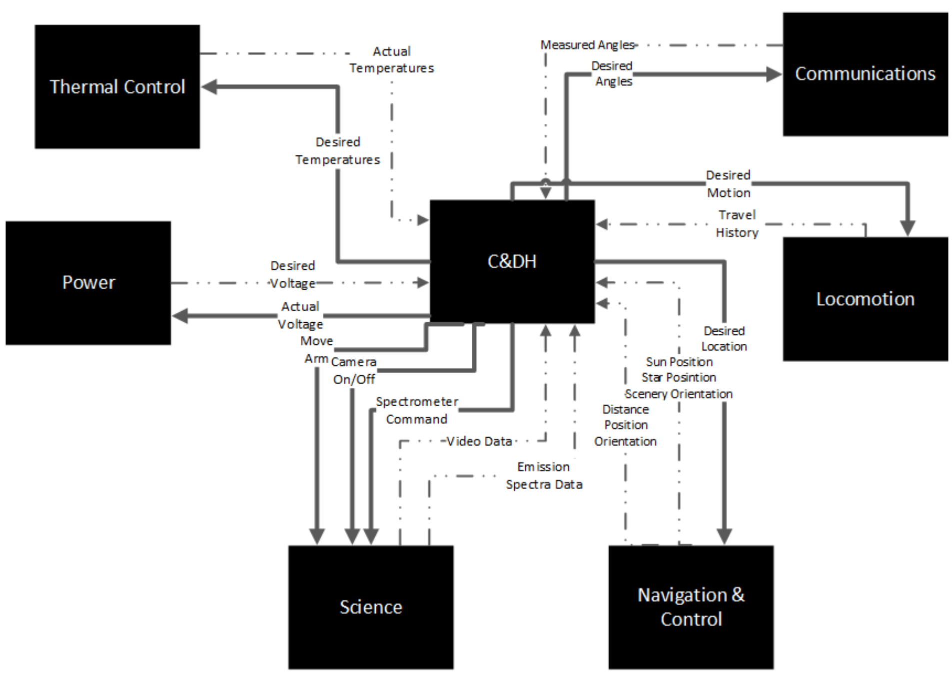

Figure 33 Command and Data Handling

5 Feedback Loops

Subsystem	Feedback loop	Description
Power	Power Distribution	The Power Distribution Unit gets required voltage from C&DH. Then the required voltage is requested from the battery. The OCP regulates this voltage for safety, which is supplied to the appropriate subsystem. We have a backup PDU, and solar panels can be directly used for power supply. The actual voltage is fed back to the PDU and C&DH. Timescale: 70 Hz
Thermal Control	Temperature Control	The real time temperature readings generated from system components and measured by thermocouples, are taken as inputs. These inputs are fed into thermal control data processing unit as well as C&DH processing unit for analysis in order to determine if the current temperature is appropriate for operation and how the heater should adjust the temperature. Timescale: 35 Hz
Communication	HGA Positioning	The difference between the desired HGA orientation and that measured by torque and angle sensors is taken as input. This input is fed to the C&DH subsystem, which determines whether the difference is within a tolerable range, and if not what actions must be taken in order to correct the orientation of the HGA. Timescale: 1000Hz
Science	Manipulator Arm Control	Measures the difference between the desired input direction and the actual angular displacement of the arm to correct the pointing accuracy of the arm. Timescale: 300Hz
Science	Video Feedback	The video frame grabber feeds back the video data output by the camera back to the local data processing unit of the Science subsystem. This video feedback is used to either send scientific data related to the mineralogy of the Martian surface (PG-M-2) or to search for potential sites of interest within the traverse site. Timescale: 24 Hz

Science	Spectroscopy Data Loop	The emission spectra data obtained from the spectroscopy experiments performed by the rover is fed back to the C&DH to save and later send back to Earth via the communication subsystem. Timescale: 33 kHz
Navigation	Position Control	The difference between the desired position sent to the Navigational subsystem and the position measured from the cameras (solar positioning, star positioning and scenery reference) along with reaction wheels and inertial measurement system. Timescale: 24 Hz
Locomotion	Wheel velocity manipulation	The difference between the desired speed of wheels and the actual speed will be fed into the feedback loop as input. Data handling subsystem calculates the desired velocity, and returns the output as voltage to resolvers and brakes in locomotion subsystem, as well as dealing with encountering unexpected hazards. Timescale: 300 Hz

Table 44 Subsystem feedback loops

6 Detailed Design

6.1 Compute Element Design

The choice of processor is very important as the processor acts as the brain of the robotic subsystem, by processing and storing data, sending commands to each subsystem and performing calculations. Due to harsh weather conditions on Mars, the processor needs to be designed such that it can fulfill temperature, environmental and power consumption requirements. Two microprocessors are considered, the RAD6000 and RAD750. These are radiation-hardened microprocessors designed specifically for space missions, and have been used in previous Mars missions, such as Spirit and Opportunity rovers (RAD6000) [125] and Opportunity rover (RAD750) [126]. Specifications of both microprocessors are outlined in Table 6 below.

	RAD6000	**RAD750**
Power Consumption	5W to 20W [127]	**5W [128]**
Temperature Range	-25°C to 105°C [127]	**-55°C to 125°C [129]**
Radiation Level	2 Mrad [130]	**1 Mrad [129]**
Speed	20 MHz [127]	**200 MHz [129]**
Throughput	35 MIPS [128]	**240 MIPS to 300 MIPS [128]**

Memory	128 MB RAM [125]	**256 MB RAM [126]**
Storage	256 MB [125]	**2 GB [126]**
Dimensions	145 mm x 145 mm [128]	**130 mm x 130 mm [128]**
Mass	< 1.2kg [127]	**9.0g [131]**

Table 45 Comparison of RAD6000 and RAD750 processors

As shown on the comparison above, both processors satisfy the power consumption requirements, which is very important as available power is very limited in space. The RAD750, however, displays more favourable characteristics compared to the RAD6000, such as a larger temperature range, higher operating speed, higher throughput, more storage and memory as well as having smaller dimensions. As a result, the RAD750 is the recommended processor for the C&DH subsystem.

6.2 Feedback Loop

An important feedback loop in our device is from the Science Subsystem's Joint Angle Resolver feedback. In this subsystem, a motor is controlled by an input voltage. The motor delivers torque and motion through a gearbox which generates a joint angle speed. The joint angle speed is measured in the joint angle resolver feedback and sent back into the system.

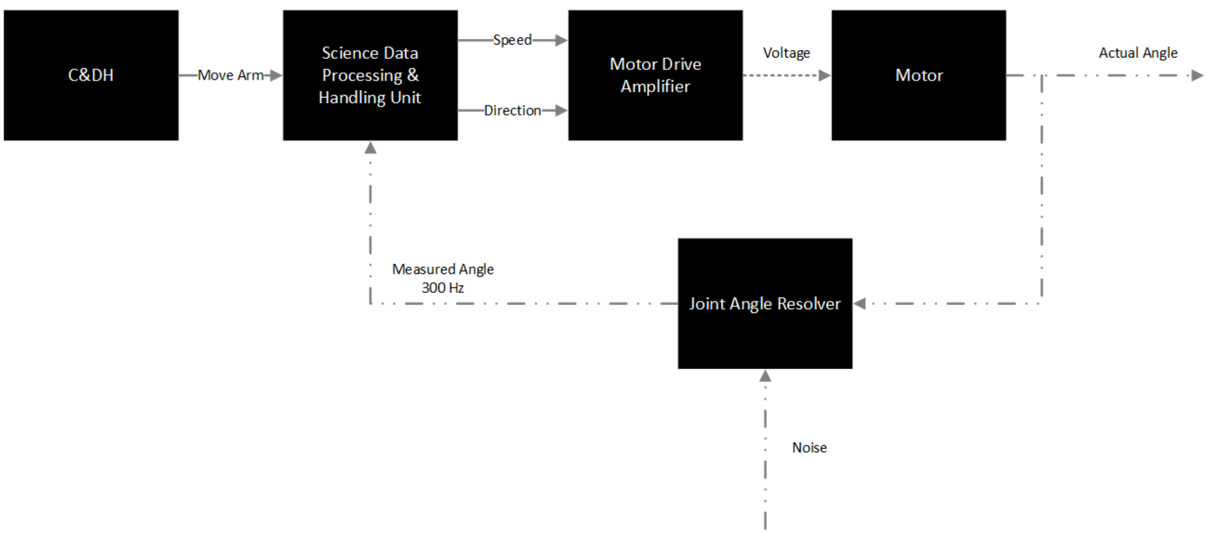

Figure 34 Typical feedback loop

The motor used is a brushless DC motor. The motor may be modeled by the following equations.

$$u(t) = Ri(t) + L\frac{di}{dt} + K_e\omega$$
$$\tau(t) = K_t i(t) = J\dot{\omega}(t) + D\omega(t)$$
$$\omega(t) = \dot{\theta}(t)$$

Here, u is the input voltage, R is the motor resistance, L is the motor inductance, i is the current, K_e is the electromotive force constant, τ is the torque, K_t is the motor torque constant, J is the moment of inertia for payload with respect to the motor, D is the friction constant, ω is the angular velocity and θ is the motor output angle. We calculate the joint angle speed by comparing the motor angular velocity with the gearbox ratio.

We take the Laplace transform to obtain the transfer function *G(s):*

$$G(s) = \frac{\Omega(s)}{U(s)} = \frac{K_t}{JLs^2 + (DL + RJ)s + RD + K_t K_e}$$

We employ a proportional-integral-derivative (hereafter PID) controller to be used for the feedback loop. The transfer function *H(s)* of the controller is:

$$H(s) = K_P + K_i \frac{1}{s} + K_d s$$

Here, K_P, K_i, K_d are the proportional, integral and derivative constant respectively.

We have the sensitivity function for the feedback loop:

$$S(s) = \frac{1}{1 + G(s) + H(s)}$$

We set an overshoot tolerance of less than 1% and zero steady-state error. The overshoot tolerance is given:

$$S(s) = \frac{s}{\omega_{BW}}$$

Here, ω_{BW} is the bandwidth parameter.

The zero steady-state error is given:

$$\lim_{n\to\infty} e_s s(t) = \lim_{n\to\infty} sS(s)\frac{1}{s} = S(0) = 0$$

In order to intake good data from the sensor, we choose a sensor sampling rate of

$$\omega_s = 10\times\omega_{BW}$$

We therefore choose the gain values by the following formulae:

$$K_P = \frac{\omega_{BW}(LD + RJ)}{K_t}$$

$$K_P = \frac{\omega_{BW}(RD + K_e K_t)}{K_t}$$

$$K_d = \omega_{BW}\frac{JL}{K_t}$$

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Appendix 1

Maximum data transmission per day would be 15minutes * 60sec * 3 times/day * 8kb/s = 21MBs. Maximum available data for downlink to Earth is 2MB per sol. Our team aims to use at least 25% of this limit for every sol.

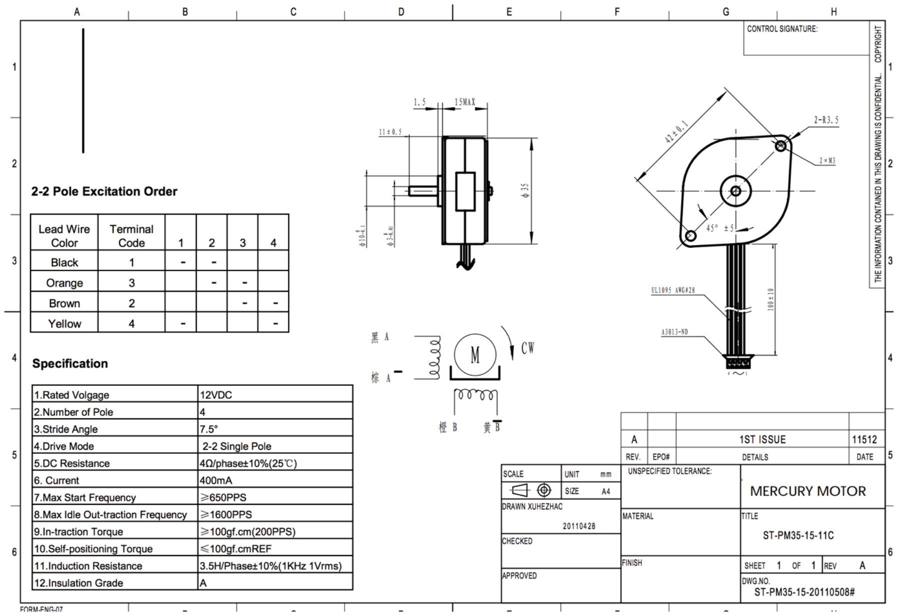
Appendix 2

Out of all active Mars orbiters, the one with the greatest distance from Mars is the Mangalyaan orbiter, with an apogee of 77 000 km [11] [12]

Appendix 3 – Thermal Requirement Table

Subsystem	Survival Temperature Range	Operational Temperature Range
Chassis & Locomotion	-128° C to 50° C	-65° C to 50° C
C&DH	-40° C to 40° C [49]	-40° C to 40° C [49]
Communication	-40° C to 70° C [50]	-25°C to 60°C [50]
Science	-128° C to 50° C	-65° C to 50° C
Power	-20° C to 60° C [51]	0° C to 45° C [51]
N&C	-128° C to 50° C [52]	-65° C to 40° C [52]

Appendix 4 – Motor Datasheet



Appendix 5 – Timescales

Feedback Loop	Timescale	Rationale
Power Distribution	70Hz	From Electrical report, the average power consumption of the system is around 200W. This corresponds to 70Hz frequency in a similar transformer. [132]
Thermal Control	35Hz	Value taken reference [133]
Science, Manipulator Arm	300Hz	Timescale used in the arm joint resolvers on NLR's European Robotic Arm [134].
Science, Camera	24Hz	The typical timescale of a 24 FPS video camera [135].
Science, Spectroscopy	33 kHz	Value taken from Adron Systems LLC for the sampling rate of a typical mass spectrometer data acquisition unit [136].
Navigational Control	24 Hz	Value taken from timescale of a typical video [135].
C&L	300 Hz	Value taken from timescale of a reference robot [137]
Communication	1000 Hz	This is taken from the response frequency of a typical force sensor [138]