A computational tool for conceptual design and optimization of planetary rovers

Aravind SEENI*[1,2], Bernd SCHÄFER[1]

*Corresponding author
[1]Institute of Robotics and Mechatronics, German Aerospace Center (DLR),
Oberpfaffenhofen, 82234 Wessling, Bavaria, Germany
[2]Department of Aeronautical Engineering, Rajalakshmi Engineering College,
Chennai 602105, Tamilnadu, India,
aravindseeni.s@rajalakshmi.edu.in

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***Abstract**: The design process of a Mars rover is driven by multiple design constraints, namely overall mass, power consumption and volume (dimensions). Various systems, such as mobility, manipulation, handling, power, thermal, communication, navigation, avionics and science instruments, together make a complete rover vehicle and they should function collectively to perform a given task. Each of the subsystems can be thought of as modular building blocks that are integrated together to form a fully functional rover vehicle. When approaching the design of such a vehicle, the designer should take into account of cross design dependencies existent between different subsystems and technology limitations. Performing any particular task, would lead to many design possibilities. Choosing the final design from many feasible solutions is arguably a daunting task. In order to make this process simple and convenient, as well as to understand the design non-linearity existing in this solution space, the authors have employed a systems engineering approach to develop a tool comprising subsystem models. The subsystem models comprise parametric and physics-based models. For designing suitable user-defined objectives, these models when integrated with Genetic Algorithm forms an effective tool to support design trade-offs during the conceptual design process. This integrated modeling and optimization approach is thought to be efficient in identifying rover system concepts.*

***Key Words:** mass models, power models, environmental models, design variables, Genetic Algorithm, minimal mass, maximal science returns, mobility subsystem, power subsystem*

1. INTRODUCTION

Rovers that have been launched for exploring the surface of Mars have yielded valuable science to date. Providing useful scientific data by traversing different sites is not an easy feat. Mars presents a challenging environment for rover operations due to unpredictable adverse environmental conditions. A Mars rover mission is technically and operationally risky. Risks are accompanied by costs. This forms the basis for making design trade-offs and finding optimal designs that are consistent with the specific mission objectives.

A design methodology based on Genetic Algorithm (GA) is implemented and a computational tool is developed to serve this purpose. In this tool, a rover model consisting of all the essential subsystems is properly described to perform a system-level design trade-off analysis using GA. GA serves the purpose of finding optimal designs by searching the trade-off space for feasible solutions, maximizing or minimizing user-defined objectives and satisfying design constraints. For designing the design of vehicle systems such as rovers, the structural design parameters of one subsystem affect the design of one or more other subsystems.

All the systems that support essential scientific tasks such as power, thermal control, avionics, navigation, communication subsystems are integrated to a mechanical structure called the suspension.

The suspension should be designed to certain kinematics to efficiently climb slopes and rocks. The mobility system requires electrical energy for operation and is supported by the power subsystem.

Since the amount of electric energy that can be produced on the ground is limited and should be efficiently used, the size of subsystems needs to be optimized. This is done to benefit from the expected scientific results without sacrificing mass and dimensional constraints. Thermal subsystems keep systems in within acceptable temperature conditions.

This interrelated dependence of system design that determines the rover design in terms of total mass and power consumption can be utilized to suitable degrees to perform a rapid trade-off and choose a final design.

Since the first missions to Mars, the rover vehicle configuration that has been successfully deployed is wheel powered. In this paper, a six-wheeled rover with kinematics based on a rover developed for ExoMars mission will be assumed. For capturing all the rover systems within the model parametric models are required.

Parametric system-level relationships are available for satellites, as provided by Wertz and Larson [1] and hence so far have been widely used by designers. For rovers, such relationships are not widely available. Empirical data mined from various sources are used to develop some of the parametric models.

The tool essentially comprises various modules that relate to each subsystem – mobility, power and thermal control modules that are integrated into GA. A GUI interface is used to receive user inputs.

Two different case studies with different design objectives - 1) designing for minimal mass and 2) designing for maximal science return will be considered to demonstrate the application of the tool. The results are analyzed and this work will be described in this paper.

2. COMPUTATIONAL TOOL MODELLING AND ARCHITECTURE

The modelling process is composed of different modules each representing different subsystems. Each of the modules interacts, feeding in and back data. For conceiving this approach, parametric and physics-based models of rover systems are essential.

Mobility, Power and Thermal Control subsystems are modelled based on conventional physics. Other subsystems such as mass relationships are necessary to be developed for some of the other subsystems.

Robotic spacecraft designers rely a lot on mass estimating relationships. This is because, detailed knowledge of mass down to all components of all assembles of various systems is needed and obtaining such a bottom-up estimate is nearly impossible. Such relationships exist in the literature for orbiting satellites.

Larson and Wertz have provided a suite of information covering mass, power budgeting relationships for satellites [1]. However, models for rovers are not widely available in the literature. Here empirical models are developed using data extracted from a comprehensive literature survey.

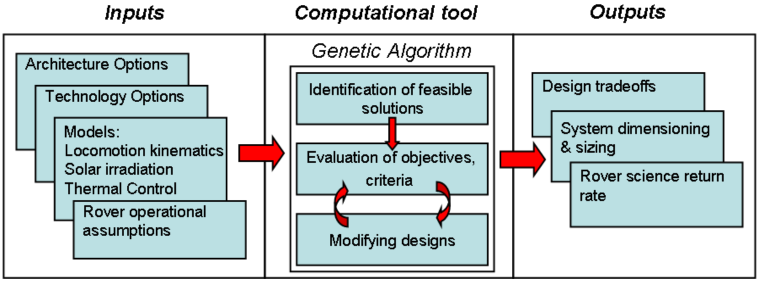
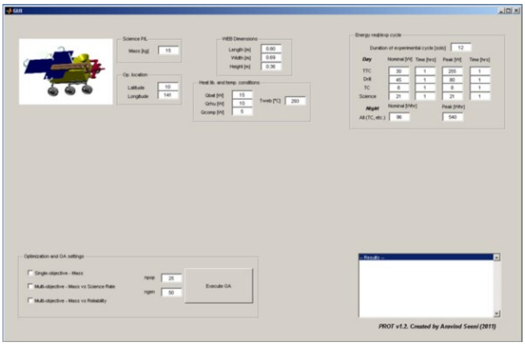


Fig. 1 - Design process model

GUI

The tool is designed to have a Graphical User Interface (GUI) that accepts essential mission level inputs from the user. The inputs generally retrieve approximate information related to location coordinates concerning rover operations, electronics box dimensions for heat accommodation and subsystem energy requirements. The GUI interface is shown in Fig. 2.



Science P/L
Mass [kg] 15

Op. location
Latitude 10
Longitude 141

WEB Dimensions
Length [m] 0.80
Width [m] 0.69
Height [m] 0.36

Heat lib. and temp. conditions
Gbat [W] 15
Grhu [W] 10
Gcomp [W] 5
Tweb [°C] 293

Energy req/exp cycle
Duration of experimental cycle [sols] 12

Day	Nominal [W]	Time [hrs]	Peak [W]	Time [hrs]
TTC	30	1	255	1
Drill	45	1	80	1
TC	8	1	8	1
Science	21	1	21	1

Night	Nominal [Whr]	Peak [Whr]
All (TC, etc.)	96	540

Optimization and GA settings
☐ Single-objective - Mass
☐ Multi-objective - Mass vs Science Rate
☐ Multi-objective - Mass vs Reliability
npop 25
ngen 50

PROT v1.2. Created by Aravind Seeni (2011)

Fig. 2 - GUI interface

Environmental models

Rover operations on Mars are generally influenced by local terrain topography and climatic conditions. The terrain topography with large boulders and rocks significantly reduces the traversal time between scientific points of interest. The rock density estimations on Mars surface presented by Golombek [2] allow a quantitative estimation of rock size in the rover operational vicinity for a certain geographical location. Based on these estimations, we plan to size the rover suspension system. Typically, the landing site locational coordinates are decided during the late mission stages. Since the topography on Mars is not as homogeneous as on Earth, during the conceptual design stages it is necessary to establish the suspension dimensional design boundaries for the chosen locations. The distance a rover can traverse in a straight path along a particular heading angle on a terrain until it encounters an obstacle to cause turning can be defined as the mean free path. The mean free path if desired to be large would increase the size of suspension and wheels in order to aid motion over obstacles such as rocks. This is called vehicle "trafficability". In our tool, the mean free path requirement is a constraint that is a function of the suspension and wheel sizes. Mean free path can be further explained through the following equation [3]:

$$x=\frac{1-\frac{L_{trak}}{2}\int_{D_0}^{\infty}D\rho(D)dD-\frac{1}{2}\int_{D_0}^{\infty}D^2\rho(D)dD}{L_{trak}\int_{D_0}^{\infty}\rho(D)dD-\int_{D_0}^{\infty}D\rho(D)dD} \tag{1}$$

Apart from rocks and boulders on the surface, rover traversal can be affected by soil. Soft soil causes high resistive losses to motion. The weight of the rover contributes to wheel sinkage in to the soft soil. The resistance due to wheel sinkage can be termed as the soil's compaction resistance. The amount of wheel sinkage depends on the soil properties and wheel dimensions. The capacity to move with low compaction resistance can be termed as "terrainability" of the rover. This can be further explained as follows:

$$R_{compaction} = \frac{b_{wheel} \times k \times z^{n+1}}{n+1} \tag{2}$$

The soil sinkage, z is given by,

$$z = \left(\frac{3 \cdot M_{rover} \cdot g}{n_{wheels}(3-n)k\sqrt{d_{wheel}}}\right)^{\frac{2}{2n+1}} \tag{3}$$

k is a factor first coined by Bernstein when he established the following pressure-sinkage relationship:

$$p = kz^n \tag{4}$$

Bekker further improved the relationship using soil parameter values of k_c, k_ϕ, and n as follows:

$$k = \left(\frac{k_c}{b_{wheel}} + k_\emptyset\right) z^n \tag{5}$$

The climate on Mars is seasonal. Mars experiences both summer and winter and this influences rover operations. A rover designed with solar arrays depends on the amount of solar insolation available or reaching Mars surface from the Sun. Solar insolation availability also would depend on the locational coordinates. The solar insolation modelled here is based on [9]. The solar insolation availability also depends on dust storms prevalent regionally and originates occasionally. This model serves the purpose of designing the solar arrays of the rover for experimental and subsystem power requirements.

Mobility module

A rover's mobility subsystem consists of the following elements - suspension bogies, wheels, actuators and interfaces. The bogies are the axles that carry the load and provide a platform for carrying all on-board systems. Actuators consist of a motor and a gear that is connected to the wheel. The motor and gear mass relationships are derived simply as follows. The mass of the motor and gear is thought to be proportional to motor torque and gear ratio, respectively. Data that accounts for 92 motor and 26 gear models are retrieved from motor designs manufactured by Maxon motors AG [8]. Motors from Maxon have been used in the past on the following missions - Mars Exploration Rovers, Spirit and Opportunity and ExoMars rover breadboard design and development. Scalar factors that relate the motor mass (M_{motor}) to the torque and the gear mass (M_{gear}) to the gear ratio are determined by least squares determination (Fig. 4 and Fig. 5). The relationships are stated as follows:

$$M_{motor} = 3.52 \cdot 10^{-3} \cdot T_{mot}(kg) \tag{6}$$

$$M_{gear} = 0.0025.10^{-3}.i_{gear}(kg) \tag{7}$$

where T_{mot} and i_{gear} are minimal required motor torque and gear ratio, respectively. The mass of wheels and axles are calculated based on physical dimensions and assumed material properties. The material chosen here is a Titanium alloy with material density of 4506 kg/m^3. A quasi-static system with kinematics based on RCL-E [7] is the suspension model considered (Fig. 3) here. The RCL-E design comprises two longitudinal bogies attached on the sides of the Warm Electronics Box (WEB) and one traverse bogie at the back. The contact forces between the wheel and the ground is necessary to be calculated in order to understand the stability conditions of the vehicle on uneven terrain and slope climbing. The suspension should be tested for contact forces variation during up, down and cross-slope motion. The interaction between the wheel and the ground is modelled as a point contact. The wheels are assumed to be rigid with no elastic properties. The contact force at all six wheels can be statically determined by solving a set of force and moment equilibrium equations.

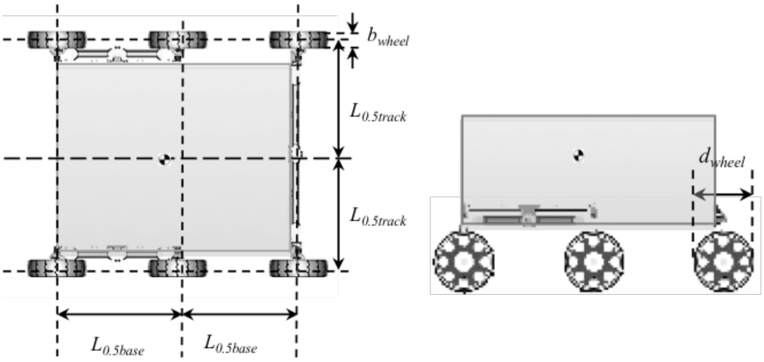


Fig. 3 - Characterization of mobility system parameters

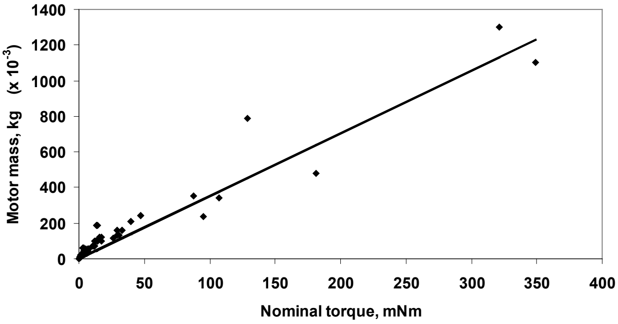


Fig. 4 - Curve fitting plot of motor mass variation with nominal torque

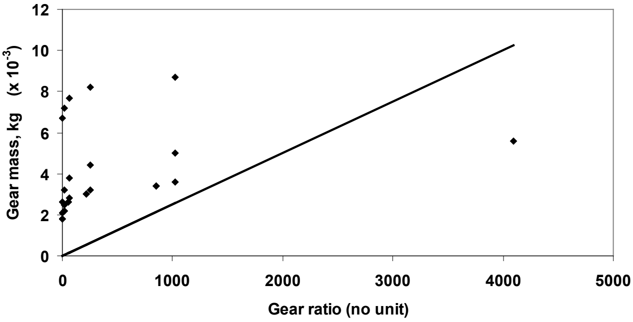


Fig. 5 - Curve fitting plot of gear mass variation with gear ratio

Power module

The power system modelled here is a photovoltaic system or solar arrays acting as the primary power source. The solar arrays must generate a sufficient amount of power to satisfy subsystem charging and battery recharging demands. Batteries supply energy during peak operations and during periods when there is no sunlight. Batteries should also maintain the temperature of rover systems during cold nights. Solar arrays consist of solar cells that are available in different technologies. They are responsible for converting solar energy into electricity through the photovoltaic effect. Here GaInP/GaAs/Ge triple junction cell technology with a conversion efficiency of 26.8% is assumed. The solar arrays are assumed inclinable or tiltable to suitable angles by means of actuators. This method enables the capability of tracking the sun to maintain maximum solar radiation reaching the cells during the entire sol. Likewise, the battery is assumed to be of Li-ion technology with an operational efficiency of 95%. Although solar cells suggest a primary element of the solar array, it may not contribute significantly to overall mass. The structure ($M_{arraystruct}$), cover glass, interconnects and substrate forms the significant portion of the overall array mass. The relationships for determining power subsystem mass is given as follows:

$$M_{arrayblanket} = 6m_{cell} \cdot A_{sa} \tag{8}$$

$$M_{arraystruct} = 0.0.82 M_{arrayblanket} \tag{9}$$

$$M_{bat} = \frac{C_{bat}}{e_{bat}} \tag{10}$$

The mass of the array blanket ($M_{arrayblanket}$) is dependent on the specific mass of solar cell and the area of solar array required. This mass is scaled by a factor 6 to account for supporting components. The area of the solar array needed is calculated based on energy requirements per experimental cycle of operation and the battery charge requirements of the rover. An experimental cycle means the duration in which a pre-defined set of science and operational activities are completed. The duration can vary anywhere between one or any number of sols.

The area of solar array is defined based on the power requirements per experimental cycle as well as battery charge requirements. The solar arrays are designed to support nominal power requirements and the batteries are designed to suffice peak power requirements during operations. Additionally, batteries are the power source during egress from lander in case the solar arrays cannot be deployed immediately after landing. The area of solar array can be calculated as per [14] and is given by,

$$A_{sa} = \frac{P_{rover,nom}}{I_{mean} \times \eta_{cell} \times (1 - FAC_{degrad}) \times cos\theta \times (1 - FAC_{tempeff}) \times FAC_{packing}} \tag{11}$$

The area of solar array, as mentioned above is defined based on the power requirements per experimental cycle as well as battery charge requirements. The power requirements, $P_{rover,nom}$ is given by,

$$P_{rover,nom} = P_{s/s,exp.cycle} + P_{bat,charge} \tag{12}$$

$$P_{s/s,exp.cycle} = \frac{\left(\frac{P^{night}_{nom,persol} \times T^{night}_{nom,persol}}{\eta_{night}}\right) + \left(\frac{P^{day}_{nom,persol} \times T^{day}_{nom,persol}}{\eta_{day}}\right)}{T_{day}} \tag{13}$$

$$P_{bat,charge} = \frac{C_{bat}}{T_{av.,persol}} \tag{14}$$

Whereas solar arrays are designed for nominal power requirements, batteries are designed to provide peak power as and when needed by the rover. Peak power requirements of each subsystem vary dependent on the operation and are also pre-defined. Batteries are the only source of power for rover egress from lander if the solar arrays cannot be deployed immediately after landing. If the solar arrays can be deployed, there is no need to consider the power requirements for the rover output.

$$C_{bat} = \frac{P_{rover,peak}}{DOD \times \eta_{bat}} \tag{15}$$

$$\begin{aligned} P_{rover,peak} = {} & \left(P_{peak,persol}^{night} \times T_{peak,persol}^{night}\right) + \left(P_{peak,persol}^{day} \times T_{peak,persol}^{day}\right) \\ & + E_{rover,egrees} \end{aligned} \tag{16}$$

Thermal Control module

The thermal subsystem of a rover is modelled to use radioisotope heating units or RHUs for heating components in the Martian cold. In order to avoid excess heating and also if there is no need for transferring excess heat from hot to cold regions, heat has to be dissipated safely to the surroundings. A passive radiator that can be fixed to any safe location on the WEB enables this task. The WEB is the box component that houses the avionics, batteries and thermal systems. The thermal subsystem has to maintain a safe temperature inside the WEB to prevent overheating of sensitive systems. Other systems such as locomotion actuators are assumed to have built-in thermal control. The mass of the radiator depends on the volume of the radiator from which heat is liberated and the material density. This can be shown as,

$$M_{rad} = \rho_{rad} A_{rad} t_{rad} \tag{17}$$

where t_{rad} is the thickness. Additionally, a WEB thermal coating made of Kapton with emissivity of 0.49 is assumed.

The heat dissipating capacity of the radiator is determined by the emissivity property of the material used for manufacturing. Radiators are passive in nature and do not require active components for functioning. In addition, paints with emissive properties are also normally used surrounding the WEB to prevent entry of direct heat due to sunlight. To choose the type of paints and the radiator size, it is necessary to determine the amount of heat the rover would be exposed to as well as the temperature at which the WEB should be maintained. The amount of heat collected inside the WEB is the heat expelled by the RHUs, batteries and avionics, in addition to external heat collected from sunlight. The solar heat rate, Q_{sun} depends on the projected WEB area in contact with sunlight at any given time. φ_{al} is the albedo flux constant.

$$Q_{sun} = I_{max} A_{WEB,proj} \tag{18}$$

$$Q_{albedo} = A_{WEB} \times \varphi_{al} \tag{19}$$

The amount of heat dissipated into the surroundings by the rover, is the summation of heat that can be dissipated by paint and the passive radiator.

$$Q_{dissp} = Q_{paint} + Q_{rad} \tag{20}$$

$$Q_{paint} = \varepsilon_{paint} A_{WEB} \sigma T_{WEB}^4 \tag{21}$$

$$Q_{rad} = \varepsilon_{rad} A_{rad} \eta_{rad} \sigma T_{rad}^{4} \tag{22}$$

σ is the Stephan Boltzmann constant.

Parametric modelling

Owing to limited number of flight missions completed, the dataset primarily comprises information from studies carried out during the early design phases of previous missions. Therefore, it is possible that the mass estimates in these missions are very optimistic. The data taken from missions from on-going rover studies may not reflect the final space-flying configuration. Some estimates did not include margins in their budgets. The data are hard to be corrected individually, and there exists a certain uncertainty in the model. With some level of uncertainty, it is attempted to analyse data heuristically to derive some relationships. Some data comes from completed space flown missions. Additionally, data are collected from JPL's Team X trade studies and the ExoMars mission studies. G.E.P.Box and K.B.Wilson introduced the method of Response Surface Methodology (RSM) in 1951 [4]. Springmann and de Weck used the methodology to model system-level parameters as functions of design variables for deriving relationships for communication satellites [5] [6]. Just like any other process of spacecraft design, it is thought that the overall rover mass is an important parameter to be estimated for establishing mission feasibility. It is thought that the rover's final mass depends on the total payload mass it carries. A relationship between rover mass and payload mass is described here based on a power law model. It is defined as follows:

$$M_{rover} = 19.6 M_{pl}^{0.76} \tag{23}$$

Wheel diameter is another variable that influences overall rover mass and design. The variation of the diameter of wheel with rover mass is quite linear. It is already known that desired improvement in rover's mean free path in rocky terrain can be achieved by increasing the wheel diameter. So far, rovers that have been designed for missions in the past, present and future, have proportionately improved in volume (size) and wheel diameter. A slightly better correlation between the data can be obtained if this variable is also introduced into the model as follows:

$$M_{rover} = 5.4\left(5.3 M_{pl} + d_{wheel}\right)^{0.76} \tag{24}$$

The diameter of wheel can range from very small size (~10 cm) to as much as 50 cm depending on the rover size and mass. Mass estimates from above relationship are shown with data points and 95% confidence levels in the Fig. 6. It also represents minor modelling improvements over relating with one single variable, payload mass. The two mass models as described by Eqs. (23) and (24) are compared in Table 1.

Table 1 - Comparison of rover mass models before and after inclusion of wheel diameter

Model	Variables	x_{rms}, kg	95% Confidence Interval, kg
Eqn. (23)	M_{PL}	138.98	±119.94
Eqn. (24)	M_{PL}, d_{wheel}	138.94	±117.39

Individual subsystem masses are best estimated as percentages of total rover mass. Data from rover studies are too sparse to provide a reasonable basis for using parametric relationships other than payload. The percentages of subsystem masses using existing data are compiled in Table 2. The mobility, power and radiator masses are estimated based on physics-based relationships. Each subsystem model is represented as a module that transfers data to other subsystem modules.

Table 2 - Typical subsystem masses as percentages of total rover mass

Subsystem	% M_{rover} (std. dev.)
ACS	2 (2)
Thermal Control	6 (3)
Communications	5 (2)
Command & Data Handling	6 (4)
Cabling	7 (2)

3. VEHICLE SYSTEM OPTIMIZATION

Integrated Modelling and Optimization

An integrated modelling and optimization approach is proposed by searching for rover design options in the feasible design space, simultaneously optimizing rover subsystems and selecting the best design. The model of the proposed approach to rover design is illustrated in Fig. 1. Technology options and architecture options available for subsystem design should be initially chosen. This consists of choosing the type of solar cells (single, double, triple junction silicon cells etc.) or the type of batteries (Lithium ion, Nickel Cadmium, Nickel-metal hydride, etc.) to be sized. Also architecture options such as fixed or inclinable solar array should be chosen. In the next steps, a Genetic Algorithm uses models defined for capturing the rover vehicle and the searches for the best design solution by minimizing or maximizing specific objective. The models used are parametric or physics-based. While GA explores the design space, several feasible design options are searched. The design space is vast and not well defined and there may be multiple feasible solutions. This is because of the parametric interdependency existing between the various subsystems. The primary factors determining the design process, such as mass, power and heat dissipation, must form a closed loop of data interaction and interdependence between subsystems. This forms the basis of optimizing systems simultaneously. To derive system mass estimates, there are two possibilities. The first method involves finding masses of individual components from the bottom up for each system and summing up. This process is tedious and almost impossible. The other method involves using empirical data of systems from past rover missions and studies to derive mass estimation relationships. The drawback of this method is that dataset should be vast to reduce errors related to uncertainty in the parametric models.

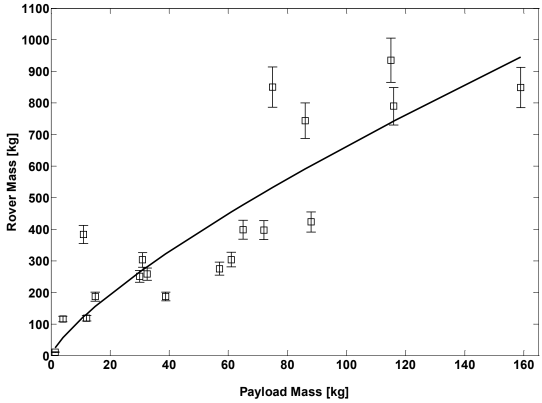


Fig. 6 - Payload vs. total rover mass data plotted with 15% uncertainty. Rover mass expressed as a function of M_{pl} and d_{wheel} and drawn as a least-square function

A case to design a rover concept that should carry scientific payloads of 50 kg in mass is considered to demonstrate the feasibility of the approach. Genetic Algorithm is chosen as the optimization technique because of the large number of design variables and serving the purpose of efficiently handling global optimization problems. GA works on the principle of life evolution process based on the Darwinian principle. Goldberg first introduced it as a meta-heuristic, numerical optimization technique [10]. In GA, a set of operations is performed on a population of encoded solutions known as individuals or chromosomes. Each possible solution is encoded as a set of genes. During each iteration (or generation), the individuals in the population undergo selection, crossover, mutation and fitness evaluation operations. The global search of design solutions followed in GA prevents convergence of solutions or trapped in the local optima. Unlike other optimization methods, GA does not require gradients or derivatives of the function to be minimized. Also it does not require initial guess values of the design variables. Only the boundary values to the design space are needed. GA varies the values of design variables over a number of generations until satisfying a set of criteria. In GA, the fitness function represents the objective functions and constraints. A higher fitness indicates better solution. In the fitness function, the constraints are handled such that unfeasible solutions are penalized by a penalty factor. With each GA generation, the fitness of the population is improved. The best solution selected is the individual with the best fitness at the end of the last generation.

Mission requirements definition

The model requires mission level inputs from the user that informs the environment and vehicle operational conditions on Mars. They help in understanding the soil type that is described by Bekker's friction and cohesion properties [11]. Also the terrain conditions are specified to understand whether the rover should operate on slopes. Operational requirements define the nominal and peak power consumption of systems. Battery recharge duration available per sol is also specified. Temperature conditions to be maintained inside WEB should be also provided.

Table 3 - Assumed operational requirements for one experimental cycle

		Nominal	Peak
Day power consumption per exp. cycle	Communication (W)	30	255
	Drilling (W)	45	80
	Science (W)	21	21
	Thermal control (W)	8	8
Night power consumption per exp. cycle	Thermal control (Whr)	96	540
Operational hours per exp. Cycle	Communication (hrs)	1	1
	Drilling (hrs)	1	1
	Science (hrs)	1	1
	Thermal control (hrs)	1	1
	Battery recharge plan: [day 1, day 2, ..,day 12] (hrs)	[2, 2, 2, 1, 2, 1, 1, 2, 2, 2, 3, 3]	
	Temperature inside WEB (K)	293	

Environmental conditions

The mission specifications are as follows: The rover is expected to operate at 20° latitude. Areocentric longitude of Mars about Sun during landing is assumed to be 180°. The rover should be capable of climbing and descending slopes up to 35° and also safely traverse obstacles. The reference soil properties are assumed based on estimated soft soil properties by [12] – Cohesive deformation modulus as 6800 N/m^{n+1}, frictional deformation modulus as 210000 N/m^{n+2} and soil deformation component as 1. The assumed operational rock coverage for the terrain is assumed to be 15%.

Operational conditions

The rover should be capable of performing necessary science activities allocated for one experimental cycle as well as complete data transfer and communications. Each experimental cycle lasts for 12 sols. The operational conditions are provided as in Table 3. Now, two different optimization procedures applicable for Mars rover designing will be discussed. One procedure involves minimizing the rover mass. The other procedure involves maximizing science returns requirement from the rover.

Designing for minimal mass

In designing for minimal mass, the GA searches for a feasible solution in the design space with the minimal total mass. The total mass is the summation of masses of all subsystems.

$$M_{rover} = M_{mob} + M_{pow} + M_{TC} + M_{ACS} + M_{telecom} + M_{C\&DH} + M_{cabl} \tag{25}$$

where, M_{rover}, M_{mob}, M_{pow}, M_{TC}, M_{ACS}, $M_{telecom}$, $M_{C\&DH}$ and M_{cabl} are the total rover, mobility (structures), power, thermal control, attitude control, telecommunication, command and data handling and cabling masses respectively. All 1,2,…N solutions in the population are evaluated for their fitness and constraint values and assigned a relative merit to each solution.

The design variables are namely, radiator area (x_1), wheel diameter (x_2), nominal motor torque (x_3), half-lengths of vehicle base (x_4), half-lengths of vehicle track (x_5) and gear ratio (x_6) and wheel width (x_7). The optimization statement can be formulated as follows:

minimize M_{rover}

s.t., $0.01 \le A_{rad} \le 2$; $0.01 \le d_{wheel} \le 1$; $0.01 \le b_{wheel} \le 1$; $0.01 \le T_{mot} \le 500$; $0.01 \le L_{0.5base} \le 2$; $0.01 \le L_{0.5track} \le 2$; $1 \le i_{gear} \le 1000$; g_1: $\frac{M_{rover} \cdot V_{rover}(a + g\sin\theta)}{\eta_{actuator}} - (T_{mot}\omega_{mot}) \le 0$; g_2: $-mfp + 15 \le 0$; g_3: $R_{compaction} - 125 \le 0$; g_4: $i_{mot} - \frac{(\pi\omega_{mot}d_{wheel})}{60V_{rover}} \le 0$; g_5-g_{10}: $[1 - F_{wheelA}, 1 - F_{wheelB}, 1 - F_{wheelC}, 1 - F_{wheelD}, 1 - F_{wheelE}, 1 - F_{wheelF}] \le 0$ (uphill); g_{11}-g_{16}: $[1 - F_{wheelA}, 1 - F_{wheelB}, 1 - F_{wheelC}, 1 - F_{wheelD}, 1 - F_{wheelE}, 1 - F_{wheelF}] \le 0$ (crosshill); h_1: $Q_{WEB} - Q_{dissp} = 0$

For GA, each design variable is provided with a boundary limits. The other equality and non-equality constraints can be explained as follows: g_1 specifies the motor power requirements. g_2 specifies the mean free path requirements of the rover for a terrain with specific rock coverage. This is then used for calculating the mean free path. g_3 restricts the compaction resistance suffered by the wheel in soft soil [13]. g_4 addresses the gear ratio requirements. g_5-g_{10}, g-g_{11} defines the static stability requirements by maintaining a positive wheel contact force of the vehicle in up-hill and cross-hill respectively. h_1 limits the temperature to be maintained inside WEB.

The number of GA individuals or population size is set at 21. The crossover and mutation probability rates are set to 0.6 and 0.01 respectively. The GA optimization is run for 1000 generations. The fitness function appears to converge on a final design after satisfying given constraints. The best fitness trend over each generation is illustrated in Fig. 7.

As seen, the design solution selects a power configuration fitted with a 2.02 m^2 solar array and a 246.85 Whr capacity battery. The wheel diameter and wheel width are 0.35 m and 0.55 m respectively.

The wheel compaction resistance for this design solution is 117.32 N. The overall mass of the rover at the end of the optimization procedure is found to be 185.55 kg. The results of the design variables are listed in Table 5 and the constraints in Table 4.

Table 6 lists the individual subsystem masses of the design solution. The full lengths of the vehicle base and track are 0.26 m and 0.31 m, respectively. In a 15% rock covered terrain, a 37.05 m mean free path performance is expected.

From Fig. 7, it can be seen that the fitness function trend is smooth. The GA performance can be additionally described by the population distribution at the 1000th generation. Fig. 8 shows the normalized values of the design variables for the final generation. As seen, the individual values for each variable remain fairly equal. The population statistics of the 1000th generation is given in Table 7.

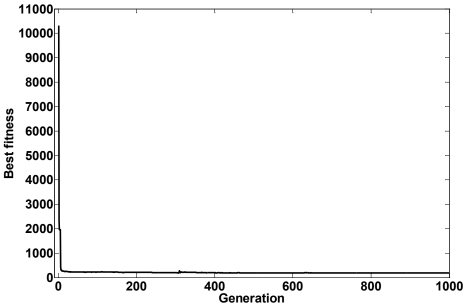


Fig. 7 - Convergence history of best fitness

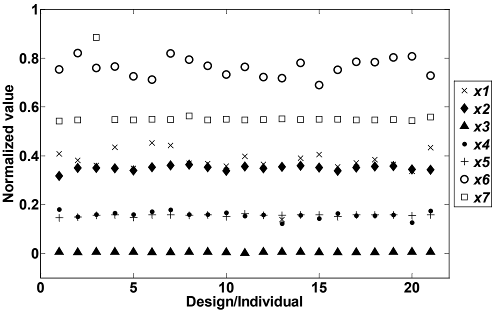


Fig. 8 - Population distribution at 1000th GA generation

Table 4 - Constraint values for final design solution

g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	
0.03	-1.46	-7.67	0	-30.93	-30.93	-30.93	-30.93	
g_9	g_{10}	g_{11}	g_{12}	g_{13}	g_{14}	g_{15}	g_{16}	h_1
-281.17	-281.17	-217.02	-11.67	-217.02	-11.67	-114.35	-114.35	0.02

Table 5 - Best design solution after 1000 iterations

Design variables	Value
Radiator area (m^2)	0.34
Wheel diameter (m)	0.35
Drive motor nominal torque (mNm)	2.92
Half wheel base length (m)	0.26
Half wheel track length (m)	0.31
Gear ratio	8067
Wheel width (m)	0.55

Table 6 - Mass breakdown of systems

Subsystem	Value
Payload (kg)	50.0
Mobility (kg)	14.26
Power (kg)	24.96
Thermal Control (kg)	19.68
Other subsystems (kg)	76.65
Total mass (kg)	185.55

Table 7 - GA final population properties

GA property	Value
Best fitness	185.5
Mean fitness	2744
Median fitness	187.8

Designing for maximal science returns

The scientific return rate from a surface mission depends on rover's capabilities to move from one site to other, place on-board instruments on soil or rock samples, measure data and transmit back to Earth. In order to achieve higher science return rate from a mission, the mobility performance and capacity to remain mobile for most period of the time is essential. The only constraining factor is the electrical energy required to cover large distances and perform experiments. If the rover travelling at 1 m/s and the cumulative time of travel per sol is equivalent to duration of one sol, then the science rate is unity. The science returns ratio per sol, $\xi_{science,sol}$ may be expressed as:

$$\xi_{science,sol} = \frac{V_{actual} \times t_{motion}}{t_{sol,day}} \tag{26}$$

where t_{motion} is the total motion time by rover. This parameter indirectly relates to the rover time for conducting science activities in different sites. The design variables are namely, radiator area (x_1), wheel diameter (x_2), nominal motor torque (x_3), half-lengths of vehicle base (x_4), half-lengths of vehicle track (x_5) and gear ratio (x_6), wheel width (x_7) and motion duration per sol (x_8). Motion duration per sol is used as a design variable in order to maximize the amount of science returns from the mission.

Table 8 - Constraint values for final design solution

g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9
0.09	0.86	-25.19	0	-0.22	-39.05	-39.05	-39.05	-39.05
g_{10}	g_{11}	g_{12}	g_{13}	g_{14}	g_{15}	g_{16}	g_{17}	h_1
-378.9	-378.9	-296.8	-7.86	-296.8	-7.86	-152.33	-152.33	-0.17

The optimization statement can be formulated as follows:

maximize $\xi_{science,sol}$

s.t.,

$0.01 \leq A_{rad} \leq 2$; $0.01 \leq d_{wheel} \leq 1$; $0.01 \leq b_{wheel} \leq 1$; $0.01 \leq T_{mot} \leq 500$; $0.01 \leq L_{0.5base} \leq 2$; $0.01 \leq L_{0.5track} \leq 2$; $1 \leq i_{gear} \leq 10000$; $0.01 \leq t_{motion} \leq 12$; g_1: $\frac{M_{rover} \cdot V_{rover}(a+g\sin\theta)}{\eta_{actuator}} - (T_{mot}\omega_{mot}) \leq 0$; g_2: $-mfp + 15 \leq 0$; g_3: $R_{compaction} - 125 \leq 0$; g_4: $i_{mot} - \frac{(\pi\omega_{mot}d_{wheel})}{60V_{rover}} \leq 0$; g_5-g_{10}: $[1 - F_{wheelA}, 1 - F_{wheelB}, 1 - F_{wheelC}, 1 - F_{wheelD}, 1 - F_{wheelE}, 1 - F_{wheelF}] \leq 0$ (uphill); g_{11}-g_{16}: $[1 - F_{wheelA}, 1 - F_{wheelB}, 1 - F_{wheelC}, 1 - F_{wheelD}, 1 - F_{wheelE}, 1 - F_{wheelF}] \leq 0$ (crosshill); g_{17}: $M_{rover} - 250 \leq 0$; h_1: $Q_{web} - Q_{dissp} = 0$

The constraints used here are similar to as used in the mass minimization problem except for total mass constraints. This assumption is prudent because larger structural components deliver better science returns and vice-versa. The GA crossover and mutation operators are set similar to earlier settings. The population size is set to be 16. The GA is run for 1000 generations. It seems that the convergence for best design solution is reached as seen in the trend of the fitness function in Fig. 9.

Some observations can be made of the design solution obtained after the optimization procedure. For producing sufficient power to sustain the rover motion, a trade-off case exists between solar array dimensions and the duration of motion in the presence of mass constraints. In order to gain high science returns, this the rover should move at high speeds. It can be seen that the GA selects duration of nearly 12 hours of motion per sol for the rover. To sustain this capability, the rover will have a 7.16 m^2 solar array and a 777.44 Whr capacity battery. This means a maximal science returns of up to 0.18 can be derived from this rover. This corresponds to a rover velocity of 0.18 m/s. Furthermore, the wheel has a size of 0.8 m diameter and 0.53 m width. This causes a compaction resistance of 99.81 N during motion on soft soil. The optimized suspension full lengths and widths are 0.52 m and 0.6 m respectively. The mean free path performance for this suspension is estimated to be 108.27 m. The overall mass of the rover is 246.65 kg. The best design solution is summarised in Table 9. The constraints are listed in Table 8. The subsystem mass breakdown is given in Table 10. Fig. 10 shows the normalized values of the design variables in the final generation. The individuals are evenly distributed which means after satisfying given constraints, a design convergence has been attained. The population statistics of the 1000th generation is given in Table 11.

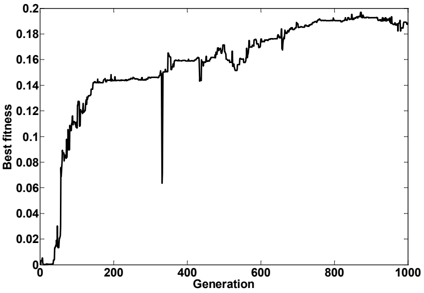


Fig. 9 - Convergence history of best fitness

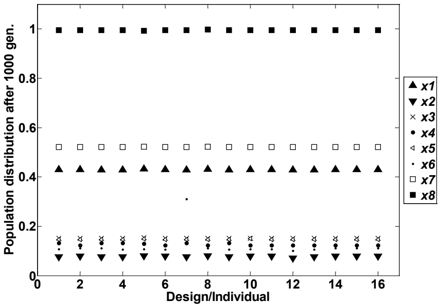


Fig. 10 - Population distribution at 1000th GA generation

Table 9 - Best design solution after 1000 GA iterations

Design variables	Value
Radiator area (m^2)	0.44
Wheel diameter (m)	0.80
Drive motor nominal torque (mNm)	75.71
Half wheel base length (m)	0.26
Half wheel track length (m)	0.30
Gear ratio	1112
Wheel width (m)	0.53
Motion time per sol (hrs)	11.98

Table 10 - Mass breakdown of rover subsystems

Subsystem	Mass value
Payload (kg)	50.0
Mobility (kg)	15.29
Power (kg)	84.89
Thermal Control (kg)	19.82
Other subsystems (kg)	76.65
Total mass (kg)	246.65

Table 11 - GA final population properties

GA property	Value
Best fitness	0.18
Mean fitness	0.11
Median fitness	0.14

5. CONCLUSIONS

Rover design trade-off studies during conceptual design phases should take into account subsystems dependencies and performance expectations. In traditional practice, engineers tend to test available components and decide the final design solely based on trial and error. In general, the concept of optimizing systems according to user objectives is not considered and the interrelationships between subsystems are not taken into account. Furthermore, conventional optimization techniques have a limited scope due to the large number of design variables and the difficulty of finding global optima.

In this paper, the author has described a GA-based methodology for optimizing Mars rover designs. In particular, two optimization approaches with different objectives – (1) mass minimization and (2) science returns maximization- are highlighted. For the same payload of 50 kg, the mass minimization procedure produced a design solution with a mass of 185.55 kg. The science returns maximization procedure produced a rover with a science returns ratio of 0.18. In both cases, the GA optimization technique is used.

The GA utilizes newly developed parametric mass models in combination with physics-based models for sizing rover subsystem. The proposed method has been found to demonstrate efficiency and satisfactory results. This reported work is part of the development of a computational tool that helps in an efficient design process of rover systems. The tool may be useful for identifying design concepts for future rover missions.

REFERENCES

[1] J. R. Wertz, W. J. Larson, *Space Mission Analysis and Design* (3rd edition), Springer Limited, London, 1999.

[2] M. P.Golombek, A. F. C. Haldemann, N. K. Forsberg-Taylor, E. N. DiMaggio, R. D. Schroeder, B. M. Kakosky, M. T. Mellon, J. R. Matijevic, Rock size-frequency distributions on Mars and implications for Mars Exploration Rover landing safety and operations, *Journal of Geophysical Research*, **108** (12), 2003.

[3] B. Wilcox, A. Nasif, R. Welch, Implications of Martian Rock Distributions on Rover Scaling, *Planetary Society International Conference on Mobile Planetary Robots and Rover Roundup*, Santa Monica CA, 1997.

[4] G. E. P. Box, K. B. Wilson, On the Experimental Attainment of Optimum Conditions (with discussion), *Journal of the Royal Statistical Society*, *Series B 13*(1), pp. 1–45, 1951.

[5] O. L. de Weck, P. N. Springmann, D. D. Chang, A Parameteric Communications Spacecraft Model for Conceptual Design Trade Studies, *21st International Communications Satellite Systems Conference and Exhibit*, 2003.

[6] P. N. Springmann, O. L. de Weck, Parametric Scaling Model for Nongeosynchronous Communications Satellites, *Journal of Spacecraft and Rockets*, Vol. **41**, No. 3, 2004.

[7] V. Kucherenko, V. Gromov, I. Kazhukalo, A. Bogatchev, S. Vladkin, A. Manykjan, *Engineering Support on Rover Locomotion for ExoMars Rover Phase A – "ESROL-A"*, Science & Technology Rover Company Limited (RCL), Report No. FR-1011/2004/RCL, 2004.

[8] * * * *Maxon Motor AG, Maxon Motor Catalog*, Program 09/10.

[9] J. Appelbaum, G. A. Landis, Solar Radiation on Mars – Update 1991, *NASA Technical Memorandum 105216*, 1991.

[10] D. E. Goldberg, *Genetic Algorithms in Search, Optimization and Machine Learning*, Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1989.

[11] M. G. Bekker, *Theory of Land Locomotion: The Mechanics of Vehicle Mobility*, University of Michigan Press, 1956.

[12] A. Ellery, N. Patel, L. Richter, R. Bertrand, J. Dalcomo, Exomars Rover Chassis Analysis & Design, P*roceedings of the 8th International Symposium on Artifical Intelligence, Robotics and Automation in Space*, Munich, Germany, 2005.

[13] J. Y. Wong, *Theory of Ground Vehicles*, 4th edition, John Wiley & Sons, New Jersey, 2008.

[14] M. D. Griffin, J. R. French, *Space Vehicle Design*, AIAA Education Series, 1991.

NOMENCLATURE

a=desired acceleration; k=pressure-sinkage factor; x_{rms}=rms deviation; d_{wheel}=wheel diameter; σ=Stefan-Boltzmann constant; φal=albedo flux constant; g=acceleration due to gravity; k_c=soil cohesion modulus; k_ϕ= soil friction modulus; n=soil deformation component; ϕ=internal friction angle; M_{PL}=payload mass; M_{rover}= total rover mass; M_{ACS}= attitude control subsystem mass; M_{pow}= power subsystem mass; M_{mob}=mobility subsystem mass; $M_{telecom}$=communications subsystem mass; $M_{C\&DH}$=command and data handling subsystem mass; M_{cabl}=cabling mass; M_{motor}=motor mass; M_{gear}=gear mass; M_{pow}=power subsystem mass; M_{TC}=thermal control subsystem mass; $M_{arrayblanket}$= solar array blanket mass; $M_{arraystruct}$=solar array supporting structure mass; M_{bat}=battery mass; $M_{radiator}$=thermal radiator mass; T_{mot}=nominal motor torque; $T_{av.,persol}$=average recharge time per sol; T_{WEB}=WEB temperature; T_{rad}=radiator temperature; T_{motion}=total motion time; $igear$=gear ratio; z=wheel sinkage; b_{wheel}=wheel width; $R_{compaction}$=compaction resistance; n_{wheels}=number of wheels; L_{track}=length of vehicle track; $L_{0.5base}$=half-lengths of vehicle base; $L_{0.5track}$=half-lengths of vehicle track; D=diameter of rock; $D0$=limiting rock diameter; $\rho(D)$=cumulative fractional number of rocks of diameter D; C_{bat}=*b*attery capacity; e_{bat}=specific energy of battery; A_{sa}=solar array area; m_{cell}=specific mass of solar cell; $P_{rover,nom}$=nominal power consumption of rover; $P_{rover,peak}$=rover power consumption of rover; $P_{s/s,exp.cycle}$=power consumption per experimental cycle; $P_{bat,charge}$=power required for battery charge; $P_{nom,persol}^{day}$=nominal power consumption per sol during day; $P_{nom,persol}^{nig\square t}$=nominal power consumption per sol during night; $P_{peak,persol}^{day}$=peak power consumption per sol during day; $P_{peak,persol}^{nig\square t}$=peak power consumption per sol during night; $T_{peak,persol}^{day}$=duration of peak power consumption during day; $T_{peak,persol}^{nig\square t}$=duration of peak power consumption during night; η_{day}=efficiency of day-time operation; η_{night}=efficiency of night-time operation; η_{bat}=battery efficiency; η_{cell}=solar cell efficiency; η_{rad} =radiator efficiency; ε_{paint}=paint emissivity; ε_{rad}=radiator emissivity; DOD=depth of discharge; ρ_{rad}=material density of radiator material; A_{rad}=area of radiator; A_{WEB}=WEB area; $A_{WEB,proj}$=projected area of WEB exposed to sunlight; $trad$=radiator thickness; Q_{albedo}=heat due to albedo; Q_{paint}=heat dissipated by paint; Q_{rad}=heat dissipated by passive radiator; Q_{dissp}=dissipated heat; Q_{WEB}=heat dissipated from WEB; Q_{sun}=solar heat rate; ω_{mot}=angular velocity of motor; $F_{wheelXY}$=Wheel contact force with soil; $\xi_{science,sol}$=science return ratio per sol; $E_{rover.egress}$=energy required for rover egress ops; I_{mean}=mean solar flux; FAC_{degrad}=degradation factor; $FAC_{tempeff}$=temperature effect; $FAC_{packing}$=pack factor of solar array