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DESIGN OF A MARS ROVER MOBILITY SYSTEM

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Future space exploration requires close study of extraterrestrial bodies such as Mars. The Mars micro-rover proposal was configured to closely meet the requirements of scientists and budget criteria. Due to the hostility of the Martian environment a reliable mobility system must be integrated to the rover concept. This project demonstrates the feasibility of such a design drawing on current data. The design was governed by the operational lifespan of the vehicle, a period of one Martian year at latitude of 30 degrees. The project provides a step-by-step simulation of the rover's mobility system design. Furthermore the design provides and integrates all vital sub-systems required for successful operation of the Mars rover. A primary consideration during the design process of the rover was ease of integration with an array of different payloads. Potential payloads are constrained by the mass of 1067 g., space availability of 110 by 100 by 45 mm and the availability of power 85.4 W. Although only a conceptual design, this report summarises of all required design parameters for future rover development.

1. INTRODUCTION

Today Mars exploration is one of the most popular areas of research. Different methodologies are implemented accordingly to various mission requirements. Observation satellite use can give wide area cover, while surface landing probes give accurate details. Mobile vehicles allow achieving both, however at a cost to pay. The mission that involves mobile rover is extremely costly and requires high reliability.

The use of small size rovers will allow minimising expenditure on a project. The design of the multi-purpose rover with possibility to use different payloads will give higher mission safety. This will be achieved by utilisation of the same structure bus.

1.1 Report Description

This report and the project itself are focused to give summary of the information required in the design process using the developed concept example.

This project will present preliminary studies for the conceptual design of Mars micro rover mobility system. Furthermore, it will summarise the steps required for the rover sub-system architecture. It is proposed that the successful mobility system is the rover design with all required sub-systems to enable onboard payload to operate safely. The report also gives description of the design process itself and aims to be a guide for a future research work.

1.2 Project Background and Description

In general the report will present micro rover design as the answer to the Mars mobility system design problem. The decision was made to concentrate on overall rover design as autonomous mobility system. The size of the rover as the micro-rover was selected to achieve low mass and low power requirement but still be capable of performing wide range of experiments.

The review of the literature available on the rover design brought to attention that information is highly divided. Author, here will try to summarise it and present stepped design process.

2. REQUIREMETS AND CONSTRAINS

The first stage of any design process is to clearly define the requirements and constrains of the project. This will give the description and will limit the design process. The design is influenced by the choice made over different possibilities. This can lead that in some cases one of the design considerations will be preferable than the other, as the requirements are much easier to be achieved. The requirements influence coefficient was used to identify better solution within proposed ones.

2.1 Requirements

All requirements for any extraterrestrial rover design can be divided into following categorise depending of its nature:

- Functional and operational requirements
- Environment related requirements
- Vehicle configuration requirements
- Delivery related requirements
- Sub-system related requirements

2.1.1 Functional and operational requirements

- The rover should operate one Martian year
- The operation is limited to latitude of 30 degrees
- The rover design should be simplified to allow high factor of safety
- The rover should operate on the slopes of 20 degrees

- The step climbing capability of the rover should allow it to pass rocks with height of 1.5 of wheel diameter

2.1.2 Environment related requirements

The rover should operate at (Rossi, 2010):

- Temperature range from 170 – 300 K
- Pressure range from 6.9 – 14 mbar
- Radiation wavelength range from 190 – 400 nm
- The solar flux range from 493 – 718 W/m^2
- Gravitational acceleration of 3.7 m/s^2

2.1.3 Vehicle configuration requirements

Those requirements usually are assigned by the payload size and its operational requirements. As the decision was to create multi-purpose rover this is no longer possible. In this case the size and mass requirements were determined by the general estimate but in the range of the micro-rover (Patel, 2008).

- The rover mass should be limited by 20 kg
- The ground clearance should be at least 20 cm
- The rover should be capable to turn around with zero radius

2.1.4 Delivery related requirements

- Launch vibrations are assumed to have range between 5 – 200 Hz (Caimi, 1990)
- The maximum acceleration at the launch and landing taken as 41g's (Darlene, 2003)

2.1.5 Sub-system related requirements

- Power should be generated using the solar panels and be stored in the batteries
- On-board computer should have multi-tasking and the emergency control reset capability
- Communication with Earth should be achieved using relay satellite but still possible to be communicated using straight link
- All sub-systems should be protected from the radioactive environment
- Payload instrumentation mass to be 800 grams

2.2 Constrains

Project constrains are as following:

- Mars environment
- Rover delivery
- Rover life time
- Project cost
- Payload requirements
- Telecommunication requirements

2.3 Requirement Influence Coefficient

It is important to analyse the effectiveness of the chosen design over the requirements that are implemented over the project.

Three terms should be implemented:

1. Requirement influence – this is the importance of the requirement for the project; what the effect over the project will be if the requirements are not achieved
2. Requirement type – how flexible the requirement is for the design process
3. Requirement effect – what the effect has the chosen design feature over the requirements

Each requirement term in all requirement categories should be valued from one to zero (from more to less critical) assigning the requirements influence and requirement type values. This is done by the comparison of all of them to each other.

As an example: the rover operational temperature. This requirement should be definitely achieved as the out of range temperature will stop the operation of the rover. It is impossible to change the requirement. The result is that for operational temperature requirement the value of the requirement influence is 1 and the value of the requirement type is 1. The table below is a summary of all requirements multiplied within the requirements category.

Requirements category	Req. influence	Req. Type	Influence coefficient
Function./Operat	0.855	1.0	0.855
Environment rel.	1.0	1.0	1.0
Vehicle config.	0.82	0.7	0.574
Delivery related	1.0	0.5	0.5
Sub-system rel.	0.855	0.3	0.257

Table 1: Requirements influence coefficient

The design selection process requires configuration comparison. The comparison can be done using the same quantitative system (from one to zero – lower to higher affect). The designs are compared in same properties based on the information available (for example: mass, complexity, strength etc.). These properties will affect the requirements and will change the influence coefficients. The design which is more preferable can be selected by comparing achieved influence coefficient to the base value presented in the Table 1. The design is more preferable when the value is closer to the base value.

3. PROJECT PLANNING

Second stage of any project is to determine the sequence of the design process. The project was divided into following phases:

1. Research phase and design configuration selection
2. Conceptual design
3. Preliminary design
4. Detailed design
5. Reanalyses of the project

Real time design requires multiple iterations. In general term, the sub-system design becomes clearer and less estimated during the iteration process. This will require updating information that previously was assumed and make the changes to already achieved decisions. For this project of concept design was used the sub-system addition in each phase (Figure 1).

3.1 Summary of the Sub-systems Required

The sub-systems that are usually required for the rover design are:

- Locomotive sub-system
- Structure sub-system
- Navigation sub-system
- Data-handling sub-system
- Electrical sub-system
- Power sub-system
- Thermal sub-system
- Telecommunication sub-system
- Payload sub-system

Based on the required sub-systems was chosen iteration process. It implies the increase of the sub-systems in overall design:

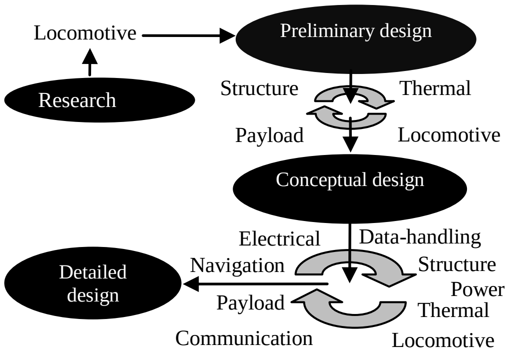


Figure 1: Iteration process (Adopted from: Griffin and French, 2004) (1. research, 2. preliminary design, 3. conceptual design and 4. detailed design)

4. PROJECT REQUIRED INFORMATION

The topic of the project requires wide range of information to be gathered before the design phases begins. This includes the operational environment and day length calculations. Also, prior to the design process the testing environment should be prepared. For this particular design wasn't available the real model testing, so the software modelled environment was created.

4.1 Mars Conditions

Surface environment of Mars dictates constrains for the protection of the sub-systems and rover itself. The table below is the summary of the Mars environmental characteristics that critical for the design.

Characteristic	Min	Max	Effects
Pressure (mbar)	6.9	14	Degassing problems
Temperature (K)	170	300	Out of normal operational temp
Radiation (nm)	190	400	Material degradation; Electrical component malfunction
Dust particles (µm)	< 2		Mechanics Malfunction

Table 2: Summary of Mars environment

Low pressure environment can cause the operational problems of some components due to the degassing. Also, some materials are in danger as the degasification can cause the materials to become brittle.

The operational temperature of the components onboard is limited and usually in range of -20 to +60 ^{o}C (Torre, 2010). For some components like batteries it is even smaller from 0 to +30 ^{o}C (Torre, 2010). The effect of the temperature going beyond components limitations can cause malfunction or breakdown of them.

Radiation environment is not so much dramatic but it can degrade the material over the year's periods. For the design proposal that is given here it is not so crucial, as the proposed operational time is limited by one year (See 2.1.1). The radiation also can cause the malfunction of electronics in single-event effect when the semiconductors are ionised (Griffin and French, 2004).

Dust particles can cause the mechanical components to stop due to the interaction within moving parts.

4.2 Mars ground properties

The ground properties are required to determine the traction of the rover wheels. There are two main concerns. For the testing environment of the locomotive sub-system it is important to reproduce correct weight and soil characteristics. Right weight is simulated by use of reduced mass of the rover. While the soil properties are modelled using the soil stimulants (Richter, 2011), (Patel, 2010). The properties that are presented in the Table 3 will be used in the wheel design sizing (Part 5.1.2) and the simulation environment wheel-soil interaction (Part 4.2.1).

Simulant type	Cohesion, kPa	Internal friction angle, deg	Exponent of sinkage	Friction modulus, N/m^{n+2}, $(x10^3)$	Cohesive modulus, N/m^{n+1}
MER-B sandy	4.8	20	1	7.6	28000
MER-B slope	0.5	20	0.8	210	6800
DLR-A	0.19	24.8	0.63	60.3	2370
DLR-B	0.41	17.8	1.1	763.6	18773

Table 3: Mars soil and Mars soil simulant characteristics

Another important aspect of the ground property is rock distribution over the surface. This becomes highly important when the design enters the test phase. The studies of Viking Lander mission have shown (Golombek, 1997) that the rock size and distribution frequency can be described by equations:

- Rock number over are of one square meter:

$$N(D) = Le^{-sD} \quad [1]$$

- Frequency of rock distribution:

$$F(D) = Ke^{-qD} \quad [2]$$

- Height of the rock over the ground level:

$$H = tD + 0.008 \quad [3]$$

Here: D – rock diameter
L, s, K, q, t – constant factors, mission based

	for VL-1	for VL-2
L =	5.61	6.84
s =	12.05	8.30
K =	0.069	0.176
q =	4.08	2.73
t =	0.365	0.506

Based on this values and the soil property the simulation environment was created (Figure 2).

4.2.1 Testing environment design

The developed ground track contains rocky flat surface and 20 degrees slope (Figure 2). The gravity and wheels loading was adjusted based on requirements in Parts 2.1.2 and 2.1.3. The test simulations that were required to be performed (Patel, 2010) included following:

- Drive up the slope
- Driving across slope
- Driving over the rocks
- Turning capability

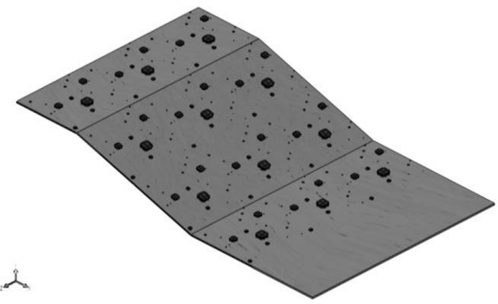


Figure 2: Simulation ground (isometric view)

Based on data the performance of the wheels was checked. The design of the rocker-bogie configuration and its sizing (given in Part 7) was analysed and selected. It was also used to find the power requirement for the wheel driving motor which was found to be 2.07 W. This was used in future power budget calculations (summary of power budget will be given in Part 5.5.1).

4.4 Day Length Calculations

This calculation was done for the rover operation at 30 degrees latitude. They are required for the power sub-system (solar arrays) sizing as well as the thermal control sub-system design. It showed that the maximum day length is 17 hours and 28 minutes, while the minimum day length is 7 hours and 8 minutes.

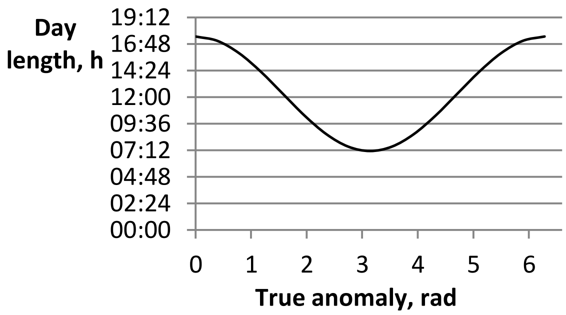


Figure 3: Mars day-night length, 30 degrees latitude

5. SUB-SYSTEM DESIGN AND ANALYSES

This part of the report contains all information that was collected and summarised to be used in the design process.

5.1 Locomotive Sub-system

The locomotive sub-system can be divided into the suspension and wheel components as these parts can be design nearly individually from each other but never should be eliminated in the calculations process.

5.1.1 Locomotive sub-system comparison

The design begins with the comparison and selection of the rover locomotive sub-system. Using the 'Requirements Influence Coefficient' was determined that for the project rocker-bogie suspension is most preferable. The comparison was done between the following systems: flexible track, rigid track, suspended track, rocker-bogie, wheeled structure, PEGASUS and legged structure (Schilling and Jungius, 1996).

Criteria that have an effect on the selection were following: traction, mass, dependability on dust, dependability on ground debris, power requirements, obstacle negotiation, track keeping, support strength, internal friction, system oscillation, robustness, complexity and manufacturing cost.

5.1.2 Wheel sizing

The wheel sizing will determine the traction capability of the rover. The real design of the wheel may complicate the calculation process so additional testing is preferable. Simplified calculations will be used of the analogue real wheel design. Also, important role in wheel diameter selection played the ground clearance requirement that was chosen to be 200 mm. The information required for calculations were previously summarised in Part 4.2.

The cylindrical body was chosen for the calculations. The first step in calculations is to determine the wheel sinkage (Dimitrios, 2001).

$$z = \frac{1}{N}\left[\frac{3W}{(3-n)(k_c+b_w k_\varphi)\sqrt{d_w}}\right]^{\frac{2}{2n+1}} \qquad [4]$$

Here: W – weight of the rover ($g = 3.7\ m/s^2$)
N – number of wheels
b_w – wheel width
d_w – wheel diameter
k_c – cohesive modulus
k_φ – friction modulus
n – exponent of sinkage

Soil trust – force that the soil creates if wheel is driven (Dimitrios, 2001):

$$H = C \times A + \frac{W}{N}\tan\varphi \qquad [5]$$

Here: A – wheel contact area
C – cohesion
φ – internal friction angle

The resistance that is created on the wheel is the sum of the following components:

- Compaction resistance – due to the soft soil compaction
- Gravitational resistance – occurs additional resistance when the rover is driving over the slopes
- Bulldozing resistance – is soil displacement to the sides, only important for the wheels with width bigger than 10 inches (Bekker, 1960)
- Rolling resistance – due to the wheel slip

For the conceptual design, it will be assumed that the rolling resistance can be neglected and for the rover size that was chosen, the wheel width cannot exceed 10 inches (Bekker, 1960). The resistance can be described by (Dimitrios, 2001):

$$R_C = \frac{b_w\left(\frac{k_c}{b_w}+k_\varphi\right)z^{n+1}}{n+1} \qquad [6]$$

$$R_G = \frac{W}{N}\sin\alpha \qquad [7]$$

Finally, the drawback pull – the force that is used to push the rover, is equal to (Dimitrios, 2001):

$$DP = H - (R_C + R_G) \qquad [8]$$

Following the calculations the graph for the wheel performance was developed. The graph (Figure 3) shows the drawback pull for different wheel width (0.06 – 0.16 mm). The performance of the wheel increases with increase of the wheel diameter and the wheel width.

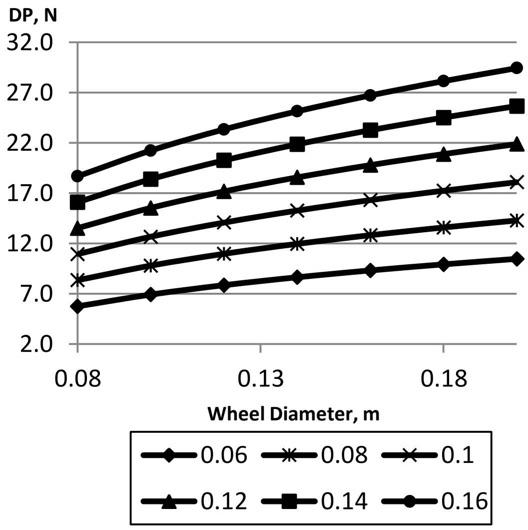


Figure 3: Wheel performance comparison (simulant property used: MER-B 'sandy loam')

Final solution on the wheel size was following: wheel diameter 80 mm and width 80 mm. It will give the 8.35 N of drawback pull. The selection has also included the required clearance of 20 cm and wheel step climbing requirement of 1.5 of wheel diameter.

This gives the safety clearance between the rover bottom and rock to be 8 cm.

The design (Figure 4) will include three load bearing disks (one centre disk and two side disks) and two wheel bases placed in between. The wheel will have two levels of grocers 6 by 8 mm (height, width). Each level will have 7 grousers on a side placed with equal angular spacing. The addition of the grocers will increase the drawback pull of the wheel.

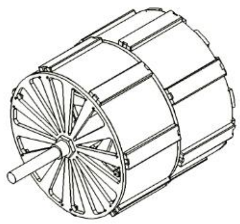


Figure 4: Wheel final design

5.1.3Suspension sub-system analyses

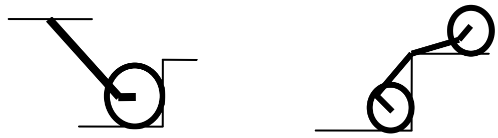
Next step is analyses of the suspension system. The performance of the conventional vehicle with two side wheels is highly limited (Potau, 2010). It is limited by the performance of the rear wheel. The study shows that the rear rocker-bogie configuration marginally increases the step climbing capability. The performance can be increased even more if the front wheel is also substituted with the rocker-bogie configuration. For this particular project using the ‘Requirements Influence Coefficient’ was decided to use three wheels design with the rear rocker-bogie.

The final design (Figure 6) of the rocker-bogie suspension was selected based on data that used simulation ground (Figure 2).

The pivot point of the bogie-bus should be placed in the centre of gravity of the bus. Based on simulation data was found that the front wheel performance when it encounters the obstacle is maximal when the bogie-wheel link has 45 degrees angle with respect to the surface. The position of the middle wheel should be on the same ground normal line with the centre gravity of the rover. The rocker configuration should be selected so that the rocker-middle wheel link would have the lowest possible angle with respect to the ground. The rocker-rear wheel joint should have 90 degrees elbow. Also, was found that the middle wheel can be driven only when it requires the obstacle negotiation. This increases the capability of the middle wheels to pass by the rocks with expense of additional motors use.

5.1.4 Rocker-bogie sizing

The final design of the rocker-bogie includes some design features that was found. The extended beams for the front and middle wheels (Figure 5.a) have increased the rocker-bogie performance. This link gives additional moment due to the fact that load bearing link is not passing through the wheel centre.



a.) b.)

Figure 5: Additional design adaptation, schematics; a.) extended beam design; b.) rocker design limitations while passing obstacle

The rocker design was limited by its clearance while passing the obstacle (Figure 5.b). The small ground clearance of the rocker allows it to be suspended on the rock edge (Figure 5.b) It was important to increase clearance of the rocker. The calculations used the step of 120 mm and wheel diameter of 80 mm to find the perfect value. This was included in calculations and the final rocker-bogie sizing was developed:

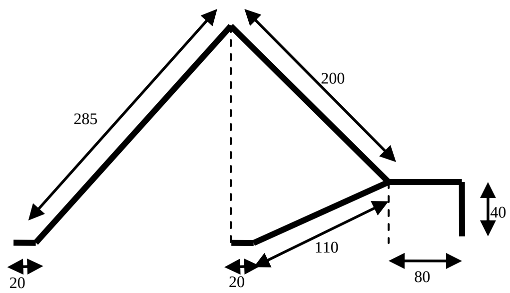


Figure 6: Rocker-bogie sizing schematics

5.1.5 Kinematics studies

The kinematics studies were performed to evaluate the rocker-bogie and find the maximal loads that can appear in the links.

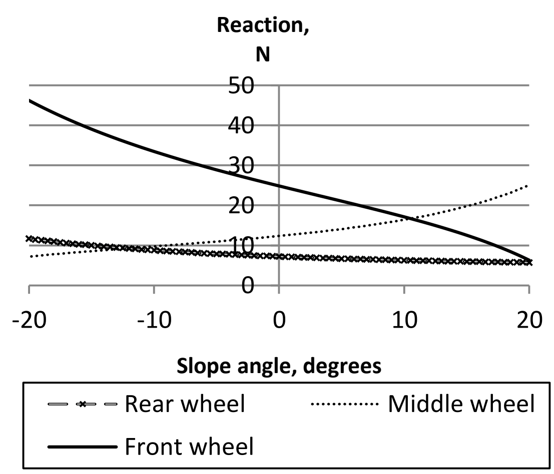


Figure 7: Quasi-static force analyses graph

The study was using the quasi-static force analyses (Patel, 2008) to find the reaction forces on the wheels. The graph below is the calculations values for the slope range between -20 to +20 degrees (Figure 7). This check was done to find if at some point the wheel can lose the contact with the ground surface (reaction force is below zero). Also, the stress values in a rocker-bogie links were found and were used in structural strength check (maximal value of reaction was found to be 47.08 N).

5.2 Structure Sub-system

The structure sub-system is the design of the rover bus or Warm Electronics Box (WEB). The main purpose of the rover bus is to be compartment for electronics. It should protect the systems inside from the dangerous Martian environment. It also should be main load bearing structure for the rover during launch and the re-entry.

Based on the instrumentation sizing and the heating sub-system sizing the dimensions of the bus protecting and sealing cover was calculated to be: width 293 mm, length 429 mm and height 147 mm. The main structure of the rover bus is made of aluminium alloys. The WEB includes the insulation and radiation protection outside cover which was selected to be Kapton (DuPont™) of 0.5 mm thick.

The required part of the analyses of the structure is the load analyses. For this purpose it is essential to run the simulations to check the values of the maximum stress and find the minimum factor of safety (FoS). Also, it is crucial to analyse the displacement under the stress or strain conditions as this might affect the rover operational capability.

5.2.1 Instrumentation sizing and its distribution

For the conceptual design is required to assign the volume available (Table 5) for each of the system and plan the components position within the WEB (Volpe, 1997). The components itself should be represented as 'black box' type.

The design solution was to assemble the components on middle plane or mounting plane.

Component	Width, mm	Length, mm	Height, mm	Volume, m^3
Thermal control	70	230	50	0.805
Communication	100	210	50	0.105
Custom electronics	100	210	50	0.105
Batteries	70	230	50	0.805
Navigation	110	100	45	0.484
Payload instrument.	110	100	45	0.484
Computer	230	270	45	0.279

Table 5: Instrumentation volume sizing

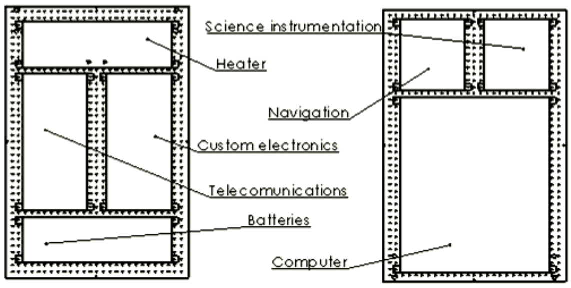


Figure: 8: Instrumentation positioning

The Figure 8 shows the design distribution on the mounting plate. Here was assigned one of the future payload constrains. The volume of the payload should be 0.484 m^3 and have maximal sizes of 110 by 100 by 45 mm.

5.3 Navigation Sub-system

The actual navigation sub-system design is out of the scope for the conceptual design but it is worthwhile to investigate the rover operational planning before heading into the sub-system programming. The design feature that should be included at this stage is the rover turning capability.

For the rover navigation it was required to create a relationship between the rover rotational radius and the wheel turning angle.

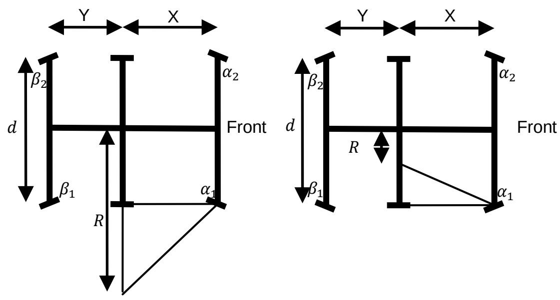


Figure 8: Steering case study configuration

The calculations for the turning angle given here are based on two scenarios (Figure 8). The required calculations were done to be used in the simulation analyses when the rover turning capability was checked (discussed in Part 4.2.1).

1. Rotational radius (R) is bigger than the rover width over two ($\frac{d}{2}$)
2. Rotational radius is smaller than the rover width over two ($\frac{d}{2}$)

$$\alpha_n = \arccos\left[\frac{X}{\sqrt{\left(aR+b\frac{d}{2}\right)^2+X^2}}\right] \qquad [9]$$

$$\beta_n = \arccos\left[\frac{Y}{\sqrt{\left(aR+b\frac{d}{2}\right)^2+Y^2}}\right] \qquad [10]$$

Here α and β is the front and rear wheel respectively. The value n describes the wheel number. The sign constants a and b are given in the Table 6:

	Case 1	Case 2
For all n	$a = 1$	$b = 1$
$n = 1$	$b = -1$	$a = -1$
$n = 2$	$b = 1$	$a = 1$

Table 6: Constants for rover rotation calculations

5.4 Data Handling and Electronics Sub-systems

The in depth design of this sub-systems is out of scope for the conceptual design. It is still worth mentioning that data-handling and electronics sub-systems are required fitting into the selected mass and size constrains. It should have available backup systems. The data storage capacity should be selected with good margin for the case of communicational problems.

Right at this point the operational planning still is important to be introduced (Table 7).

Tasks	Long day %	Short day %
Heating	100	100
Payload	15	11
Driving	50	12
Communication	6	6
Sleep	29	71

Table 7: Rover operational planning

The data here is based on the time availability during the day. The information later will be used in the power budget approximation (Part 5.5). The proposed operation planning shows the operational time in percentage of one Martian day. It is also divided into long and short day. This will later show the approximate power usage difference (Table 14).

5.5 Power Sub-system

The requirements have specified that all power required should be generated using solar arrays and be stored in batteries. Here will be discussed the solar arrays design and the battery sizing based on the power budget (Table 14).

Power budget was proposed based on the simulation and reference data. All sub-systems contained multiple components that had specific power requirement. The calculations were assuming two different day lengths (minimal and maximal day length based on Part 4.4). Approximate operational time for each of sub-systems components was estimated (Table 7). This leads to the total power required per sub-system for long and short day. The payload required power was chosen to be 50% (85.43 W) of the average day power required (2103.63 Wh). After that, the payload total power required for the long and short day was calculated (313.45 Wh and 61.34 Wh). 20% additional margin was added. This has lead to the rover average power requirement to be 136.79 W.

5.5.1 Solar arrays sizing

For the current project were selected gallium arsenide 2x4 cm solar cells with efficiency assumed as 18% (Griffin and French, 2004). This was selected as one of widely used solar cells with the highest efficiency. The solar cells losses depend on many characteristics (Table 8):

Name	Symbol	Value
Solar distance effect	H	0.837
Temperature effect	η_t	0.56
Dust storm effect	η_s	0.5
UV discoloration	η_{uv}	0.987
Thermal cycling	η_{cy}	0.99
Cell mismatch	η_m	0.975
Resistance in interconnects	η_l	0.98
Contamination	η_{con}	0.99
Radiation degradation	η_{rad}	0.98

Table 8: Solar cell losses

Solar panels were chosen as 3-part design (one base and two side ones). Design decision also assumed the possibility actuators for side panels. It will be used to help to protect the arrays in the dust storm times; visibility of this should be investigated.

The solar array size is based on the worst case scenario when the maximal Sun azimuth has minimal value (during the shortest day). Based on calculations for the Mars 30 degrees latitude Sun azimuth is reaching only 34.81 degrees. At the level when the Sun azimuth goes below 5 degrees it was assumed that the solar cells do not generate any power.

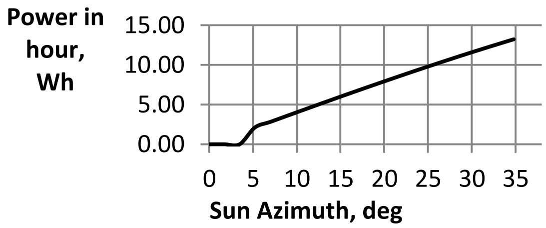


Figure 9: Power received from solar cell in a day time

The Figure 9 shows the value of power that is generated throughout the day. The average power generated for one cell per day including all losses is

7.05 W (based on the Figure 9). The cell requirement was calculated to be 477 with the array area of 0.434 m^2 (Figure 10). The solar array sizing is shown below:

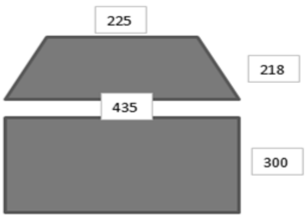


Figure 10: Solar array sizing

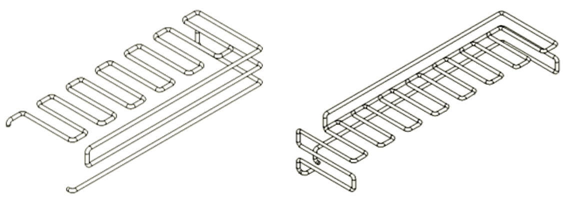
5.5.2 Battery sizing

The nickel cadmium battery was selected for the rover design. Battery system voltage is 28 V. Power losses during the charging and discharging were assumed to be 3%. The total power required to be stored was taken as 37.24Wh and this includes the thermal control sub-system requirements for the maximal night period (31.04Wh) plus additional 20% margin. Capacity of the battery required was calculated to be 1.66 Ah. Selected battery cells capacity was taken to be 1 Ah and it is required three battery cells to be installed onboard. The total mass of the batteries was calculated to be 2.333 kg.

5.6 Thermal Control Sub-system

The temperature control within the WEB will be achieved using the heater and heat pipes. The heating mediums usually used in heat pipes are: water or ammonia. The temperature requirements for the most vulnerable components is summarised in Torre, 2010. The system component that has determined the selection of the WEB temperature was batteries.

The operational temperature of the rover bus was selected to be 20 ± 5 ^{o}C. The heating medium was chosen to be ammonia for its lower density (880 kg/m^3) hence the lower mass. Heat pipes material was chosen as cooper. The proposed design of the heat pipes is given in Figure 11, below:


a.) b.)
Figure 11: Heating pipes design. a.) top b.) bottom

The design will consist of 2 pairs of pipes. The pipes will cover all sub-system electrical components.

The maximal distance between the pipes is 25 mm. They will contain 44.7 mm^3 of fluid with mass of 39 grams.

Calculations of the energy required for heater are based on the equilibrium temperature (T) of 293 K. The Martian day is divided into two parts (day and night phases). It was assumed that during these phases the outside temperature remains constant. It is assumed that only way of energy exchange is by radiation. The constants that are used in calculations given in a Table 10. The absorption and emissivity constants are based on Kapton (DuPont™) characteristics. Mars and Solar absorption surface areas are the total surface area of the rover bus less the base area. Mars infrared emissivity power and solar incident power was obtained from Griffin and French, 2004. The calculations were using two scenarios: Mars is at perihelion and at aphelion.

Thermal constants	Value	Notes
Absorption constant	0.34	
Emissivity constant	0.55	
Mars IR emissivity power	162	Perihelion
(W/m^2)	120	Aphelion
Solar incident power	718.1	Perihelion
(W/m^2)	493.8	Aphelion
Area Mars IR (m^2)	0.338	
Area Solar IR (m^2)	0.338	
Area of rover (m^2)	0.464	

Table 10: Thermal budget calculation constants

The equilibrium state for night and day respectfully is given (Berlin, 2005):

$$\varepsilon A_e \sigma T^4 = \alpha A_{IR} S_{IR} + q \quad [12]$$

$$\varepsilon A_e \sigma T^4 = \alpha A_{IR} S_{IR} + \alpha A_S S_S + q \quad [13]$$

Here: ε – emissivity
A_e - emitting surface area (total area)
σ – Stefan-Boltzmann constant
T – is a body temperature (297 K)
α – absorption constant
A_{IR} – absorbing area of Mars IR radiation
S_{IR} – Mars IR emissivity power
As – absorbing area of Sun IR radiation
S_S – Solar incidence power
q – heater output power

Mars day time, h	Mars night time, h	Total day capacity, W/h	Total night capacity, W/h	Total power, W
17.48	7.14	342.192	2261.491	29.4
7.14	17.48	926.439	2385.586	37.4

Table 11: Thermal budget

The Table 11 gives the thermal budget at two scenarios (perihelion – long day, aphelion – short day). The maximum required average day energy is 37.4 W at aphelion. The additional 3% margin was added to encounter for the losses bringing the heater power requirement to 38.52 W.

5.7 Telecommunication Sub-system

The communication link will happen through the retranslation satellites. A worst case scenario link budget calculation will be provided here (Berlin, 2005) when is required to send or receive data using straight link with Earth. It was chosen that the minimal link margin should be above 3 dB. Modulation type was chosen as (15, 1/6) convolutionally encoded (Harcke, 1997). Bit error rate was taken as 0.05 with concatenated coding. The antenna design assumed the diameter of 140 mm with the gain of 24 dB. The antenna is using X-band. The receiving antenna diameter is 36 m and gain of 68 dB (DSN Antenna JPL).

Distance, $x10^6$ (km)	Power require (W)	Bitrate (bps)	Margin (dB)
152	19	8295	3.0
200	19	4740	3.0
274	19	2520	3.0
338	19	1659	3.0
400	19	1185	3.0

Table 12: Link margin summary

It is possible to achieve communication link margin of three (Table 14) at different distance from Earth (152 – 400 million kilometres). The power was chosen to be 19 W for the operation of the rover, while the achieved bitrate will be reduced due to increase in distance.

5.8 Payload Sub-system

Project decision was not to select the payload and specify the future mission possibilities. The design tried to investigate the design of the rover without the information on the payload type. This gives an opportunity for the use of multiple type payloads that fits in volume-size constrains given in Part 5.2.1 and mass of 800 g given in requirements (Part 2.1.5). Still the design should consider the systems that are required for most of the research payloads based on previous missions.

5.8.1 Camera mast and robotic-arm description

The robotic-arm was designed as 3-joits arm to allow for higher degrees of freedom to be used. The joint rotation was achieved by the use of actuators placed within the arm.

Camera has two degrees of freedom and it is mounted on the mast. The robotic-arm and camera mast were attached through the single place to minimise the support structure required.

6. DESIGN FINAL SOLUTION

The final design solution of Mars rover is shown in Figure 12. The final mass of the rover was calculated to be 16.445 kg with the safety margin of 5%. The rover's height is 442 mm; width is 623 mm; and length of 517 mm. The ground clearance achieved to be 200 mm. The mass budget given in the Table 13 estimates the payload mass to be 1067 g with 800 g allowance for payload instrumentation. Payload should fit into the volume size of 100 by 110 by 45 mm.

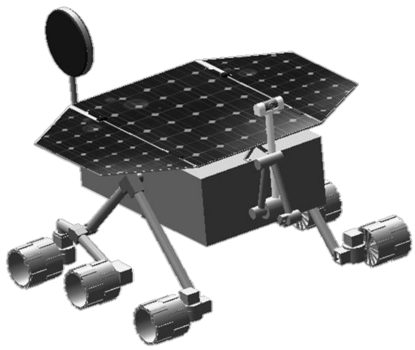


Figure 12: Rover final design

Sub-system	Mass, g
Locomotive	2331
Thermal control	848
Data-handling	2500
Telecommunication	1654
Navigation	102
Power	5268
Structure	1892
Payload	1067
Sub-total	15662
Margin	783
Total	**16445**

Table 13: Mass budget summary

The total average power required for the rover operation was found to be 136.79 W (Table 14). The payload power was estimated at 85.43 W based on maximum available operational time (Table 7). The operation available time based on data achieved in the day length calculations (Part 4.4) for the aphelion is 47 minutes and for perihelion 157 minutes.

		Power in Sol, Wh	
Sub-system	Power, W	Long Day	Short Day
Locomotive	62.88	695.70	277.38
Thermal control	43.72	1076.50	1076.50
Data-handling	51.00	429.10	154.40
Telecommunication	107.72	161.58	161.58
Navigation	9.62	30.05	12.02
Payload support	12.20	100.34	32.12
Sub-total (without payload)		2493.27	1714.00
Average		2103.63	
Payload	85.43	313.45	61.34
Sub-total (with payload)		2806.71	1775.34
Margin		561.34	355.07
Total per day		3368.05	2130.41
Average power	**136.79**		

Table 14: Power budget

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