In Proceedings of the 9th ESA Workshop on Advanced Space Technologies for Robotics and Automation
'ASTRA 2006' ESTEC, Noordwijk, The Netherlands, November 28-30, 2006

DESIGNING THE NEXT GENERATION OF ROVERS THROUGH A MID-ROVER ANALYSIS

9th ESA Workshop on Advanced Space Technologies for Robotics and Automation ASTRA 2006

28 – 30 November 2006 at ESTEC,
Noordwijk, the Netherlands

Julien-Alexandre Lamamy(1), David W. Miller(1)

(1) ***Space Systems Laboratory***
Massachusetts Institute of Technology
70 Vassar St, Cambridge, MA 02139, USA
jal@mit.edu, *millerd@mit.edu*

INTRODUCTION

The 2009 Mars Science Laboratory (MSL) mission and the 2013 ExoMars mission developed by NASA and ESA, respectively, will perform breakthrough science in the search for life on Mars. Whereas the 2003 Mars Exploration Rovers were designed by NASA in just three years [1], the design and development phases of both MSL and ExoMars span over more than 8 years [2, 3]. The scopes and objectives of the two missions have evolved since their first formulation. The original objective of MSL, first called Mars Smart Lander, was to demonstrate Entry Descent and Landing (EDL) technologies for the subsequent Mars Sample Return (MSR) mission. After three years, the emphasis shifted from a technology demonstration mission to a science driven mission. The ExoMars mission has evolved from an aggressive science mission to one balancing science and technology. In 2004, the ExoMars phase A design called for 24 kilograms of instrumentation; subsequent revisions have led to significantly lower mass requirements [4].

The MSL and ExoMars missions illustrate how stakeholders of the Mars exploration programs (e.g. science and technology communities, national governments) drive the scientific and technical definition of space missions. This article presents a systems engineering tool called, Mars Surface Exploration (MSE), and a systems architecting approach that help understand the influence of these forces on the design of rover missions. MSE is a rover modeling tool that creates families of rover designs variants, called *mid-rovers*, based on science objectives. The tool, coupled with a systems architecting approach, enables mission designers to identify early on the stakeholders and their objectives, and to quantify their impact on mission systems in order to accelerate the design phase and the convergence to a stable mission implementation. The article first introduces the functionality of the MSE tool and then presents an analysis of the ExoMars mission.

MARS SURFACE EXPLORATION ROVER MODELING TOOL

Functionality

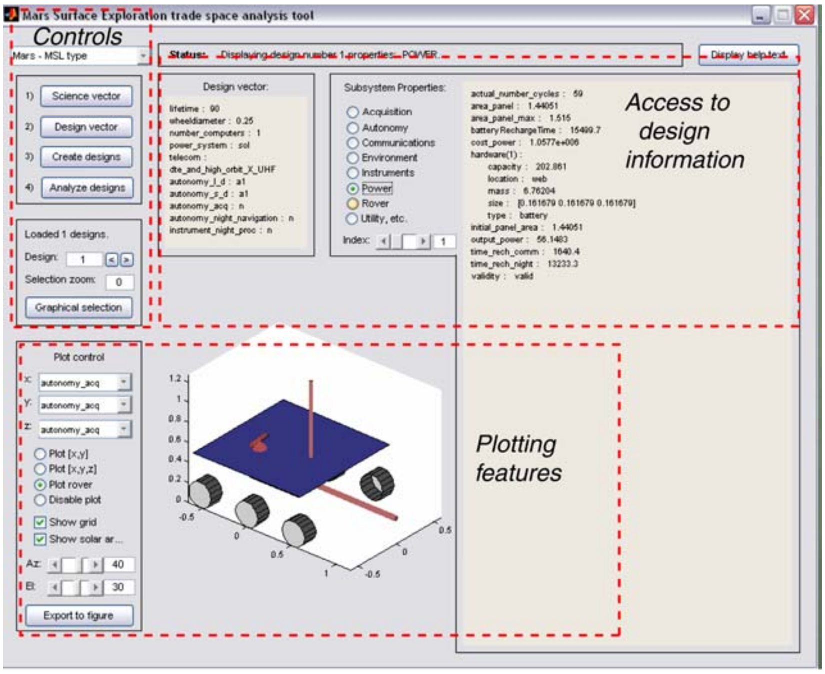
MSE is a systems engineering tool for the design of rover missions originally developed in 2003 by the Space Systems Engineering graduate class at MIT [5]. It has since been further enhanced by the MIT Space Systems Laboratory with the support of the Jet Propulsion Laboratory (JPL). The tool is intended to help designers during pre-phase A rover mission design. MSE enables designers to model and analyze very rapidly a wide range of design options for a mission whose science goals have been defined. The emphasis is on breadth rather than on in-depth modeling of specific designs. Other rover modeling tools exist at NASA’s and ESA’s concurrent engineering facilities that take the approach of interconnecting sophisticated software design environments to conduct detailed analyses of a particular mission. MSE's approach complements in-depth modeling techniques which, in return, assist in the validation of MSE's models at various points of the design space.

The simulations done in MSE capture the engineering, science performance, and cost aspects of a rover mission. Other elements supporting the rover, such as the cruise stage, Entry Descent and Landing (EDL) system, and lander, are not included in the primary functionality of MSE. However, a first order model of a lander and EDL systems has subsequently been added to MSE in order to analyze surface strategies for the Mars Sample Return mission. In addition, the six wheel rocker-bogie suspension [6] is the default mobility system in MSE. Other mobility types are currently being added, including four wheel, legged, and hybrids legged-wheel systems. Furthermore, MSE does not model component failures and rover fatigue. The only factors of performance degradation considered are the obscuration of solar panels by dust and the limited number of measurements a given instrument can perform (e.g. the limited number of sample cups for the Sample Analysis at Mars instrument on MSL).

MSE users can generate a wide range of rover variants by tuning several key engineering characteristics of the design, which are called *design variables*. The design variables were carefully selected in MSE to minimize feedback loops between calculation modules and to capture the design trade-offs relevant to mission designers. In addition, the tool was conceived to be reliable, rapid, easily usable, open-source, and extensible. To meet these specifications the tool has been implemented in a modular structure that matches the morphology a rover system itself. Each rover subsystem is modeled in an independent piece of MATLAB code easily accessible for review, update, and validation. The user interacts with MSE through a graphical user interface which makes the tool accessible to users not familiar with MATLAB (Fig. 1). Thanks to its inherent flexibility, the tool has evolved and the scope of its applications has expanded from the design of traditional Mars rover missions to that of MSR type missions and Lunar missions. The subsequent section describes the approach to rover design modeling implemented in MSE.

Tool Description

MSE enable designers and scientists to explore and analyze a range of design options that meet their science objectives. The tool generates a family of mid-rovers, which differ by the technologies they are built with, based on a user-defined science scenario. The science scenario, common to all rovers, is parameterized in the *science vector*. The technology options, which vary from rover to rover, are parameterized in the *design vector*. Once the trade space is created several built-in tools enable the user to analyze it. The controls for the definition of the science and design vectors, and for the creation of the trade space and its analysis are available in the graphical user interface of MSE (Fig. 1).



Status: Displaying design number 1 properties POWER

lifetime : 90
wheeldiameter : 0.25
number_computers : 1
power_system : sol
telecom :
dte_and_high_orbit_X_UHF
autonomy_l_d : a1
autonomy_s_d : a1
autonomy_acq : n
autonomy_night_navigation : n
instrument_night_proc : n

Index: 1

actual_number_cycles : 59
area_panel : 1.44051
area_panel_max : 1.515
batteryRechargeTime : 15499.7
cost_power : 1.0577e+006
hardware(1) :
capacity : 202.861
location : web
mass : 6.76204
size : [0.161679 0.161679 0.161679]
type : battery
initial_panel_area : 1.44051
output_power : 56.1483
time_rech_comm : 1640.4
time_rech_night : 13233.3
validity : valid

Loaded 1 designs.
Design: 1
Selection zoom: 0

X: autonomy_acq
Y: autonomy_acq
Z: autonomy_acq
Az: 40
El: 30

Fig. 1 Main graphical user interface of MSE

Science Vector
The rover design approach implemented in MSE is a science-driven approach. Each rover is designed to meet science requirements regarding the instrument suite, the landing site characteristics, and the exploration scenario. All these parameters constitute the *science vector*. The science and navigation instruments, and acquisition tools are selected from a database which currently includes all those used on Sojourner and MER, and those which have been selected for

MSL and ExoMars. Other instruments and tools can easily be added to the list by providing such features as mass and power requirements, operation time, and lifetime. A generic exploration scenario is parameterized by a *site to site distance* and a *number of samples analyzed per site*. After a rover design is created, the exploration models simulate its performance against this generic scenario. Based on the rover capabilities, the models calculate the number of sites the rover is able to investigate and the total number of samples it can analyze during the mission lifetime.

Design Vector

The *design variables* are the properties that vary from one design to another in the trade space; they are gathered in the *design vector*. The following design variables were selected for MSE: mission lifetime, rover wheel size, computational power, power source type, traverse autonomy, and sample approach autonomy. Two types of power sources are modeled in MSE, solar power sources and Radioisotope Power Systems (RPS). The two autonomy design variables also have binary *levels*: state of the art autonomy and advanced autonomy. The other design variables have continuous levels. For example, the user can choose to simulate rovers with arbitrary wheel sizes. The only restriction on the number of levels the user should input for each design variable is the calculation time the user is ready to tolerate.

Rover Modeling

The complex rover system is subdivided into smaller disciplinary *subsystems* for each of the following areas: surface environment, science instruments, sample acquisition tools, rover vehicle, autonomy, communication, and power. These seven subsystems are further subdivided into *calculation modules* in order to minimize computation time. For example, the modules *Raw Speed* and *Rover Hardware* both belong to the *Rover Vehicle* subsystem; they are computed separately to minimize the number of feedback loops in the execution. The feedback loops are easily identified in the design structure matrix representation of MSE (Fig. 2). The modules are executed along the diagonal, a connection between two modules above the diagonal is a feedforward flow, a connection below the diagonal is a feedback flow. Feedback loops remain unavoidable between *Avionics*, *Power* and *Rover* subsystems.

The Power, Communications, and Rover Hardware (structures, mobility, and thermal) modules use physics-based models. The remaining modules use parametric relationships to size components; for example, the avionics mass scales with the number of instruments and acquisition tools. The rover development and launch cost is modeled as a function of the rover total mass. Total mission cost includes two other components: the power subsystem cost (calculated independently in order to capture cost factors in the solar versus RPS trade-off) and the operations cost.

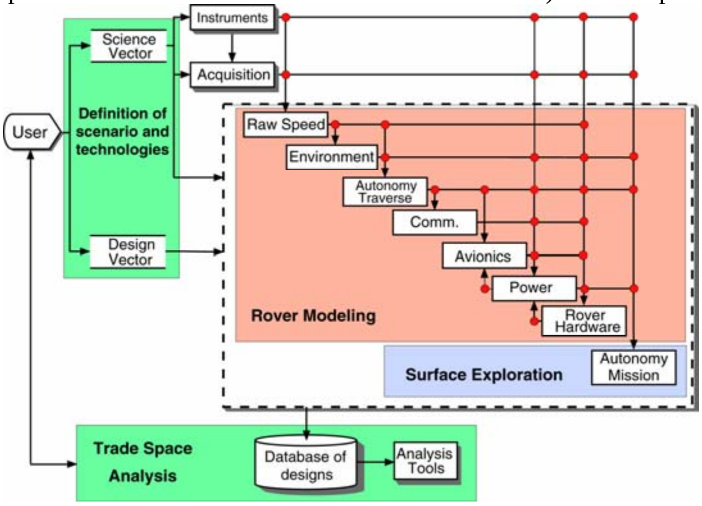


Fig. 2 Design Structure Matrix of MSE

Validation

In order to develop confidence in the part of the users in the outputs of MSE, the tool's engineering and exploration models are regularly validated. Engineering subsystem models have been benchmarked with data from similar subsystems on existing rovers and other spacecraft when applicable. The integrated tool is validated by benchmarking simulated Sojourner, MER, and MSL rovers against the actual designs (insufficient design information about the ExoMars design precluded benchmarking with ExoMars). The exploration models of MSE, managed by the *Autonomy* subsystem, have been successfully benchmarked against MER exploration data.

For the three NASA rovers the simulated system-level outputs (number of samples analyzed, total mass, total power) compare well with the reference values. MSE mass estimates are within 10% to 15% from the design values (the mass of Sojourner is overestimated whereas those of MER and MSL are underestimated). At the subsystem level, the benchmarking reveals weaknesses in the modeling of the mast and the WEB. The WEB model was originally based on the simple box concept used for Sojourner and MER; this model needs significant revisions for RPS powered rovers due to the presence of the RPS at the back of the WEB and of the fluid loops around the WEB [7]. The satisfactory benchmarking of MSE with Sojourner, MER, and MSL demonstrates its ability to model a wide spectrum of designs.

APPLICATION OF MSE TO THE EXOMARS MISSION

The previous section described the ability of MSE to generate a wide range of mid-rovers and to provide relevant information about the engineering and scientific merits of each design. This section shows how these competencies can help the decision making process for the design of future missions by using ExoMars as an application example. The ExoMars mission is part of ESA’s Aurora exploration program. The mission is planned for launch in 2013 and is currently in design phase B1 [8]. Several design options were investigated during previous phases which have led to three potential scenarios for the implementation of ExoMars. In the first scenario, called *baseline scenario*, the rover carries 8 kilograms of science instruments (not including acquisition tools); it is launched on a Soyuz launcher and uses MER-like airbags for landing. In the second scenario, called the *option scenario*, the rover carries 12.5 kilograms of science instruments (not including acquisition tools); it is launched on a Soyuz launcher and uses vented airbags. In the last scenario, the rover carries 16.5 kilograms of science instruments (not including acquisition tools); it is launched on an Ariane 5 launcher and uses vented airbags.

The *baseline scenario* is the low-cost solution for ExoMars; the rover is expected to weigh between 120 kilograms and 180 kilograms [4]. The *option scenario* uses the full capability of the Soyuz 2b to launch the payload recommended by the science community at the second Aurora Science Conference [4] on a rover weighing less than 200 kilograms. The deliverable rover mass is further increased in the third scenario by using an Ariane 5 launcher. Each scenario addresses the needs from the ExoMars stakeholders (e.g. science community) in different proportions. The final design of the ExoMars mission will be decided at the conclusion of the Implementation Review in late Spring of 2007 [8].

The selection of the best ExoMars mission is a systems architecting problem. Systems architecting differs from systems engineering in that engineering aims for technical optimization while architecting aims for client satisfaction [9]. The final implementation of ExoMars will not be selected solely based on technical excellence but based on how the mission satisfies the variety of objectives of the ExoMars stakeholders. The subsequent section describes how the association of MSE, a systems engineering tool, with a systems architecting approach can support the decision making process of the ExoMars selection. The following paragraphs present a systems architecting approach to identify the stakeholders of the ExoMars mission and their objectives. Next, MSE is used within this framework to quantify the performance of the first two scenarios with respect to these objectives. Lack of reference data about the third scenario prevented its analysis in this article. Even though this analysis is set in the context of the ExoMars phase B, its aim is to demonstrate competencies of MSE in pre-phase A studies. Accordingly, the results presented here have a level of detail appropriate for pre-phase A analyses but not for phase B ones.

A Systems Architecting Approach to ExoMars

The selection of the ExoMars mission would benefit from a systems architecting approach based on stakeholder satisfaction. The ExoMars designs generated during phase A were science driven; the desire for large science payloads resulted in designs that exceeded the original 200 kilogram rover mass limit [10]. Mass reduction efforts are being performed in phase B1 in order to reach a balance between the objectives of high science return and affordability. This illustrates how the consideration of only one objective (or stakeholder) caused to the dissatisfaction of other objectives (or stakeholders) and led to another design iteration. To ensure sustainability, the final implementation of a system should aim for, at least, a partial satisfaction of *all* stakeholders [11]. The first step in the systems architecting approach presented in this article is to identify the important stakeholders and their objectives. In a second step, proximate metrics are defined to quantify the performance of a given mission with respect to these objectives. In the third and fourth steps, five science payloads are defined for which a trade space of rover designs is created using MSE. In the last step, design recommendations for the ExoMars design are derived from the analysis of the trade space.

Identifying the Stakeholders and their Objectives

A previous evaluation process of Mars robotic mission alternatives took place at the second international Aurora Science Conference in April 2005. The key criteria for the evaluation process were [4]:

1. Scientific merit of the mission in relation to the Exploration Program objectives
2. Mission's relative scientific excellence versus cost
3. Timeliness of the mission's science in the international context
4. Importance of the mission's technology for future exploration activities

These criteria can be considered as stakeholder objectives for the ExoMars mission. The first and third objectives express the needs from the science community. The fourth objective addresses the needs of the technology community. The science and technology communities as well as the public are direct beneficiaries of the mission value. The second objective is one of affordability that expresses the need from the national governments that subsidize the mission.

Two key considerations are missing in the list above: development risk and policy robustness. In April 2004, the ESA Technical Board evaluated the development risk of candidate instruments to descope those that were considered insufficiently mature [12]. Policy robustness, as considering the interests all Aurora participating countries, also influenced the instrument selection process [12]. The flow of valued benefits to stakeholders (objectives 1 and 3), affordability (objective 2), risk management, and policy robustness are all factors contributing to the sustainability of the Aurora program [13].

Assessing the Performance of Candidate Missions

The performance of a candidate mission is assessed with respect to all the objectives identified above. For this analysis, simple proximate metrics are defined to be quantifiable measures of these objectives (Table 1). The instrumentation diversity and the number of samples analyzed capture the qualitative and quantitative aspects, respectively, of a mission's scientific merit. The science timeliness is measured by the number of instruments that are used at Mars for the first time. The importance of the mission technology is assessed by its relevance to future missions. Future missions will benefit from drilling and sample preparation and distribution (SPDS) technologies, as well as mobility systems [10]. At first order, the value of a mobility system scales with its size which is proportional to that of the wheel. Indeed, the larger the vehicle, the wider the spectrum of science payloads it can potentially accommodate in subsequent missions. The metrics of affordability are rover mass and total mission cost. Development risk and policy robustness are measured by the instrumentation's Technology Readiness Level (TRL) and international participation, respectively. This set of proximate metrics is satisfactory for pre-phase A analyses but would need to be refined for phase B studies.

While the evaluation of some of these metrics is straightforward, that of the number of samples analyzed, rover mass, and mission cost requires some level of computation. In this study, MSE is used to evaluate these metrics for the *baseline* and *option* scenarios. While the 12.5 kilogram instrumentation of the *option scenario* has been identified [4], the composition of the 8 kilogram *baseline* payload is still undefined. For this reason, variants of the *option* payload have been constructed and analyzed not only for their scientific merits but for the insights they provide about the interactions between rover instrumentation and rover design.

Table 1 Figures of merit for the assessment of mission performance

Objectives	proximate metrics
Scientific merit	Number of geology and life instruments Number of samples analyzed during the mission
Science timeliness	Number of "First at Mars" instruments
Technology	Use of drill and SPDS Wheel size
Affordability	rover mass mission cost
Development risk	TRL
Intn participation	Number of participating countries

Creating Science Payload Variants

Several science payload variants are considered that each keep the fundamental step-wise approach to exploration, i.e. observations at the remote, contact, and analytical levels [12]:

- *Option*: payload recommended by the ESA science community
- *TRL>3*: instruments with TRL less than four are removed from the list
- *No GCMS/Urey*: either the GCMS or Urey is removed from the instrument list

- *Corer*: the drill is replaced by a corer
- *Life focus*: some geology instruments are removed to lower the instrument mass to 8 kilograms

The *Option* payload is the 12.5 kilogram instrumentation recommended by the ESA science community. The four other ones are lighter science packages defined to meet some of the stakeholder objectives. The *TRL>3* package minimizes the development risk by descoping instruments whose TRL is less than 4. The *No GCMS/Urey* and *Corer* are packages for which the heaviest instrument and the heaviest acquisition tool, respectively, are descoped. Even though these two packages may not be valid from a science perspective, there are interesting for this analysis because they exhibit the largest mass reduction for the smallest number instruments removed. In the *No GCMS/Urey* package, either the GCMS or the Urey is descoped. Both instruments have the same weight (3 kilograms); from a systems engineering perspective, they have the same effect on the rover design. In the *Corer* case, the 11 kilogram drill is replaced by a 4 kilogram corer similar to the Corer Abrader Tool (CAT) developed by Honeybee Robotics. The *Life focus* package has 8 kilograms of mostly life instruments; it meets the mass requirement of the *baseline scenario*. Its geology instruments are reduced to the panoramic system for remote observations and the Mössbauer instrument for contact observations. Table 2 presents the science packages and their performances with respect to the proximate metrics defined previously.

Table 2 shows that while the *Life focus* package satisfies the needs of the geology community only to a small extent, it addresses the remaining mission objectives satisfactorily. In the next section, the five science packages are inputted in MSE to generate families of rover missions and evaluate their performances with respect to the remaining metrics.

Table 2 Science Payload Variants

Science Payload	Life # instr	Geology # instr	First at Mars # instr	Mass of instr+ acq kg	Risk Min TRL	Intn Participation # countries	Potential tech. for MSR
Option	3	8	9	28.5	2	18	drill + spds
TRL > 3	2	6	7	25.9	4	17	drill + spds
No GCMS/Urey	2	8	8	25.3	2	18	drill + spds
Life focus	3	2	4	24	2	18	drill + spds
Corer	2	8	8	20.7	2	18	spds

Generation of a Trade Space of ExoMars Mid-Rovers

The environmental conditions and exploration scenario are defined (in the *science vector*) according to that planned for ExoMars. The landing date is June 2013 which corresponds to an areocentric longitude of 328 degrees [14]; the landing site is assumed to be in the equatorial band. A generic exploration scenario is defined with 100 meter site to site distance, the planned daily traverse capability of ExoMars [15], and one sample analyzed at each site. The terrain is assumed to have a 5% rock abundance which is the rock abundance observed in the Meridiani region [16].

A trade space of rover designs is generated by changing only the wheel diameter. For each science package, rovers are modeled with wheel diameters ranging from 0.20 to 0.40 meters with one centimeter increments. The wheel diameter is the key parameter of the mobility system; in MSE, the dimensions of the suspension scale with the wheel size. Therefore, as the wheel size increases, the rover mobility system is progressively oversized. This trade space is created to study the synergies between the science payload and the rover engineering design. The trade space analysis identifies the smallest rovers that can accommodate each of the packages and the largest rovers that meet the 200 kilogram constraint. In addition, the analysis shows whether oversized suspensions improve exploration via higher clearance.

The remaining design variables are set to values corresponding to the current ExoMars definition. The nominal mission lifetime is set at 180 sols [4]. All rovers are modeled with solar power, state of the art (MER) autonomy, and with a processing power equivalent to one RAD750 processor [17]. The resulting trade space composed of five payloads and rovers with 21 different wheel sizes counts 105 designs. MSE computes each design in only 600 milliseconds.

Analysis of the ExoMars Mission Trade Space

The analysis process first identifies the designs that meet the mission constraints before examining them further. Out of the 105 designs generated only a fraction satisfies the 200 kilogram mass constraint of the *option scenario*. Fig. 3 shows the trend of the rover mass as a function of the wheel size for each of the five science packages. The figure shows that the trend is similar across all science packages; the rover mass is a power function of the wheel size whose exponent is between 2.75 and 3. Surprisingly, there is not an exact parallel between the mass distribution of science packages (Table 2) and the resulting mass distribution of rovers (Table 3). As expected, the rovers carrying the *Option* payload are the heaviest. However, the *Corer* payload, the lightest of all the packages, does not produce the lightest rovers. In the *Corer* package the drill is replaced by a corer which is 7 kilograms lighter. But the mass savings in instrumentation are offset by the mass increase of the arm which carries the corer; the arm of a corer rover is five times heavier than the arm of a drill rover.

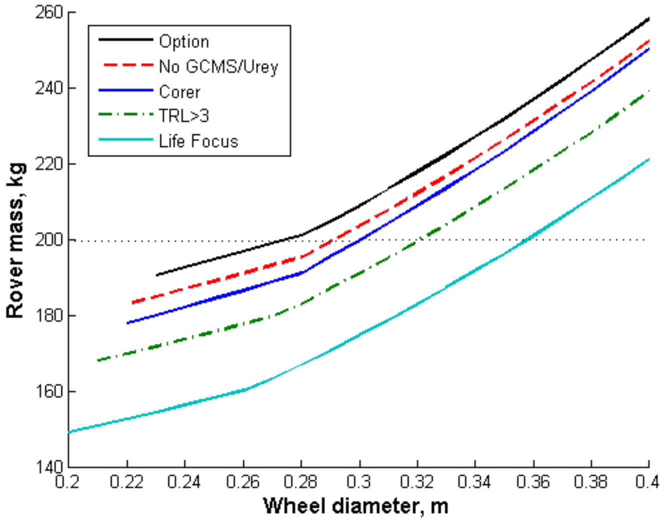


Fig. 3 Trade space of ExoMars missions with five science packages and wheel sizes ranging from 0.2 m to 0.4 m

In addition, because in MSE the avionics mass scales with the number of instruments and acquisition tools the *Life focus* and *TRL>3* rovers have lighter avionics and consequently lighter structures. As a result, the *Life focus* payload with 8 kilograms of science instruments produces the lightest rovers. For the same reasons the *Life focus* payload fits on 0.20 meter wheel rovers, while rovers with the *Option* payload require a least 0.23 meter wheels to have sufficient clearance. In addition, Fig. 3 shows that *Option rovers* with a wheel size larger than 0.27 exceed the 200 kilogram constraint. Therefore, the design space of *Option rovers* is limited to the class of MER designs with wheel sizes around 0.25 meters.

In the *Life focus* case, the designers have a broader spectrum of wheel sizes available to select from; possible wheel sizes range from 0.20 meters to 0.35 meters (Table 3). On the one hand, a 0.20 meter rover is the minimum mass and minimum cost solution. On the other hand, designing a *Life focus* rover with a larger mobility system would increase the potential use of the vehicle as a platform for future missions. In particular, according to Fig. 3 a mobility system designed with a 0.23-0.25 meter wheel would be large enough to accommodate the *Option* payload on a subsequent mission, such as MSR. The resulting mass increase is approximately 10 kilograms which is only 7% of the rover mass. In addition, a bigger rover would accommodate a larger surface area of solar panel and therefore would lengthen the potential mission lifetime. However, Table 3 shows that for a terrain with 5% rock abundance, oversizing the mobility system does not improve the exploration performance of the mission (measured by the number of samples analyzed).

In conclusion, the design of the *option scenario* is challenging because the design space is highly constrained and exhibits very little margin. The growth of the *Option* payload [8] would likely require more instruments to be descoped. Removing the GCMS or the Urey would only save 3 kilograms of instrumentation and 5 kilograms of structural mass. Regarding the *baseline scenario*, while a 0.20 meter wheel rover is attractive from the point of view affordability, a slightly larger rover would reinforce the rover’s capabilities and technological value for future rover missions.

Table 3 Range of valid rover missions for each science payload

Science Payload	Number of samples	Min mass rover kg	Min mission cost $M	Wheel range cm
Option	17-19	191	605	23-27
No GCMS/Urey	17-19	183	594	22-29
Corer	17-19	178	586	22-30
TRL > 3	17-19	167	570	21-32
Life focus	17-19	149	539	20-35

CONCLUSIONS

The association of MSE with a systems architecting approach provides a means for a traceable decision making process flowing from stakeholder objectives to mission design recommendations. This approach can help accelerate early conceptual design phases for which satisfaction of stakeholder objectives takes the place of design requirements. In addition, the brief study presented in this article and performed in just a few days demonstrates some of the modeling and analytical features of MSE. The tool captures in sufficient detail the design interactions between the science instrumentation and the rover vehicle. Furthermore, it is able to generate a wide spectrum of rover variants very rapidly. During the early design phases of ExoMars such a tool could have helped the scientists understand in real time the impact of their science payloads on the design of ExoMars. For MSE to be useful in phase A and B analyses, its fidelity would need to be improved and its scope broadened to include supporting systems, such as the descent module, launch vehicle, and communication relays.

ACKNOWLEDGEMENTS

This paper was prepared at the Massachusetts Institute of Technology (MIT) by the Space Systems Laboratory. The development of the Mars Surface Exploration tool is under contract to Jet Propulsion Laboratory. Publication of this paper does not constitute approval by NASA of the findings or conclusions contained herein. It is published for the exchange and stimulation of ideas.

REFERENCES

[1] R. B. Roncoli, J. M. Ludwinski, "Mission Design Overview for the Mars Exploration Rover Mission", *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, AIAA 2002-4823, 5-8 August 2002, Monterey CA

[2] R. Arvidson et al., "NASA Mars Exploration Program Mars 2007 Smart Lander Mission Science Definition Report", October 2001

[3] ESA, "ExoMars09 CDF Study Report", Ref. CDF-14-(A), August 2002

[4] ESA, "ExoMars Science Management Plan", EXM-MS-PL-ESA00002, May 2006

[5] J.-A. Lamamy, "Enhancing the Science Return of Mars Missions via Sample Preparation, Robotic Surface Exploration and in Orbit Fuel Production", Master Thesis, Massachusetts Institute of Technology, SERC #7-04, chap. 4, June 2004, available at http://ssl.mit.edu/publications/theses/SM-2004-LamamyJulien-Alexandre.html

[6] B. Bickler, "A New Family of JPL Planetary Surface Vehicles", *Missions, Technologies and Design of Planetary Mobile Vehicles*, pp. 301-306, September 1992, Toulouse, France

[7] P. Bhandari et al., "Mars Science Laboratory Thermal Control Architecture", *SAE technical papers*, vol. 114-1, p. 130, 2005

[8] ESA, "Progress Letter Pasteur Instrument Payload for the ExoMars Rover Mission, Number 5", October 2006

[9] M. W. Maier, E. Rechtin, *The Art of Systems Architecting*, CRC Press, second edition, 2002

[10] P. Baglioni, R, Fisackerly, B. Gardini, G. Gianfiglio, A. Pradier, A. Santovincenzo, J. Vago, M. Van Winnendael, "The Mars Exploration Plans of ESA", *Robotics and Automation Magazine, IEEE*, vol. 13, pp.83-89, June 2006

[11] G. R. Singleton, A. L. Weigel, "Policy Robustness Analysis of Space Exploration Architectures", *AIAA Space 2005*, AIAA 2005-6661, August 2005, Long Beach CA

[12] ESA, "Pasteur Working Group Meeting # 2, Final Report", EXO-ESA-RP-03001, Rev. 1, September 2005

[13] E. S. Rebentisch , E. F. Crawley, G. Loureiro, J.Q. Dickmann, S. N. Catanzaro, "Using Stakeholder Value Analysis to Build Exploration Sustainability", *1st Space Exploration Conference: Continuing the Voyage of Discovery*, AIAA-2005-2553, 30 Jan - 1 Feb 2005, Orlando FL

[14] J. Vago, "ExoMars – Searching for Life on the Red Planet", *ESA bulletin*, No. 16, pp. 16-23, May 2006

[15] M. van Winnendael, P. Baglioni, J. Vago, "Development of the ESA ExoMars Rover", *Proc. 8th Int. Symp. Artif. Intell., Robot. Automat. Space*, Sep. 5–8 2005, Munich, Germany, available at http://robotics.estec.esa.int/

[16] M. Golombek, et al., "Assessment of Mars Exploration Rover Landing Site Predictions", *Nature*, vol. 436, pp. 44-48, 2005

[17] D. Rea, D. Bayles, P. Kapcio, S. Doyle, D. Stanley, "PowerPC^{TM} RAD750^{TM} – A Microprocessor for Now and the Future", *Aerospace 2005 IEEE Conference*, pp. 1-5, March 5-12 2005, Big Sky MT