CHASSIS DESIGN & PERFORMANCE ANALYSIS FOR THE EUROPEAN EXOMARS ROVER

Alex Ellery[1], Lutz Richter[2], Reinhold Bertrand[3]

[1]Surrey Space Centre, University of Surrey, Guildford, Surrey. GU2 7XH, UK

[2]Deutschen Zentrum fur Luft und Raumfahrt (DLR), Koln, Germany

[3]von Hoerner & Sulger GmbH, Schwetzingen, Germany

Abstract

The European Space Agency's (ESA) ExoMars rover has recently been subject to a Phase A study led by EADS Astrium, UK. This rover mission represents a highly ambitious venture in that the rover is of considerable size ~200+kg with high mobility carrying a highly complex scientific instrument suite (Pasteur) of up to 40 kg in mass devoted to exobiological investigation of the Martian surface and sub-surface. The chassis design has been a particular challenge given the inhospitable terrain on Mars and the need to traverse such terrain robustly in order to deliver the scientific instruments to science targets of exobiological interest. We present some of the results and design issues encountered during the Phase A study related to the chassis. In particular, we have focussed on the overall tractive performance of a number of candidate chassis designs and selected the RCL concept C double rocker-bogie design as the baseline option in terms of high performance with minimal mechanical complexity overhead.

Introduction

The Aurora programme is a European vision of Mars and planetary exploration for the next two decades, culminating in a human mission to Mars around 2030. This ambitious programme comprises a series of large, "flagship" missions interspersed by smaller, "arrow" missions. The Aurora programme is structured around two major technological themes – the development of human support technologies, and a series of robotic exploration missions. The first flagship mission in the Aurora programme is the ExoMars rover which is an exobiology-focussed science mission based on a rover design. The scheduled launch at the time of the study was 2009 (though 2011 is more likely). This paper presents some of the results of the Phase A study for the ExoMars rover and its Pasteur payload – the Phase A study was led by EADS Astrium UK and involved von Hoerner & Sulger GmbH Germany, University of Surrey Space Centre UK, Deutschen Zentrum fur Luft und Raumfahrt (DLR) Germany, Ecole Polytechnique Federale Laussane (EPFL) Switzerland (collectively, the rover chassis design team), Laboratory for Analysis & Architecture of Systems (LAAS-CNRS) France (autonomous navigation), University of Wales Aberytstwyth (operations), SciSys Ltd UK (autonomy), and Galileo Avionica Italy (Pasteur payload). In particular, we consider the issue of mobility as this aspect has two major implications:

(i) mobility determines access to areal exploration, and thereby, the selection of scientific targets, and so, scientific return;

(ii) mobility in terms of traversability of terrain determines the level and sophistication requirements of the autonomous navigation system;

We are concerned with both the chassis design and performance analysis in realistic Martian environments.

The ExoMars Rover & Pasteur Payload

The scientific objectives of the ExoMars rover are to search for evidence of extant and extinct biota through the deployment of scientific instruments and in-situ soil analysis. In addition, the mission is to enhance our knowledge of the Martian environment, particularly with regard to future human exploration missions. The Descent Module (DM) was assumed to provide for the entry descent and landing (EDL) phases which was beyond the scope of this study – options included traditional aeroshell braking/parachute/airbag and inflatable braking device systems. The ExoMars mission is based on delivery to the Martian surface between $\pm10^o$ and $\pm45^o$ latitude of a large rover payload of ~200 kg mass, carrying an exobiology-focussed scientific instrument suite with sample acquisition and handling devices (the 40 kg Pasteur payload package) (Fig 1). The surface mission is to be designed to operate for 120 sols (10 experiment cycles). During the design, attention was given to the requirements of planetary protection to minimise the prospect for forward contamination of the Martian environment.

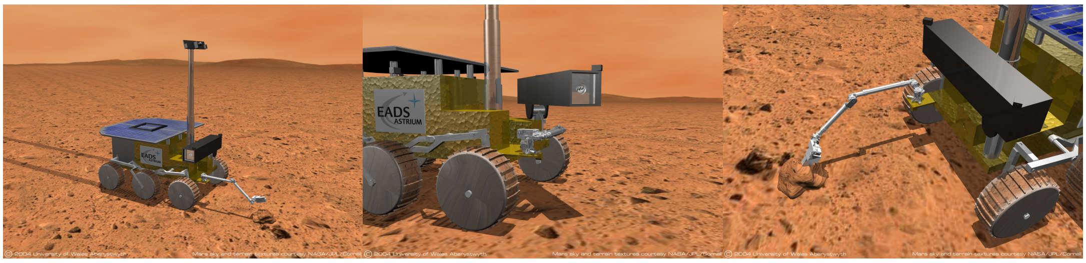


Fig 1. ExoMars rover (a) overall view; (b) drill deployment; (c) arm deployment (EADS Astrium)

The DM interfaces considered including shared DM/rover power and control, and dedicated DM power and control, the latter being the preferred option. The rover was to be held down onto a baseplate during the cruise, entry, descent and landing in a stowed configuration, and deployed after landing – the requirement for deployment effectively introduced the capability for wheel-walking mode of locomotion "for free". The ExoMars rover comprises three major elements – Pasteur science suite, rover chassis, and rover support subsystems. Power is a critical design issue. The baseline design was a solar-powered rover with batteries for energy storage supported by radioisotope heating units (RHU). The power loss from the solar arrays due to dust deposition at the end of life (EOL) was estimated to be ~30%. Given the solar flux dependency which is subject to considerable uncertainty, a long life rover option was considered which used a Stirling cycle generator to convert RHU thermal energy into electrical energy but this option was discarded on the basis of lack of technological maturity in comparison to more traditional energy conversion approaches adopted in off-the-shelf RHUs. The need for autonomous capability was essential to minimise ground intervention (nominally one command cycle/sol).

Chassis Design

The ExoMars rover is required to traverse hostile terrain comprising different types of soil, a variable distribution of obstacles, and variable slopes. The baseline velocity of traverse was taken to be 100 m/sol. A number of chassis designs were considered [1] – legged locomotion was discarded on the basis that leg control is inherently more complex and less developed than for wheeled or tracked vehicles; articulated bodies were also discarded on the basis of payload integration complexities (eliminating Marskhod-based concepts); four-wheel concepts were also discarded on the basis of poor traction and obstacle climbing capability (eliminating many lunar rover designs); eight-wheeled concepts were considered to have high mass penalties. All-in-all, 19 chassis concepts were considered – tracked vehicles were rejected on the basis of poor power efficiency. The elastic loop mobility system (ELMS) uses a pair of elastic tracks which do not require bogie wheels to maintain contact with the terrain – this was rejected on the grounds of technological immaturity but potentially offers good performance without the high power losses of conventional tracks of pinned links (Fig 2).

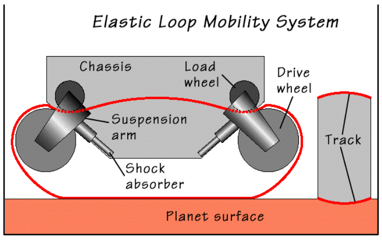


Fig 2. Elastic loop mobility system concept (NASA)

The baseline chassis designs selected for consideration were six-wheeled concepts on the basis of technology demonstration and high maturity. Furthermore, a discrete suspension frame was selected to provide body-averaging and wheel load averaging capability. The selected designs included the US rocker-bogie mechanism as used on Sojourner and the Mars Exploration Rovers, RCL concepts C, D (with symmetrical rocker bogie design) and E (orthogonal bogie design) [2], the Solero parallelogram rocker design, and the Crab symmetric parallelogram rocker concept.

Wheel Design

From the point of view of traction analysis, suspension kinematics has no effect on drawbar pull. The critical parameter is ground contact area which is determined by the wheel design. The MERs adopted curved tyre geometries to accommodate the oblique orientation of the steering actuators with respect to the wheel – the curved wheels ensured a constant surface contact with the soil during steering. For ExoMars, each wheel is independently powered with dedicated drive motors. Each motor is sensorised for speed and torque control and provides the basis for slippage detection. Drawbar pull computations were based on Bekker theory of traction [3-5] and included consideration of soil thrust (dependent on soil parameters), soil sinkage resistance and soil bulldozing. The algorithms employed are detailed in [6]. The soil thrust less the motion resistances determines the drawbar pull, the standard metric for traction performance. We initially assumed an ExoMars vehicle of mass 200 kg with a footprint of 1.2m by 1.0m. In particular, we considered the effects on drawbar pull of varying the dimensions of the wheels – given the necessity of accommodation of the rover within the DM, large diameter wheels were adopted at the expense of wheel width (Table 1).

Vehicle	Wheel width (m)	Wheel diameter (m)	Rover drawbar pull (N)
CDF[1] report baseline	0.08	0.4	85.96
Smaller wheels	0.08	0.3	18.74
Larger wheels	0.08	0.5	129.23
Very wide wheels	0.4	0.4	180.87
Narrow wheels	0.05	0.4	62.94
Wide wheels	0.15	0.4	119.85

Table 1. Predicted drawbar pull for different wheel dimensions

The addition of grousers increases soil thrust, and so drawbar pull, with minimal impact on mass overhead but they increase the drive power requirements (Table 2).

Vehicle	No. wheels	Wheel width	Grouser height	Wheel Diam.	Soil thrust	Drawbar Pull
6 wheel baseline	6	0.08	0.01	0.4	466.259422	112.44657
No grousers	6	0.08	0	0.4	452.198059	103.210058
Large grousers	6	0.08	0.015	0.4	474.304858	117.731389
Larger grousers	6	0.08	0.02	0.4	483.026797	123.460584

Table 2. Predicted drawbar pull for wheels with different grouser configurations

Following a number of design iterations, our final wheel parameters listed below provide sufficient performance for ExoMars (Table 3):

[1] Critical Design Facility, ESA-ESTEC, Noordwijk, Holland

No. wheels	Wheel width (m)	Grouser height (m)	Wheel diameter (m)	Vehicle mass (kg)	g (m/s^2)
6	0.1	0.016	0.35	220	3.73

Table 3. Vehicle parameters for the traction analysis on different soils

Using the above baseline wheel design, the drawbar pull values were computed for a number of different soils including DLR Mars soil simulant, Viking and Pathfinder landing sites soil, representative terrestrial soil types and Mars Exploration Rover landing sites soil (Table 4).

Soil	Specific gravity (ρg)	Soil Cohesion (Pa)	Friction angle (°)	K_c (N/m^{n+1})*	K_ϕ (N/m^{n+2})*	Consistency ($k=k_c+bk_\phi$)	Deformation coeff (n)**	Draw bar Pull (N)
DLR soil simulant A	4.24	188	24.8	2370	60300	8400	0.63	112.7
DLR soil simulant B	4.24	441	17.8	18773	763600	95133	1.1	155.0
VL1 drift	4.29	1600	18	1400	820000	83400	1.0	151.28
VL1 blocky	5.97	5500	30.8	1400	820000	83400	1.0	319.5
VL2 crusty-cloddy	5.22	1100	34.5	1400	820000	83400	1.0	378.8
PL drift	4.36	380	23.1	1400	820000	83400	1.0	215.2
PL cloddy	5.70	170	37	1400	820000	83400	1.0	421.45
Dry sand	5.67	1040	28	990	1528000	153790	1.1	293.2
Sandy loam	5.67	1720	29	5270	1515000	156770	0.7	298.8
Clayey soil	5.67	4140	13	13190	692200	82410	0.5	79.2
MER-B 'sandy loam'	4.24	4800	20.0	28000	7600000	788000	1.0	202.7
MER-B 'slope soil'	4.24	500	20.0	6800	210000	27800	0.8	137.2

* as there is no experimental data from VL1, VL2 and PL, we have used lunar values for those soils
** as there is no experimental data from VL1, VL2 and PL, we have assumed n=1 for those soils

Table 4. Predicted drawbar pull on different soil types

The baseline chassis dimensions and configuration is thus robust for all Martian soil types and all terrestrial soils. The poorer performance on clays is due to its very low frictional properties and such soils are considered unlikely on Mars. The Martian drift soil represents the worst-case soil type (with marginal performance similar to DLR soil simulants) and VL2 crusty-cloddy soil is considered to the most representative Martian soil type (more favourable than terrestrial sandy-loam).

The baseline chassis system was developed further with the introduction of flexible wheel options which offer increased soil thrust and reduced sinkage in soils allowing the use of smaller wheels for the same drawbar pull performance, thereby easing the accommodation problem within the DM. Wheel deformation yields reduced mean maximum pressure (MMP)[2] beneath the wheel and so wheel sinkage and sinkage resistance. All-metal flexible wheels with elastic leaf springs mounted within a metal tyre is a suitable approach to elastic wheel design (Fig 3).

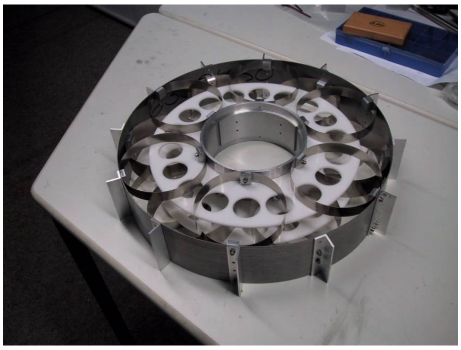


Fig 3. Flexible wheel design (DLR)

Three rows of metal leaf springs mounted to a rigid hub surrounded by a metallic tyre provided the basis for smaller wheels of 0.3m undeformed diameter with a predicted drawbar

---

[2] $MMP_{wheel} = \frac{KW}{2nb^{0.85}d^{1.15}(\delta/h)^{0.5}}$ where W=vehicle weight

n=number of axles
d=wheel diameter
b=wheel width
δ/h=fractional radial tyre deflection
K= parameter defined by proportion of axles driven

pull of 260 N for a 200 kg ExoMars rover in DLR soil simulant A, ie. more than double the performance of a larger rigid wheel. For the power budget, estimates of the power consumption during driving were required – this was computed from the soil resistances. As listed in Table 5, the power consumption at different rover speeds, slopes and slippages are given – the effective locomotion speed is 100m/sol but the nominal locomotion speed is taken to be 72m/h to account for other operations such as rover localisation, path planning, data acquisition, obstacle avoidance and obstacle negotiation.

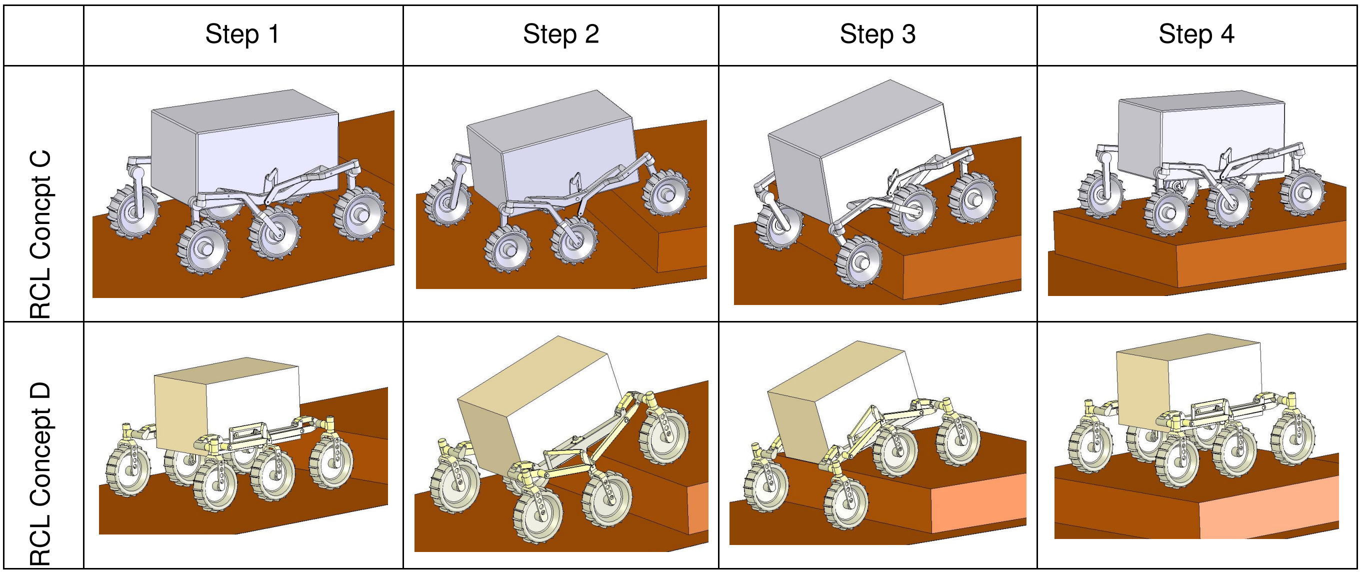
#	Locomotion Function	Speed [m/h]	Slope [degrees]	Mech. Output Power [W][3]	Slip [%]	Design Margin [factor]	Electr. Input Power [W][4]	Duration per sol [minutes]	Remark
1	Driving on Soil C	72	10°	4.67	10	2.0[5]	27.65	100[6]	10° slope is the mean slope on a 100 m basis
2			18°	7.54	22	2.0	44.67	100	
3			25°	16.63	53	2.0	98.52	100	
4		100	10°	6.48	10	2.0	38.41	20	
5			18°	10.47	22	2.0	62.04	20	
6			25°	23.09	53	2.0	136.83	20	
7	Obstacle Climbing (0.3 m step)	2 cm/s	90	6x6.87	n.a.	1[7]	102	5[8]	worst case assumption[9]

Table 5. Predicted input power for different speeds and slope angles

Chassis Kinematic Design

[3] This is the mechanical power needed to drive the wheels, i.e. the power acting on the hubs of the wheels.
[4] This figure accounts for mechanical losses in the gear stages, motor efficiency as well as power electronics efficiency
[5] A design margin of 2.0 is assumed to compensate for uncertainties in design loads for driving operations.
[6] 100 minutes represents the duration needed to traverse 100 m/sol with the nominal speed of 72 m/h.
[7] the design load assumption of one wheel pair to shift 1/3 of the rover's weight is already considered to be very conservative. Consequently, no further design margin is applied.
[8] 5 minutes is the net time estimated to be necessary to climb an obstacle, e.g. a unit step.
[9] assuming Earth gravity; each wheel pair must lift 1/3 of the rover's weight, this power need is multiplied by 3 for each axle. Design margin comes from Earth Gravity (factor 2) and equal load assumption for all wheels.

The chassis kinematics defines the wheel suspension and steering. One of the requirements was for on-the-spot turning capability. Passive springless suspension is the commonest approach for planetary rovers whereby the wheels are suspended to the rover body with a number of kinematic links. This provides the means for obstacle climbing and/or crevasse crossing by equilibriating the nominal ground pressure beneath each wheel. There were five candidate suspension concepts selected from the initial 19 reviewed (Fig 5). The US rocker-bogie is longitudinally asymmetric in that front and middle wheels are linked by rocker levers while the rear wheels are fixed at the end of the bogie. The RCL concepts C and D add an additional lever to make the kinematic structure longitudinally symmetric – a double rocker-bogie design. Concept C is simpler than concept D which utilises double rather than single levers and so imposes a greater mass overhead. RCL concept E represents a return to the longitudinally asymmetric design in which the rear wheels are linked laterally to the longitudinal axis by an orthogonal lever. The front and middle wheels are also linked longitudinally through levers. However, unlike the US rocker-bogie system, the rear wheels are not connected through levers to the middle/front wheel assemblies. The solero design is altogether novel in that it utilises a springed front fork wheel and side rocker levers. The fixed back wheel is a problem but could be replaced by a rear forked wheel at the cost of mechanical complexity. The crab parallelogram rocker suspension links front and rear wheels through the middle axle.



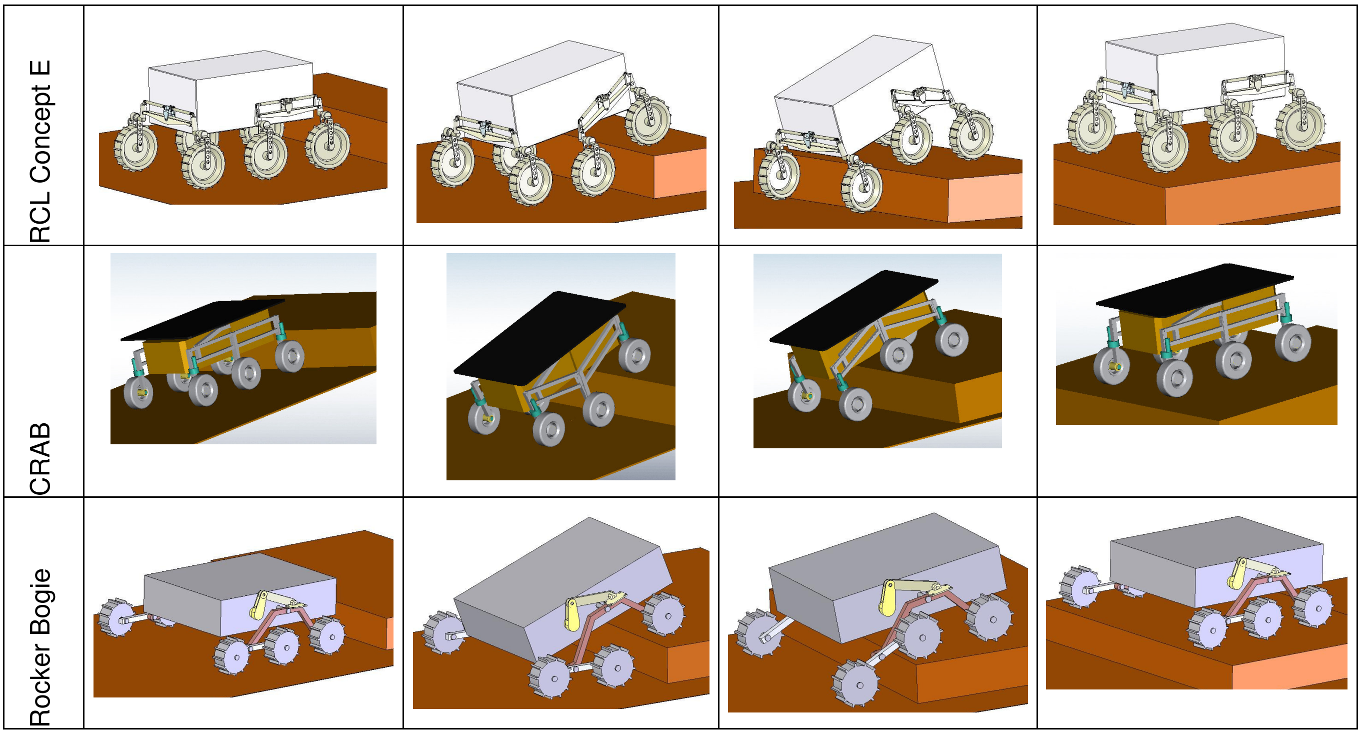


Fig 4. Candidate suspension systems deployed for obstacle avoidance (EADS Astrium)

The symmetric designs (RCL C, RCL D and Crab) have superior obstacle climbing capabilities as determined from simulation using SolidWorks™ and Cosmos-Motion™ software. Relevant issues in the final selection of the chassis design include mechanical complexity (and so mass overhead) for which the US rocker-bogie and concept E are favoured. However, for obstacle climbing performance, RCL concept C was selected as the baseline but is simpler than RCL concept D.

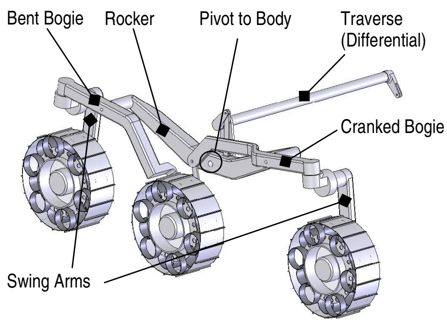


Fig 5. RCL concept C chassis design (EADS Astrium)

Ackermann steering is to be implemented on the four corner wheels through independent steering actuators – the implementation of 6-wheel steering which allows crab-like movement was disfavoured due to the mass impact of two additional steering motors. The steering motors were to be accommodated within the wheels similar to that adopted on MERs. Due to the requirement for compact stowage in the DM and subsequent deployment of the wheels, wheel walking is provided “for free”. Stowage requires rotating the front wheels aft and the aft wheel forward to minimise the rover length. Wheel walking provides movement of the rover centre of mass, high performance traction for climbing slopes and traversing drift material, and the possibility of “posing” during instrument deployment. The mass budget for the chassis assumes Ti rods and levers, wheels of stainless steel and CFRP bumpers (Table 6).

	per unit mass	no of units	mass w/o margin	maturity margin	mass incl. margin
wheels	2.00	6.00	12.00	0.15	13.80
corner wheel motor, gear, wheel walking	3.80	4.00	15.20	0.15	17.48
center wheel motor and gear	2.50	2.00	5.00	0.15	5.75
suspension system (levers)	6.60	2.00	13.20	0.15	15.18
suspension system (differential)	4.40	1.00	4.40	0.15	5.06
cable harness	1.70	1.00	1.70	0.15	1.96
embedded sensors	1.00	1.00	1.00	0.15	1.15
total			**52.50**		**60.38**

Table 6. Chassis mass budget

Autonomous Navigation

The degree of autonomy required by the ExoMars rover may be quantified by computation of the mean free path of the rover through a Mars-like rock distribution [7]. The mean free path defines a statistical average of straight-line paths that may be followed before a steering change is required due to the incidence of an obstacle. The ExoMars rover is required to have a minimum obstacle climbing ability of 0.3m, above which an obstacle must be avoided. Furthermore, we have considered a worst-case rock distribution defined by the Viking lander 2 site (Fig 6).

Fig 6. Viking Lander 2 site rock distribution

Mean free path for ExoMars through a Viking Lander 2 site rock distribution is 29.6m assuming point turning which decreases to 18.7m with a 3m turning diameter.

Conclusions

We have considered issues in the design of the ExoMars chassis. We have discussed an approach to wheel design using Bekker theory to quantify drawbar pull as a traction performance metric over Martian soils. We have considered the kinematic design of the suspension system, selecting a double rocker-bogie mechanism to minimise mechanical complexity within the required obstacle negotiation requirements. We have also quantified this in terms of mean free path indicating the impact of the chassis design on the navigation autonomy requirements.

References

[1] Rover Team[10] (2004) "Pasteur Exobiology Payload & Rover for ExoMars: Technical Note 2/3 – Design Concepts & Trade-Off Analysis" EADS Astrium Ltd Technical Note ROV.TN2/3.01.EU.ASTR.C, Stevenage, UK

[2] Kucherenko V, Gromov V, Kazhukalo I, Bogatchev A, Vladykin S, Manykjan A (2004) *Engineering support on rover locomotion for ExoMars rover phase A – ESROL-A*, Science & Technology Rover Co Ltd (RCL) Final Report FR-1011/2004/RCL, Russian Transport Machinery Engineering Institute (VNIITRANSMASH), St Petersburg, Russia

[3] Bekker M (1960) *Introduction to Terrain Vehicle Systems Part 1 – The Terrain & Part 2 – The Vehicle*. University of Michigan Press, Ann Arbor, USA

[4] Bekker M (1959) *Theory of Land Locomotion: the mechanics of vehicle mobility.* University of Michigan Press, Ann Arbor, USA

[5] Bekker M (1960) *Off The Road Locomotion.* University of Michigin Press, Ann Arbor, USA

[6] Ellery A (2005) Environment-robot interaction – the basis for mobility in planetary rovers. In press with *Robotics & Autonomous Systems*

[7] Wilcox B (1998) A nanorover for Mars. *Space Technology* 17 (3/4) (1998) 163-172

[10] Enrico Battistelli, Reinhold Bertrand, Francesco Butera, Raja Chatila, Alessandro Del Biancio, Chris Draper, Alex Ellery, Rolando Gelmi, Felix Ingrand, Charles Koeck, Simon Lacrois, Pierre Lamon, Piergiovanni Magnani, Nildeep Patel, Carlo Pompei, Eduardo Re, Lutz Richter, Roland Seigwart, Richard Slade, Mark F Smith, Gregoire Terrien, Ronan Wall, Roger Ward, Lester Waugh, Mark Woods