Methods and Tools for the Formulation, Evaluation and Optimization of Rover Mission Concepts

by

Julien-Alexandre Lamamy

Dipl. Ing., Ecole Centrale de Lyon, Lyon, France (2004)
S.M., Massachusetts Institute of Technology (2004)

Submitted to the Department of Aeronautics and Astronautics
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2007

Author ....
Department of Aeronautics and Astronautics
April 24, 2007

Certified by.......
David W. Miller
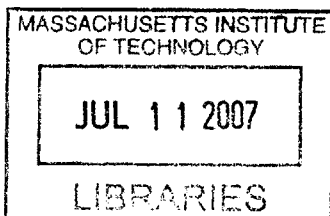Professor of Aeronautics and Astronautics
Thesis Supervisor

Certified by ....
Olivier L. de Weck
Associate Professor of Aeronautics and Astronautics & Engineering Systems
Committee Member

Certified by ....
Jeffrey A. Hoffman
Professor of the Practice of Aeronautics and Astronautics
Committee Member

Certified by ...
Alberto Elfes
Principal Member of Technical Staff at the Jet Propulsion Laboratory
Committee Member

Certified by ......
Manuel Martinez-Sanchez
Professor of Aeronautics and Astronautics
Minor Advisor

Accepted by .
Jaime Peraire
Professor of Aeronautics and Astronautics
Chair, Committee on Graduate Students

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Abstract

Traditionally, Mars rover missions have been conceived with a single point design approach, exploring a limited architectural trade space. The design of future missions must resolve a conflict between increasingly ambitious scientific objectives and strict technical and programmatic constraints. Therefore, there is a need for advanced mission study engineers to consider a wider range of surface exploration concepts in order to identify those with superior performance and robustness with respect to evolving mission objectives. To this end, a three stage trade space exploration approach has been developed to supplement point design development in the early conceptual phase of Mars rover missions. The product is an integrated set of theoretical methods and analytical tools which enhances the understanding and enables the rapid exploration of the rover mission trade space.

In the formulation stage, the first stage of the approach, a parallel decomposition of the functional and physical aspects of Mars exploration architectures is employed to explore trade space of surface mission concepts. At each step of the decomposition, architectural alternatives are assessed with respect to stakeholder figures of merit. The resulting concept development trees allow for a rapid assessment of a given design's strength and robustness with respect to stakeholder priorities.

In the evaluation stage, the Mars Surface Exploration (MSE) rover system design tool is used to support quantitative analysis of the superior designs identified in the formulation stage. This tool, for advanced mission studies, offers unique functionality: breadth of exploration, system-level modeling fidelity and rapidity. As a demonstration of its capabilities, the tool is used to model and evaluate a multi-rover mission concept in less than two hours.

In the optimization stage, two systems engineering methods are developed to optimize, with MSE, the more complex technical and physical aspects of rover mission architectures. The first method assesses the value of autonomy technologies in future missions; it is based on the principle that the monetary worth of autonomy can be evaluated by benchmarking its performance against competing solutions with known cost. The method is applied to value autonomy development for site-to-site traverse and sample approach activities. The second method optimizes platform strategies for space exploration systems; an innovative optimization technique is developed to enumerate of all platform options. In the six rover mission campaigns analyzed, the best platform strategies are shown to generate very limited savings compared to traditional strategies. The two case studies demonstrate that the analytical capabilities of MSE combined with a theoretical structure form a valuable decision making tool for early conceptual design trade-offs.

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David W. Miller
Title: Professor of Aeronautics and Astronautics
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Minor Advisor

Acknowledgements

I would like to thank my advisor David W. Miller for his guidance and support throughout my experience at MIT. His insights, both complex and practical, have broadened my understanding of systems engineering and the world beyond and I am grateful for the opportunity to have worked with him. I also would like to thank the members of my committee and my thesis readers, Afreen Siddiqi and Mike Wilson, for their precious help and feedback.

My family and Molly McGuire deserve special gratitude for their constant love and support. Their continued encouragement pulled me through the difficult times and I am sincerely grateful for the sacrifices they have made.

I would like to say thank you to Marilyn Good, for the administrative help she is never reluctant to give, to my friends and colleagues at the Space Systems Laboratory, especially Scott McCloskey for collaborating on MSE and Simon Nolet for his advice, to my friends of the group 312-H of JPL, especially Hamid Habib-Agahi who gave me the opportunity to work at JPL, to all the winners of the Scared Hitless softball team, and to my friends of the Mellens and Woodspoon.

This thesis is dedicated to my mother Nicole Lamamy for her precious love and to my grandfather Jacques Lamamy and my uncle Georges Ivanoff-Novikoff, science and engineering enthusiasts who did not have the chance to receive higher education to pursue their dreams.

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Acronyms

AFL	Astrobiology Field Laboratory
APXS	Alpha Particle X-Ray Spectrometer
CheMin	Chemistry & Mineralogy X-Ray Diffraction/X-Ray Fluorescence Instrument
DAN	Dynamic of Albedo Neutrons
DARTS	Dynamics And Real-Time Simulation
DTE	Direct-to-Earth
EDL	Entry Descent and Landing
ESA	European Space Agency
GCMS	Gas Chromatograph Mass Spectrometer
HazCam	Hazard Avoidance Camera
JPL	Jet Propulsion Laboratory
MAHLI	Mars Hand Lens Imager
MastCam	Mast Camera
MBED	Model-Based Engineering Design
MEPAG	Mars Exploration Program Analysis Group
MER	Mars Exploration Rover
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MSDW	Mission Scenario Development Workbench (tool)
MSL	Mars Science Laboratory
MSR	Mars Sample Return
NASA	National Aeronautics and Space Administration
PMCM	Parametric Mission Cost Model
RAD	Radiation Assessment Detector
RAT	Rock Abrasion Tool
RPS	Radioisotope Power System
REMS	Rover Environmental Monitoring Station
ROAMS	Rover Analysis, Modeling and Simulation (tool)
SPDS	Sample Preparation and Distribution System

Team X	JPL's Advanced Projects Design Team
UHF	Ultra High Frequency
WEB	Warm Electronics Box
sol	Martian solar day

Chapter 1

Introduction

In January 2004, the National Aeronautics and Space Administration (NASA) successfully landed the twin Mars Exploration Rovers (MERs) on Mars. The MERs have since exceeded all expectations and demonstrated the value of *mobile* instrumentation for planetary science [Arvidson, 2006]. However, in order to meet increasingly challenging scientific and programmatic goals, future rover missions will need to exhibit competencies far beyond those of MER. While some of these goals are achievable by improving existing technologies, the accomplishment of other goals, such as network science and Mars sample return, will require more fundamental modifications to the functional, physical, technical, and operational aspects of rover mission architectures. It is the role of advanced mission study engineers to produce a broad spectrum of architectural alternatives and to identify those that best meet scientific and programmatic objectives.

Increasingly, it is necessary to understand the trade space of deep space missions early in the design phase [Morse, 2006]. This thesis presents methods and tools that help organize and explore the trade space of future Mars rover missions. A review of the Mars Exploration Program (MEP) and of the design practice of deep space missions highlights a need for better rover concept formulation, evaluation, and optimization techniques. A review of the work done to date indicates that existing trade space exploration capabilities do not yet meet this need. This thesis proposes to provide advanced study engineers with theoretical and quantitative tools to better explore the broad spectrum of architectural options and produce sound mission concepts.

1.1 Motivation and Background

In the subsequent paragraphs, the description of past, current and future Mars rovers and of the rover design process provides the motivation for the research proposed in Section 1.3.

1.1.1 Mars Surface Explorers

Past, current and future rover missions

NASA is so far the only space agency that has successfully landed and operated Mars surface vehicles. In 1971 and 1973, the Soviet space program made two attempts to deploy a small surface vehicle called Prop-M on the Martian surface. Unfortunately, both times the lander carrying Prop-M failed before the vehicle could be operated. The next attempt to deploy a Martian surface vehicle did not happen until 1997 when NASA successfully landed and operated its first Mars rover called Sojourner. The mission's success prompted enthusiasm for more sophisticated Mars rover missions both at NASA and at the European Space Agency (ESA). In the next paragraphs, short descriptions are given of past, current, and planned missions.

Prop-M, 1971 and 1973

Prop-M was the first Mars surface vehicle flight project. Prop-M weighed approximately four kilograms and was designed with a pair of skis for locomotion (Figure 1-1). The vehicle walked on the two flat skis each driven by two rotating levers. It was equipped with a basic hazard detection and avoidance device. If the tactile collision sensor in front of the vehicle detected an obstacle, it initiated a sequence of moving one step backward, turning slightly and moving forward again [Schilling, 1996].
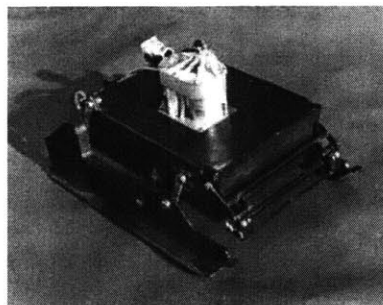
Figure 1-1 Prop-M Mars vehicle [RMVEI, 2002]

After landing, the rover was planned to be placed on the surface by a manipulator arm to move in the field of view of the television cameras located on the lander, and to stop to make measurements every one meter and a half [Carrier, 1992]. The exploration range of the vehicle was limited by its cable connection to the lander which provided power and communication link. The vehicle was not equipped with navigation cameras but used contact sensors in the front of the vehicle to sense obstacles and change course.

Marsokhod, 1992

The Marsokhod (Figure 1-2) is a Russian Mars rover concept that was planned for several mission opportunities but never was launched. The Marsokhod had several original features [Kemurdjian, 1992]:

- the rover had two modes of locomotion, wheel-rolling and wheel-walking (by a contraction and extraction movement of the body);
- the chassis consisted of six conical wheels with no ground clearance;
- the wheels were capable of housing payload equipment and batteries in their structure;
- and the rover had a modular body.

The design principle of this concept was to simplify, as much as possible, the rover control by implementing a robust mechanical locomotion system [Schilling, 1996].

Figure 1-2 Engineering model of Marsokhod [RMVEI, 2002]

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Sojourner, 1996

The Mars Pathfinder (MPF) mission was composed of the Sojourner rover and the Pathfinder lander. Sojourner was the first NASA flight project for a Mars surface mobile vehicle. Like Prop-M, Sojourner depended on the lander for its navigation and communications functions. However, the rover and lander were not structurally connected and Sojourner was equipped with hazard avoidance cameras and basic autonomous navigation capabilities. The rover autonomously drove off the lander (egress) and drove a total of approximately 100 meters during its 60 sol (Martian solar day) mission; the nominal mission duration was seven sols. Figure 1-3 is a picture Sojourner next to the Yogi rock; the tracks leading from the egress ramp to the rock are visible on this picture.
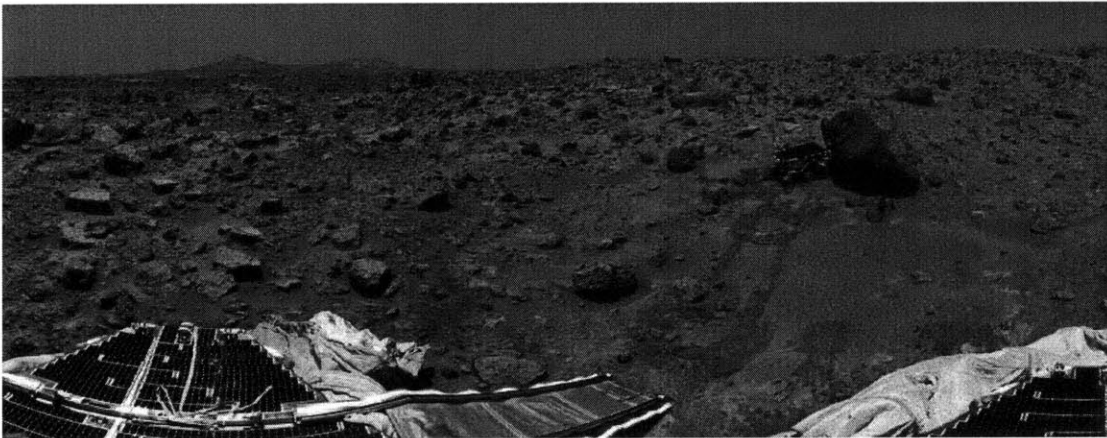
Figure 1-3 Picture taken by the Pathfinder lander of Sojourner at the Yogi rock (courtesy of NASA)

The success of the Sojourner operations validated the use of rovers for Mars surface exploration and, more specifically, the use of the rocker-bogie six-wheel configuration. The Mars Pathfinder mission is a successful example of the space exploration approach that had come to be known as "faster, better, cheaper" and which defined the Mars Surveyor Program [Hubbard, 2002]. The design of Sojourner was technology-driven and the total cost for hardware and software development and operations was only FY97 $25M [Shirley, 1995].

Mars Exploration Rovers, 2003

The Mars Exploration Rover (MER) mission represents a shift in the priorities of, and approach to, Mars exploration following the failures of the Mars Climate Orbiter (MCO) and

Mars Polar Lander (MPL) in 1999 [Roncoli, 2002]. The review of the MCO and MPL failures identified a number of problems with the "faster, better, cheaper" paradigm; the Mars Surveyor Program became the Mars Exploration Program (MEP) which would develop a science-driven, technology-enabled strategic plan to more fully understand the planet and to provide a measured approach to search for evidence of life [Hubbard, 2002].

As a result, the design of the MER twin rovers was developed around a very sophisticated and integrated scientific payload which enabled the rovers to conduct remote geologic investigations and to search for clues of past water activity [Roncoli, 2002]. The outstanding success of the mission demonstrated the value of mobile scientific payloads for planetary exploration. Figure 1-4 shows a picture of a MER next to an engineering model of Sojourner. The two rovers use the same basic technology but at two different scales in terms of geometry and sophistication.
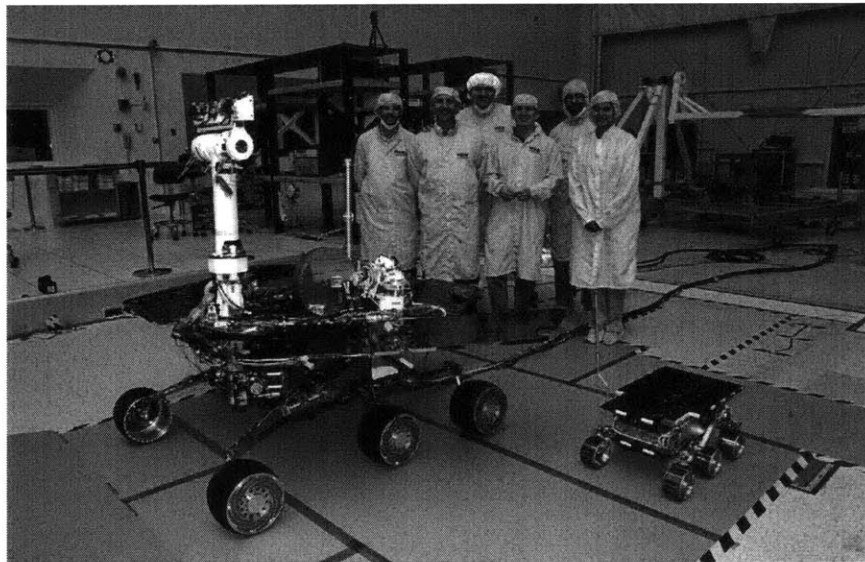
Figure 1-4 Comparison of Sojourner and MER (courtesy of NASA)

Mars Science Laboratory, 2009

The Mars Science Laboratory (MSL) will be the third generation of NASA Mars rovers. Like MER dwarfed Sojourner, MSL is expected to dwarf MER; Figure 1-5 is an artist illustration which shows MER following MSL. Besides scale, the major design difference between the

two rovers is the use of a radioisotope power system (RPS) on MSL, instead of solar panels on MER. The mission concept evolved from a technology demonstrator of landing for the Mars Sample Return (MSR) mission to an ambitious science-driven mission. Figure 1-6 shows an early design of MSL, which in 2002 stood for Mars Smart Lander, as a technology demonstrator for a MSR rover; the parallelepiped at the center of the rover is where the Mars Ascent Vehicle (MAV) was meant to fit in the MSR version of the rover. A MAV is a vehicle which brings Mars samples, collected by the rover, to Mars orbit where they are captured by another spacecraft and returned to Earth. Over the years, MSL has become a mission with its own scientific objectives and it is expected to be the first rover mission to perform analytical science on Mars.

One of the consequences of the change in mission scope has been that the formulation phase of MSL has been longer and more expensive, relative to total mission cost, than that of most missions of the same size. The cost of MSL's formulation phase (pre-Phase A to Phase B in NASA project lifecycle [Shishko, 1995]), including RPS development, is expected to represent 36% of the total formulation and development budget; in the case of MER, the formulation phase cost was 9% of the total formulation and development cost (for both rovers).
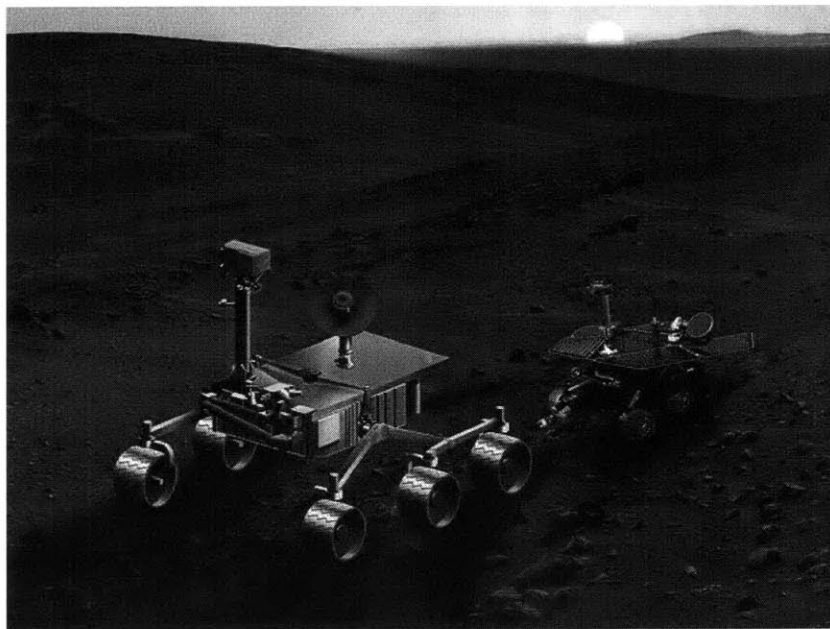
Figure 1-5 Illustration of MSL followed by MER (courtesy of NASA)

MAV location
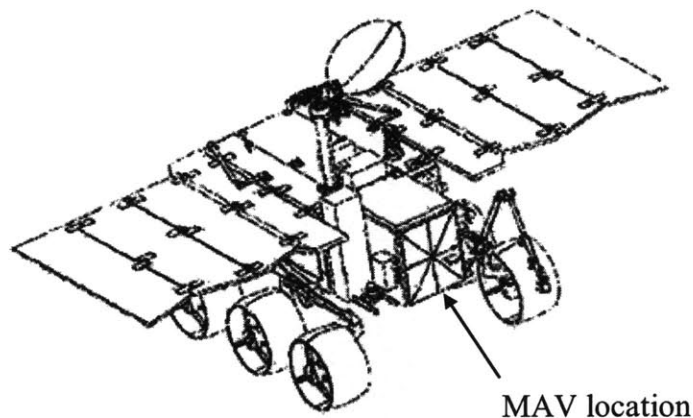
Figure 1-6 Original MSL design as precursor for MSR rover [Woerner, 2002]

ExoMars, 2013

ExoMars is the first planned European rover mission to Mars. As currently planned, it will be the first Mars rover mission to carry instruments able to identify extinct and extant Martian life and a drill able to reach underground layers at a depth of two meters. The original ExoMars payload, called Pasteur, had a mass of 24 kilograms. During the second half of 2004, two Phase A studies were conducted; their goal was to propose well-integrated concepts for Pasteur and the rover, capable of realizing the ExoMars science objectives. These activities were concluded in February 2005. The resulting rover models are shown in Figure 1-7 [ESA, 2006]. The major design difference between the two rovers is in the thermal control architecture. The design on the left uses radioisotope heating units (RHU) to heat electronics in the rover body at night; the advantage of RHUs is that they do not draw energy from the rover power system and instead rely on the heat resulting from the radioactive decay of plutonium. The design on the right uses the rover's power to heat its electronics at night; as a consequence, it has a higher power demand. In order to minimize the incidence angle on the solar panels and increase the solar power collected and battery charging, the solar power system was designed with mobile solar panels able to follow the Sun. The decision regarding the use of RHUs on ExoMars has technical and policy aspects; RHUs are based on radioisotope elements and therefore their use is strictly controlled.
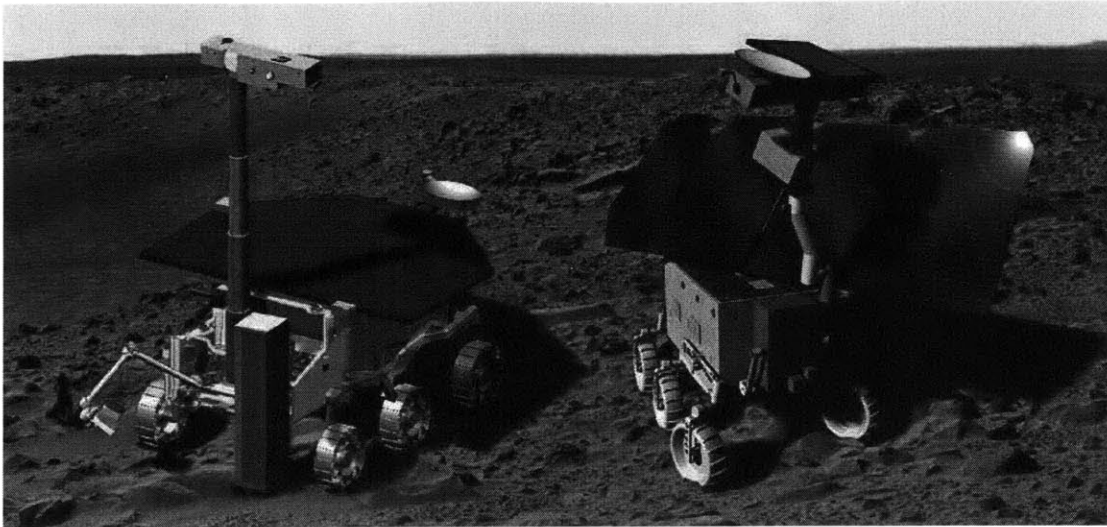
Figure 1-7 Two ExoMars designs resulting from Phase A studies

The design on the left uses RHUs for thermal control; the one on the right uses electrical power [ESA, 2006]

Both ExoMars designs of Figure 1-7 weigh more than 240 kilograms which is over the 200 kilogram mass limit that was imposed on the Phase A design [Baglioni, 2006]. For budgetary reasons, the Pasteur payload is in the process of being reduced to eight kilograms in order to converge on a rover design weighing between 120 kilograms and 180 kilograms [ESA, 2006].

2016 and 2018 Opportunities

For the 2016 and 2018 launch opportunities, NASA is considering several mission options including three rover mission concepts [MAPG 2006 and 2006b].

- *Astrobiology Field Laboratory (AFL)*: the AFL rover is based closely on MSL heritage but with an astrobiology-focused payload and the next-generation of sample processing system, and the capability to land in more difficult regions of Mars. The mission relies on the heritage of MSL's cruise stage, entry descent and landing (EDL) system and rover design. Current plans estimate that the AFL science payload to be 35 kilograms more massive than that of MSL [Schmidt, 2006].

- *Mid-rovers*: this mission concept involves two MER-derived rovers directed to different sites to explore the geologic diversity on Mars.

- *MSL-clone*: this mission concept is an exact copy of MSL, or a mission that is identical to MSL in all respects except that the payload is re-competed. The MSL-clone concept is a cost-driven mission but would still be quite valuable in evaluating habitability by Martian organisms in a different location and possibly with more advanced instrumentation than MSL [MAPG, 2006b].

Comparison of Russian, American, and European rovers

Figure 1-8 compares the aspect, mass and science capability of the Russian and American rovers (ExoMars is not shown because its final design has not been made public at the time of writing). The images of the rovers, on the top row of the figure, highlight the differences between the Russian and American approaches to Mars rover design. While the American rovers share some common physical features, such as the rocker-bogie mobility system, the Russian rovers have radically different design characteristics, such the ski-walking mobility, conical wheels and modular body structure. The Russian vehicles suggest that there exist a large trade space of alternatives to NASA rover designs. Moreover, Figure 1-8 shows that the size, mass and science capabilities of NASA rovers has increased at a rapid pace. This review of Mars rover missions showed that a large spectrum of the rover design space has been covered in terms of scale and science capabilities but not in terms of rover design alternatives. The delays in the design of MSL and ExoMars also suggest that rover missions, as they become more technologically sophisticated and scientifically ambitious, are more sensitive to evolving customer requirements during the formulation phase. The conclusion is that a rover design trade space exploration capability would help identify design alternatives and improve the robustness of the selection of a particular rover point design.

	Prop-M	Marsokhod	Sojourner	MER	MSL	
	4.5kg	100kg	10.5kg	185kg	850kg	Rover mass
year	1971-73	1992	1996	2003	2009	

contact		contact	remote contact	analytical remote contact	Science capabilities
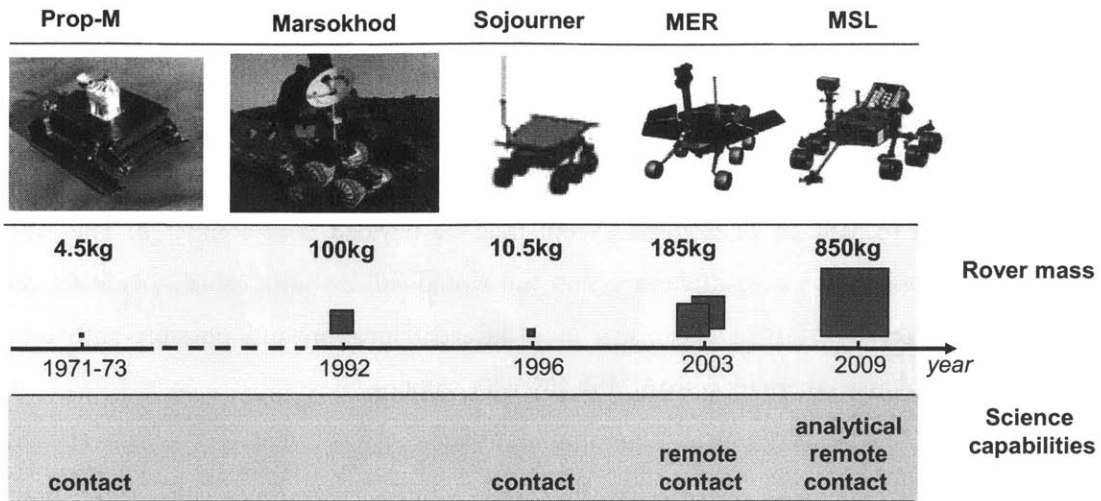
Figure 1-8 Comparison of Russian and American Mars rovers

Proposed Mars Surface Exploration Concepts

Numerous concepts have been proposed for exploring the surface of Mars with robots (Figure 1-9). The proposed concepts use alternative modes of surface locomotion [Antol 2003, Dubowsky 2005, Jones 2001], involve collaborating vehicles [Sujan 2004, Williams 2003] and implement alternative physical design properties, such as modularity and reconfigurability [Lichter 2000, Yim 2003]. Each concept addresses a particular challenge of Mars exploration or design aspect of mobile robotics. The concepts have emerged from independent efforts, and form an unstructured and heteroclite set. As a result, it is difficult to know how much of the conceptual design space has been explored and what options have not yet been investigated. There is a need for a structure and an approach to organize the design space and the set of proposed concepts, and to identify other promising concepts that have not yet been studied.

This review of Mars concepts highlighted the fact that many concept proposals are based on qualitative arguments and lack the support of quantitative analyses. A rapid, first-order rover design model would be helpful to concept developers; it would enable them to get a quantitative evaluation of their concept performance.
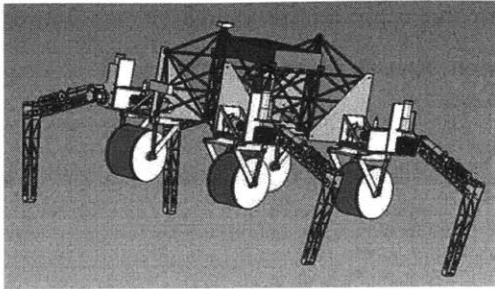
Modular Rover for Extreme Terrain Access
(MoRETA) [Massie, 2007]
Wheel-legged hybrid mobility system
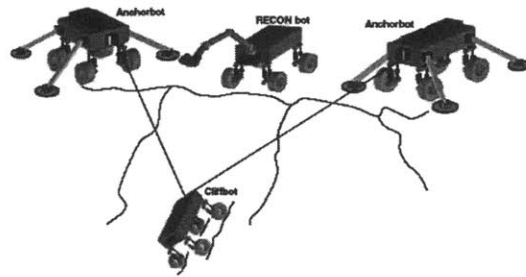
Cliffbot [Sujan, 2004]
Multi-vehicle mapping of cliff using tethered
mobility
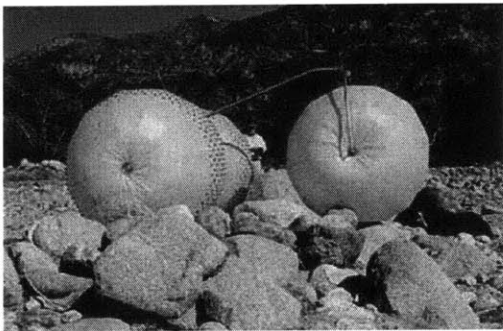
Inflatable rover [Jones, 2001]
Three 1.5 m inflatable wheels
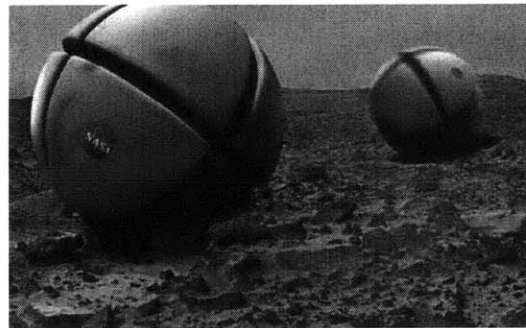
Tumbleweed, wedges concept [Antol, 2003]
Wind-powered rover

Figure 1-9 Example of Mars surface exploration vehicle concepts

1.1.2 Design Process for Deep Space Missions

The following paragraphs describe the mission lifecyle and trade space exploration process for deep space missions at NASA.

Deep space mission lifecycle

Most space project follow a six-phase design and development cycle, each phase culminating with a review by projects management and funding agencies [Shishko, 1995].

- Pre-Phase A: advanced studies

The purpose of this phase is to produce a broad spectrum of ideas and alternatives for missions from which new projects can be selected. For the Mars program, these mission

options are typically subject to high-level programmatic and scientific guidance (e.g. National Science Academy input or NASA Headquarters input) that inform the overall MEP.

- Phase A: preliminary analysis

The purpose of this phase is to determine the feasibility and desirability of a proposed system and its compatibility with NASA's strategic plans.

- Phase B: definition

The purpose of this phase is to establish an initial baseline capable of meeting mission needs; technical requirements should be sufficiently detailed to establish firm schedule and cost estimates for the project.

- Phase C: design and build

The purpose of this phase is to establish a complete design that is ready to fabricate, integrate, and verify.

- Phase D: assembly, test and launch operations

The purpose of this phase is to build and verify the system designed in the previous phase, deploy it, and prepare for operations.

- Phase E: operations

The purpose of this phase is to meet the required mission objectives.

Following the nomenclature introduced in NASA budget requests, pre-Phase A, Phase A, and Phase B are grouped and constitute the *formulation phase*; Phase C and Phase D constitute the *development phase*.

Trade Space Exploration for Deep Space Missions

Lamassoure et al. [Lamassoure, 2004] have already highlighted the fact that traditional design practices stem from the assumption that high level requirements are well developed and fairly stable in the formulation phase. Experience with MSL and ExoMars has shown that, in reality, requirements fluctuate and result in several design cycles and point designs. The design process followed by NASA uses science requirements as chief design drivers [Lamassoure, 2004]; this process leads to a point design that is optimized for these scientific requirements but which may perform poorly with respect to other metrics such as cost, schedule, risk, and policy robustness. More specifically, Lamassoure describes the NASA design process with following steps:

1. Level 1 requirements are set based on the key mission and program goals.

2. The Science Team develops a Science Traceability matrix tracing the mission goals to key NASA goals, and tracing them down into qualitative measurement objectives and quantitative measurement requirements.

3. The Science and Instruments Teams decide on an instrument suite, and flow measurement requirements down into quantitative instrument requirements, used to develop the design of the instruments.

4. The Instruments and Engineering Teams translate instrument designs into payload accommodation requirements, to be used together with Level 1 requirements as the basis for system design.

5. A mission-level tree of trade options is developed and analyzed mostly qualitatively, taking into account likely impact on cost, risk, and performance towards meeting the requirements; state of technology, potential design heritage, and programmatic considerations also play an important role. One or a few options are retained for further study.

6. A design team is formed, with expert representatives of all subsystems for the mission. The team first develops a feasible design that meets the mission objectives, and estimates its cost.

7. A – If the design and cost constraints are met, the team uses this baseline architecture and system-level design as the basis for subsystem-level trades, to finally conclude on a design that is near optimal, i.e. meeting the science requirements while minimizing project cost, at an acceptable level of risk.

7. B – If the cost estimate exceeds the cost cap for the project, the team revisits its architectural trades (5), its measurement and instrument requirements (3, 4). Several cycles through the whole process are often required to converge on a solution with satisfactory design and cost.

Typically, NASA competitively selects a payload through a procurement process (announcement of opportunity) which is not explicitly shown in the process above. Payload accommodation constraints are defined in the procurement process, for example, through a proposal information package.

With the process described above, designers rapidly converge on a mission architecture before many aspects of the mission are understood. More emphasis on an early (pre-Phase A) exploration of the design trade space would help the customers, as well as the design team, understand the trade space they are building, its dimensions, the interdependencies between elements of the mission, and the design and cost drivers.

1.2 Literature Review

The subsequent review of the literature on concept formulation, evaluation, and optimization highlights a gap between the current research and the previously identified needs for a structure to organize rover concepts and for rover design tools to rapidly explore trade spaces.

1.2.1 Rover Concept Formulation Research

Research on the conceptual development of planetary surface vehicles falls into three categories: concept proposal, concept history review and concept categorization. A discussion about the research on the Mars surface exploration concept is provided in the *Mars Surface Explorers* section. Historical reviews provide information about past planetary flight projects of the American [Muirhead, 2004] and Russian [RMVEI, 2002] space programs, about research robotic testbeds and paper concepts [Schilling 1996 and Malenkov 2004]. These reviews are useful sources of information about the characteristics of past concepts but they do not process the information to extract the design drivers and lessons for future concepts. Research of the last category attempts to organize the creation of concepts with a systematic approach. In this category, Hirose et al. have made significant contributions in the area of vehicle mobility [Hirose 1991 and 1995]. Hirose et al. classified types of locomotion into three modes: rolling, walking and crawling. They considered mechanism simplicity to be the paramount figure of merit for mobility system; for this reason, wheel-based locomotion was preferred. Zakrajsek et al. [Zakrajsek, 2005] reviewed past rover missions and concepts and provided a comparison of their technical characteristics, benefits and limitations. Based on this comparison, they also discussed the design and environmental challenges for the next generation of crew mobility vehicles on the moon. They concluded that modularity would be the most important factor in the

development of a surface mobility architecture capable of meeting reliability and affordability requirements. Although Hirose and Zakrajsek provided the first attempts at classifying rover concepts, there is still a need for an approach and structure to organize the design space of Mars surface exploration concepts outside of the particular aspects related to vehicle mobility.

1.2.2 Concept Evaluation Tools

The Mars Surface Exploration (MSE) tool is the main rover design tool used in the subsequent cases studies to evaluate the performance and cost of rover concepts. The first version of this tool, created in 2003, represented an early attempt of integrate subsystem models into a rover system-level modeling tool with the goal of carrying out systematic trade space exploration of future missions [Lamassoure 2005, Lamamy 2004].

The tool presented in Chapter 3 is a mature version of MSE with proven modeling fidelity and trade space exploration capability. Section 3.2 presents the benchmarking of MSE with a variety of deep space mission trade space exploration and modeling tools. The tools reviewed fall into three categories: concurrent engineering design models, operational scenario models, and subsystem models. The tool capabilities are assessed in terms of scope (ability to model all elements involved in a mission), modeling fidelity, resources (human and computational resources needed to use the tool), and run time. The benchmarking exercise showed that MSE offers a unique mix of capabilities; it is a system design tool which enables rapid and broad trade space exploration with pre-Phase A fidelity and has minimum resource requirements.

1.2.3 Concept Optimization tools

Deep space mission optimization efforts have focused on the technical aspects of deep space probes. In comparison, little research has been conducted to address their physical aspects. The JPL Strategic Assessment of Risk and Technology (START) group has been leading research efforts on technology investment optimization. The goal of START has been to develop quantitative analytical methodologies and tools to support decision making regarding technologies and capabilities [Elfes, 2006]. The START methodology is a sophisticated framework which provides probabilistic, utility-based assessments of

technologies and captures the interdependencies between technologies and goals, as well as the impact of funding levels [Elfes, 2006]. The methodology has been applied to various areas including the analysis of the Mars Technology Program [Smith, 2003] and the Vision for Space Exploration. In Chapter 4, this thesis examines the particular case of autonomy technology investments in rover missions. A literature review of the work performed by the START group in this area is provided in section 4.1.

Research into the optimization of the physical implementation of deep space probes has extensively covered modularity and reconfigurability. Siddiqi has contributed a significant body of work on the study of reconfigurability as applied to planetary surface vehicles [Siddiqi 2006, 2006b]. In comparison, the study of platform strategies for space applications has received less attention. Gonzalez-Zugasti et al. proposed a method for optimizing spacecraft platform strategies [Gonzalez-Zugasti, 2000]. The method has two limitations. First, the optimization process is based on concurrent engineering design and, therefore, necessitates expert assistance for the critical step of platform component identification and modeling. Second, the method only optimizes families of spacecraft using a single platform.

1.3 Research Objectives and Approach

The review of the literature highlighted needs, identified in Secion 1.1 and not addressed by the on-going research, for a) a method and structure to organize Mars surface exploration concepts, b) a rover system design model with rapid trade space exploration capability and c) an analysis of the technical and physical implementation aspects of rover design.

1.3.1 Objectives

The goal of this research is to provide advance study engineers and mission planners with theoretical and quantitative means to better explore the broad spectrum of architectural options and produce sound mission concepts. This goal is decomposed into three research objective components.

The first objective is to organize the space of Mars surface exploration architectural options in order to aide the creation, selection and analysis of future rover projects. The second objective is to demonstrate the feasibility of creating system level design models, with pre-Phase A fidelity, for *rapid* rover mission trade space exploration. The third objective is

to demonstrate that the combining of the analytical capabilities of a system design tool with theoretical methods based on system engineering and architecting forms a useful toolkit for decision making during conceptual design.

1.3.2 Approach

The thesis objectives are addressed by a three stage approach described in this section. Figure 1-10 is an illustration of the flow from advanced study engineers needs to the development of the approach. The illustration uses the Object Process Methodology (OPM) representation [Dori, 2003]; objects are represented by rectangles and processes, such as actions performed by these objects, are represented by ovals. The left half of the illustration shows the desire of advance study engineers for a better understanding of mission trade spaces, with sufficient breadth and fidelity, in order to produce a broad spectrum of interesting mission alternatives. The right half shows how this need is satisfied by the development of methods and tools with rapid trade space exploration capabilities. More specifically, the trade space exploration capability specializes into concept *formulation*, *evaluation* and *optimization* which are the three stages of this thesis.

A more detailed representation of the approach followed in this thesis is given in Figure 1-11. The figure has a matrix structure with three rows and four columns. The three rows correspond, from top to bottom, to the concept formulation, evaluation and optimization stages. The four columns correspond, from left to right, to the previous research on which this thesis is based, the major developments of this thesis, the resulting methods and tools developed, and the application of the methods and tools to form a toolkit for pre-Phase A decision-making.

The concept formulation stage is a qualitative exploration of the space of all Mars surface mission options; it is represented in the first row of Figure 1-11. The objectives of this stage are to structure the Mars surface exploration design space and to understand the influence of stakeholder figures of merit on concept selection. This results of this stage are a better understanding of the the current rover design practice and of the implicit chain of design decisions that have lead to NASA's rover design implementation, as well as the identification of promising surface exploration concept alternatives.

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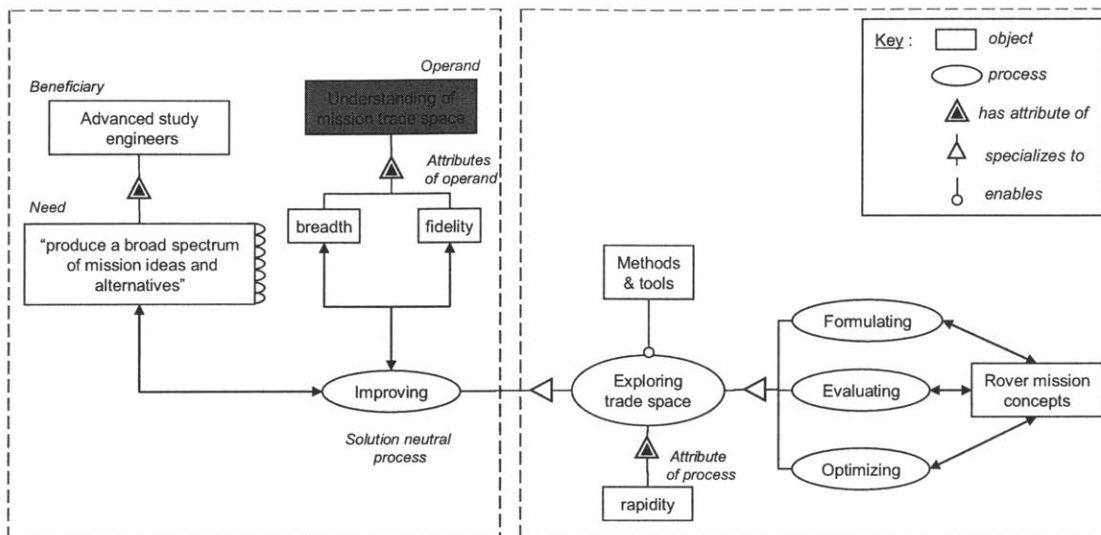
Unsatisfied need of advance study groups
for tools that improve the understanding of a
mission trade space.

This thesis addresses this need by enabling the
rapid formulation, evaluation and optimization of
rover concepts

Figure 1-10 Representation of how this thesis addresses the need of advance study groups for improved understanding of the mission trade space
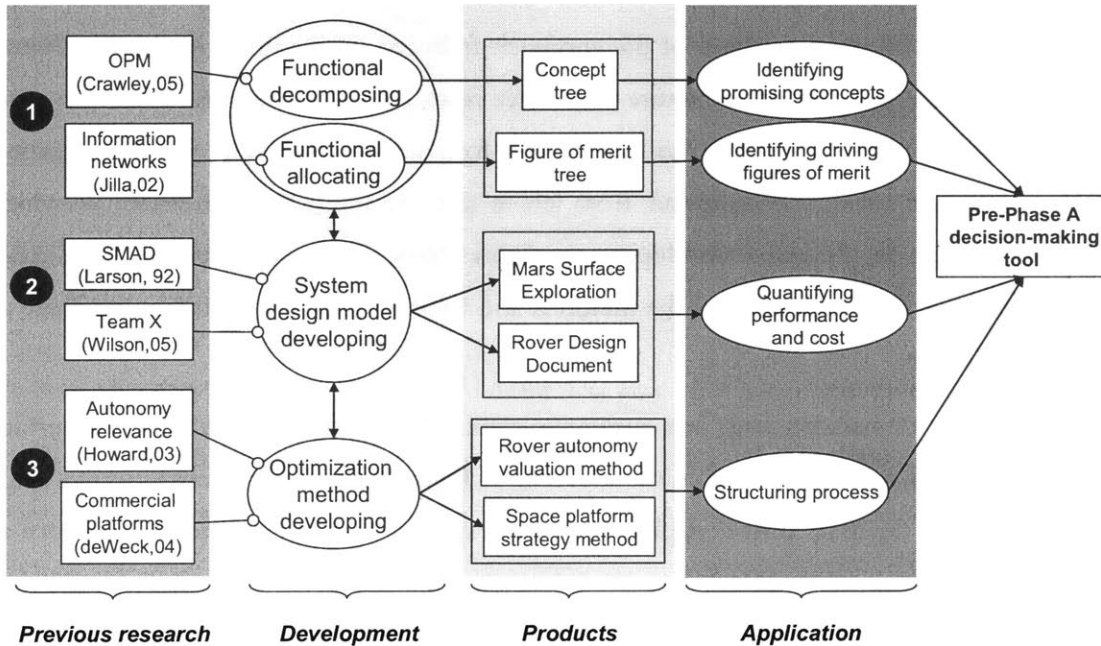
Figure 1-11 Thesis approach and implementation

The concept formulation stage is organized into three steps. First, a reverse-engineering examination of the Sojourner, MER, and MSL designs provides the basis for understanding NASA's current rover design approach. Second, a functional decomposition of is employed to qualitatively explore the trade space of surface exploration concepts. A top-level concept of a Mars mission's required functions is broken down into sub-functions, and, at the same time, the most abstract version of its physical form is broken down into sub-elements capable of performing the sub-functions. The decomposition process uses the OPM representation and a method developed by Crawley [Crawley, 2005]. The association of the functional and physical decompositions generates a concept tree which shows the possible implementations of a surface exploration concept. The concept generation process uses an analogy, developed by Shaw [Jilla, 2002], between information networks and space systems. In addition, a figure of merit tree indicates how each concept implementation alternative meets Mars exploration stakeholder needs. The concept tree and figure of merit tree are used in the third step of the formulation stage to identify promising surface exploration concepts.

The purpose of the evaluation stage, the second stage in Figure 1-11, is to produce system design models able to provide a rapid and quantitative assessment of rover performance and cost. Two sets of models are developed for two different customers: advanced mission study engineers and concept developers. A rover system design tool, called Mars Surface Exploration (MSE), is developed and targeted for use, in pre-Phase A, by advanced mission study engineers. MSE models are physics-based and parametric; the Space Mission Analysis and Design book [Larson, 1992] is used as a reference for many parametric relationships. In MSE, the emphasis is on rapidity and breadth of exploration of rover concepts; the validation of MSE's models with existing rovers and designs simulated by JPL's Team X [Wilson, 2005] ensures that the fidelity of the tool is appropriate for pre-Phase A applications. The tool is able to evaluate subsystem level design characteristics, scientific performance, and cost of a variety of rover mission concepts. A design document, called Rover Mission Analysis and Design (RoMAD), is created to address the need of concept developers. As mentioned previously, many concept proposals lack quantitative analyses to support performance and cost figures. RoMAD is a resource for rapid rover design evaluation; it contains several

meta-relationships and rules of thumb, collected during the development of MSE, which enable a quick assessment of a rover's speed and mass, for example.

In the optimization stage (Figure 1-11), theoretical methods, based on systems engineering and architecting, and MSE's analytical capabilities are combined in order to assess and optimize two of the valuable alternative concepts identified in the formulation stage. Two methods are proposed to value autonomy technologies and to develop and optimize platform strategies for Mars rover missions. In both studies, MSE provides quantitative estimates of the benefits and costs of autonomy and rover platforms. When, as in the latter case, benefits and costs balance, the remaining qualitative figures of merit defined in the formulation stage, drive the decision. These two application cases prove that the combined products of the three stages form a valuable pre-Phase A decision-making tool.

1.4 Thesis Overview

The layout of this document replicates the three stage approach of the thesis. In Chapter 2, the theoretical process is presented for the formulation of a rover mission concept. The process starts with the definition of a NASA Mars rover class; this step sets the context for the subsequent functional decomposition of the generic Mars exploration concept. The products of this step, a concept tree and a figure of merit tree, are two graphical representations of the option space of Mars surface missions. The examination of the option space with consideration of Mars exploration objectives and constraints highlights the most promising concept ideas. Some of these concepts are subsequently evaluated and optimized in Chapter 3, 4 and 5.

The description of the evaluation stage (Chapter 3) is focused on the Mars Surface Exploration design tool. The purpose, structure, models, and capabilities of the tool are described in detail. The rapid evaluation capability of the tool is demonstrated through a study performed in less than two hours of a scout-laboratory multi-rover mission concept, identified in the formulation stage (Chapter 2).

The optimization stage is comprised of two studies that address the optimization of autonomy technology investment and platform strategies. The first study (Chapter 4) provides a method for evaluating the relevance of autonomy technology in future missions. The method is applied to sample approach and site-to-site traverse surface exploration

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activities. The second study (Chapter 5) gives a method for defining and optimizing platform strategies in the context of deep space exploration. A general method is developed for space exploration platforms and applied to the particular case of Mars rover exploration. The thesis summary, contributions and recommendations for future work are provided in Chapter 6.

Chapter 2

Formulation of Rover Mission

Concepts

The work presented in this chapter addresses the need identified, during the review of Mars Surface exploration concepts in Chapter 1, for a method and structure to organize the design space of rover missions and concepts, and to identify promising concepts that have not yet been studied. The proposed approach is to follow a decomposition process of the function and form of Mars exploration. This process results in a concept tree and figure of merit tree which structure the design space of Mars surface exploration concepts by providing an overview of the design space and an understanding of the impact of stakeholder figure of merits on concept selection. This research focuses on the hardware architecture, as opposed to the software architecture, of surface exploration systems.

The process is organized in three parts illustrated in Figure 2-1, which is a diagram using the Object Process Methodology (OPM) [Dori, 2003]. The figure has a matrix structure; it has three rows, which correspond to the three parts of the process, and three columns, which correspond to third-party methods and tools used in this process, the steps of the process and the resulting products. In the first part (Section 2.1), a reverse-engineering examination of the Sojourner, MER and MSL designs provides the basis for understanding NASA's current rover design approach. The examination results in the distinction between rover *class attributes* and rover *design choices*. The former are design attributes common to all NASA rovers; the latter are design attributes specific to some. In the second part (Section

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2.3), the rationale for a functional and form decomposition of the Mars surface exploration architecture is developed. The Generalized Information Network Analysis (GINA) methodology [Shaw, 2001] is used to create a wide array of surface exploration concepts via an analogy between exploration systems and information networks. In the third part, the results of the process are synthesized in concept tree and figure of merit tree (Section 2.4). The trees provide two perspectives of the design space of surface exploration concepts and make explicit the chain of architectural and design decision steps between a generic definition of Mars exploration and particular instantiations of exploration systems (Figure 2-2). An application example, the formulation of lunar Modular Rover for Surface Exploration (MoRSE) concept, is described in Section 2.5.
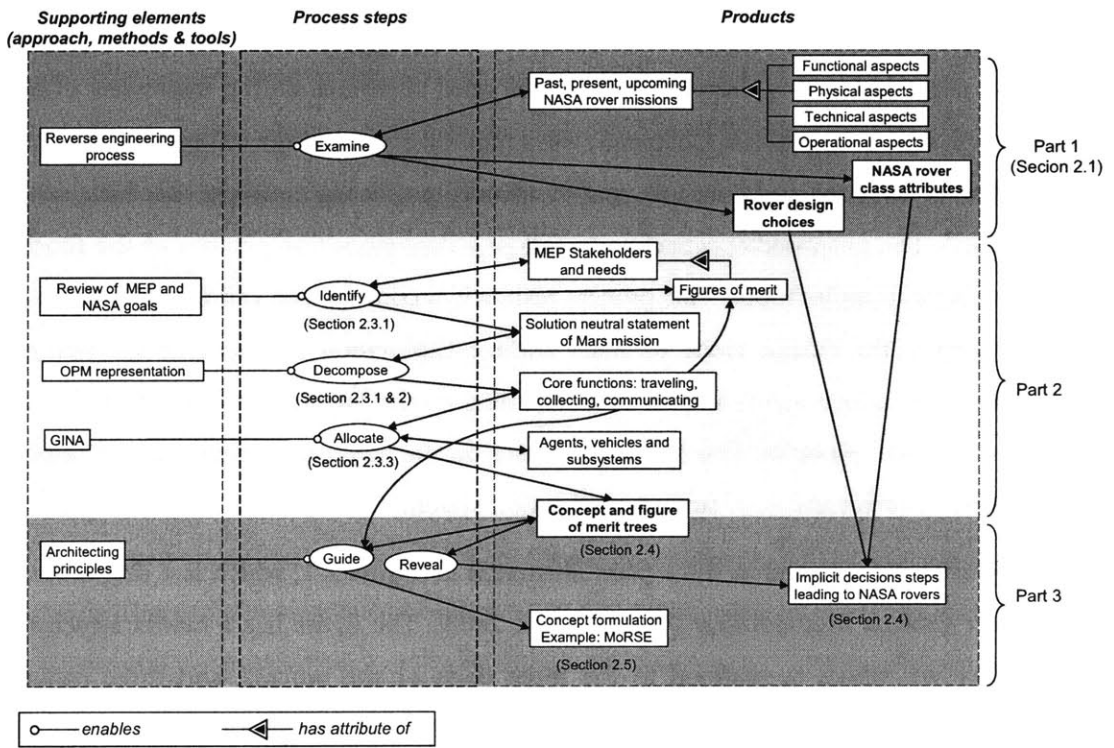
Figure 2-1 Process for formulating rover mission concepts

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Function   Concept   Form

solution A

solution-neutral
expression

Sample return
mission

Six-wheel
suspension

Exploring
Mars

Rover

One-wheel
suspension

solution B

1 surface vehicle

In-situ mission

Plane

N surface vehicles
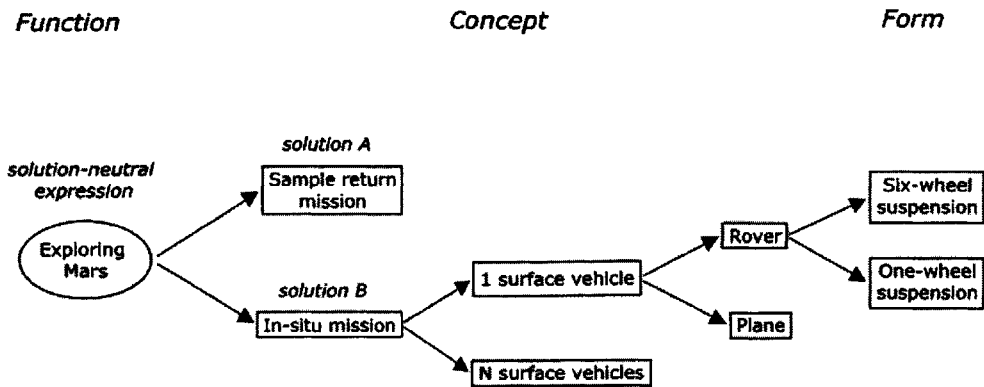
Figure 2-2 Illustration of decision nodes leading from a solution-neutral expression
of the architecture to a solution specific expression

2.1 Synthesis of past, present, and upcoming NASA rover missions

In this section, the requirements and attributes of Sojourner, MER and MSL are compared. The attributes that are shared by all three NASA rover missions define a *NASA rover class* while those that vary across missions represent rover *design choices*. Requirements and attributes are examined from functional, physical, technical, and operational perspectives. The *functional architecture* is a hierarchy of functions that together achieve the set of system requirements; the *physical architecture* is a representation of the physical resources that constitute the system and their connectivity; the *technical architecture* is a representation of the system implementation; the *operational architecture* is a description of the use context of the elements and of their interactions in the process of achieving goals [Levis, 1999]. The following paragraphs describe the functional, physical, technical, and operational attributes of NASA rover missions (Part 1 in Figure 2-1).

2.1.1 Functional Architecture

The mission objectives of Sojourner, MER, and MSL fall into three categories: science, technology and programmatic. The technology and programmatic objectives were mission-dependent whereas NASA rover science objectives, defined in broad terms, have been to provide mobility to a set of instruments which return measurement data on sample targets

selected by the Earth-based science team. Sojourner demonstrated the feasibility of a mobile scientific payload concept and MER demonstrated its value [Arvidson, 2006].

Figure 2-3 shows a simple OPM representation of the general scientific function of a rover as an object which drives to scientific targets, performs measurements on these targets and communicates the scientific telemetry back to Earth. The function of rover missions, and of planetary exploration in general, is discussed extensively in Section 2.3. In Figure 2-3, the rover system is represented in the middle; the data on which it acts is represented on the left; the processes of the actions are represented between the rover and data objects; and the operators and supporting elements are represented on the right.
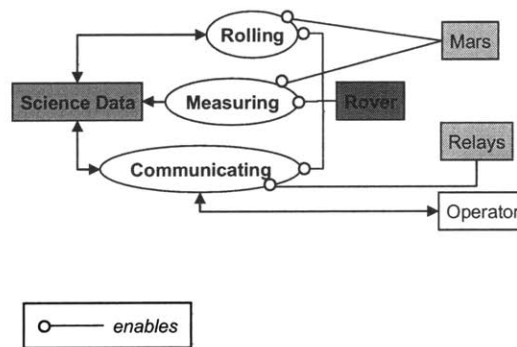
Figure 2-3 Rover primary function

Table 2-1 shows some characteristics of Sojourner, MER and MSL that are related to their scientific and exploration objectives.

Table 2-1 Scientific and exploration objectives of Sojourner, MER, and MSL

	# instruments	Instrument type	Total traverse capability requirement m
Sojourner	1	contact	10
MER	6	remote and contact	600
MSL	10	remote, contact, and analytical	20,000

The dramatic increase in the scientific payload and exploration capability across these three rover missions reflects an ambitious scientific program and a strong influence of the scientific and exploration stakeholders in the design of NASA Mars rovers.

2.1.2 Physical Architecture

The description of the NASA rovers' physical architecture decomposes the rover system into generic and specific subsystems, characterizes the evolution of NASA rovers across generations and describes their interactions with other elements of the Mars Exploration Program.

System decomposition

From a physical perspective, the composition of a rover system is similar to other spacecraft with subsystems that include:

- Scientific payload
- Mobility (propulsion)
- Structures
- Thermal
- Avionics
- Navigation (Guidance, navigation and control)
- Communications
- Power
- Flight software

Figure 2-4 shows a second layer of decomposition of the rover hardware system (without flight software). Elements in boxes with solid edges are common to Sojourner, MER, and MSL; elements in boxes with dash edges are substantially different. The specific implementations of these components on Sojourner, MER and MSL constitute a first set of *design choices*.
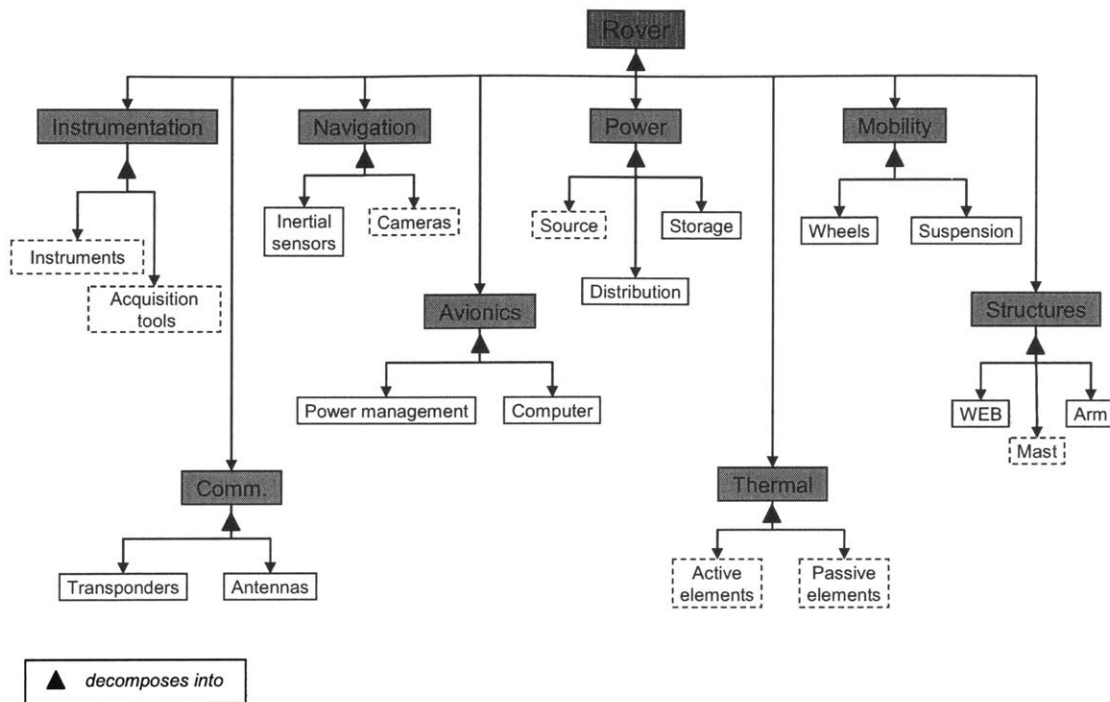
Figure 2-4 Two layer decomposition of a NASA Mars rover system.
Elements in boxes with solid edges are common to Sojourner, MER, and MSL.
Elements in boxes with dash edges have specific implementations on each mission.

In general, Figure 2-4 shows that Sojourner, MER and MSL share a broad design base. Most of the design specificities come from Sojourner which, as opposed to MER and MSL, was not equipped with acquisition tools, did not have a mast, and relied only on passive thermal control. MSL's major design choice is its radioisotope power system (RPS) which is a departure from the solar panels used by Sojourner and MER. The RPS design choice also impacts the thermal control strategy; instead of using RHUs and heaters, MSL transfers heat from the RPS to the warm electronics box (WEB) by using fluid loops [Bhandari, 2005]. Figure 2-5 is an illustration of the generic class of physical hardware elements of these rovers. The drawing was created using the Mars Surface Exploration (MSE) tool (Chapter 3) which does not have the capability to depict suspension elements (the rocker-bogie system is not shown).
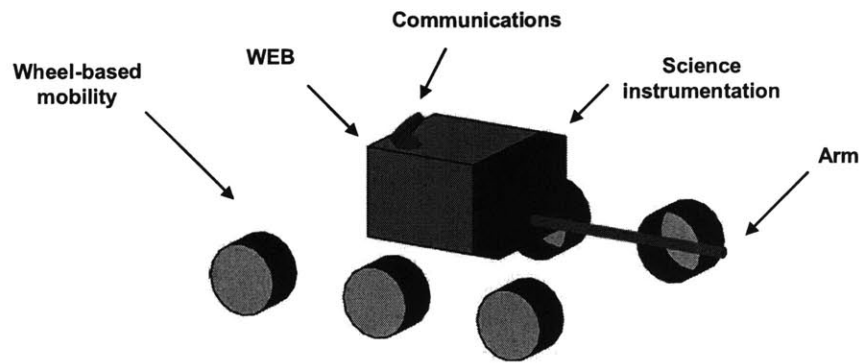
Figure 2-5 Mars rover generic physical attributes

The illustration highlights the integral nature of NASA rovers. Notably, the WEB is the structural hub for the science payload, suspension, arm, mast, antenna and power source; in addition to its structural role, it acts as a passive thermal control system for the electronics that are housed within. The physical hardware architecture is integral and rigid in that it exhibits neither modularity nor flexibility. The centralized WEB architecture, as well as the rocker-bogie suspension system, are rover class attributes.

System evolution

One obvious characteristic of the evolution of these rovers is the growth of their capabilities accompanied by the growth in their dimensions and mass. Figure 2-6 and Figure 2-7 illustrate rover mass growth from Sojourner, to MER, and MSL.
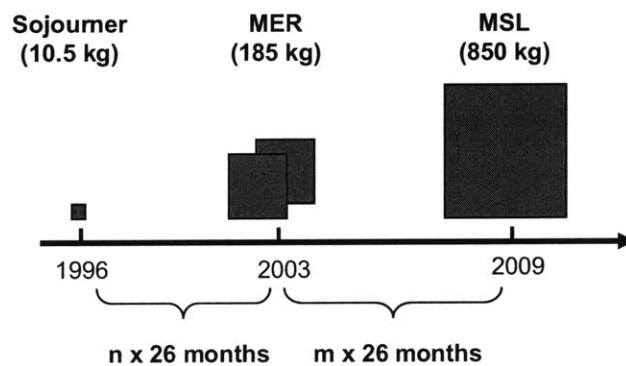
Figure 2-6 Evolution of NASA Mars rovers

Each square has an area proportional to rover mass (MSL mass from [NASA, 2008])
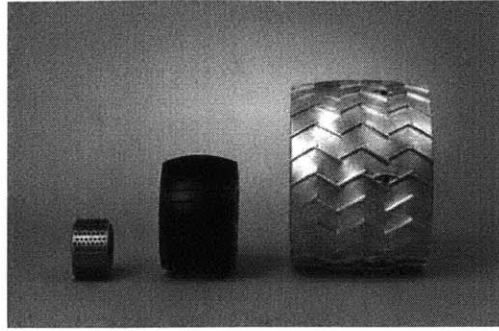
Figure 2-7 Comparison of the wheels of Sojourner, MER and MSL

(courtesy of NASA Caltech-JPL)

In just two missions, rover mass has grown more than eighty times; the progression reflects the increasing scientific and exploration ambition of MEP stakeholders. This rapid growth has limited the possibility of reusing rover hardware, one exception is the hazard avoidance cameras (HazCam) which have been used on Sojourner and MER and will be used on MSL.

System interactions

With the exception of Sojourner's navigation and communications capabilities, both of which depended on the Pathfinder lander, NASA rovers are independent and self-sufficient robots which have only limited interactions with other systems of the MEP. The Pathfinder mission is so far the only example of a surface-to-surface communication link on Mars. The two MER rovers have demonstrated orbiter-based Mars communications infrastructure but were not designed to communicate with each other (they are physically located on opposite sides of the planet). The current MEP campaign, which alternates between orbiting and surface missions every 26 months, does not facilitate the collaboration between successive generations of surface systems.

2.1.3 Operational Architecture

The use context of the MER and MSL rovers is illustrated in Figure 2-8. The figure highlights rover interactions with the Martian environment and other MEP systems.
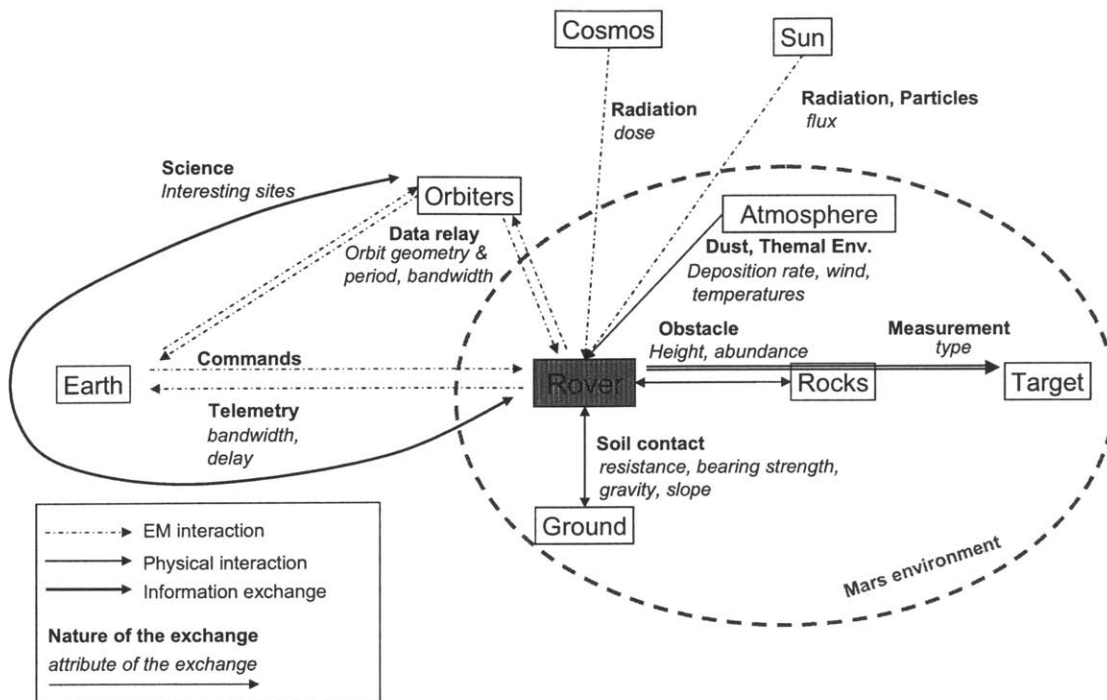
Figure 2-8 Rover mission operational context

The Orbiter-Earth-Rover information link represents the flow of scientific knowledge acquired by orbiting missions that is used to design rover missions (e.g., rover landing site selection based on orbital imagery). Conversely, surface data collected by rovers and other surface probes are used to calibrate orbiter instruments. Operations in the Martian environment are characterized by:

- a thin atmosphere, not well understood, which makes the entry descent and landing (EDL) phase one of the riskiest operations phase;
- a delay in communications which ranges between from a few minutes to over forty minutes (round trip) and which forces Martian rovers to have minimum autonomy;
- a Martian solar day (sol) which lasts approximately 24 hours and 40 minutes;
- and a solar irradiance in Mars orbit which is less than half that in Earth's orbit.

On Mars, the pattern of surface exploration has been mostly linear; a NASA rover explores one site and moves on to the next one, rarely going back to a previously visited location. Because Sojourner relied on the lander for communications relay and navigation, its exploration radial range was limited to 12 meters from the lander.

NASA rovers have had increasing traverse capability (Table 2-1) but paradoxically, rover speeds have not increased significantly. The mechanical speeds of Sojourner, MER, and MSL are 0.01, 0.04 and 0.05 meters per second, respectively. The mechanical speed of a rover is defined as its maximum speed on hard flat ground as determined by the rotational rate of its drive motors [MSL, 2006]. To achieve more traverse capability, NASA's approach has been to extend the duration of mission operations, and to increase rover autonomy and rock clearance. The nominal mission durations of Sojourner, MER and MSL are 10, 90 and 668 sols respectively.

2.1.4 Technical Architecture

In this study, the technical architecture corresponds to the third layer of decomposition of the rover system. In Figure 2-4, which shows the first two layers, subsystems with specific design choices have been identified. The mission-specific implementations of subsystem components are listed in Table 2-2; the various component implementations are *design choices*. The rows correspond to various rover components and the columns to their implementation on Sojourner, MER and MSL. The chronological evolution of a component is illustrated by arrows connecting its implementations one each mission. Text over an arrow highlights the driver for the change in implementation.

The need for samples of improved quality motivates the selection of acquisition and processing tools which can expose unweathered surfaces and access rock sample cores (Table 2-2). MER was equipped with the rock abrasion tool (RAT) and MSL is expected to have a sample acquisition/sample preparation and handling (SA/SPAH) tool [Udomkesmalee, 2005]. The desire to improve scientific production, through longer mission durations, and scientific range, by reaching higher latitudes, forced the selection of a radioisotope power system (RPS) for MSL, instead of solar power, previously used by Sojourner and MER. As mentioned in Section 2.1.2, the selection of the RPS significantly affected the thermal control architecture [Bhandari, 2005]. MSL is also equipped with double-string avionics to satisfy minimum reliability requirements over its two-year mission duration. The computational and communications capabilities have increased on each rover generation. The trend of increasing wheel diameter (Figure 2-7) reflects the trend increasing scientific payload and rover mass.

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Table 2-2 Technical Attributes of Sojourner, MER, and MSL subsystems

Subsystem	Sojourner		MER		MSL
Acquisition & processing tools	no tools	scientific quality →	Rock Abrasion Tool	scientific quality →	SA SPAH
Power source	solar + batteries	→	solar + batteries	scientific production & range →	RPS + batteries
Thermal control	Aerogel+ RHU	→	Aerogel+ RHU+heaters	RPS →	Mechanically pumped fluid loops
Avionics architecture	single string	→	single string	reliability →	double string
Computer	80C85	→	RAD6000	→	RAD750
Communications architecture	to lander	→	DTE and orbital relay	→	DTE and orbital relay
Wheel diameter	0.13 cm	→	0.25 cm	→	0.50 cm

2.1.5 Summary of the attributes of Past and Current NASA Mars rovers

The description of the functional, physical, operational, and technical aspects of past and current NASA rover systems has led to the distinction between attributes of a rover class and rover design choices.

NASA Mars rover class

A generic NASA Mars rover is described as:

- A system whose main functions are to *move* a given instrument payload to selected targets, *measure*, and *communicate* telemetry to Earth.
- A system with increasingly ambitious scientific and exploration objectives.

- A system whose exploration capability is improved over generations through longer mission durations, autonomy infusion, and higher rock clearance.

- A *non-collaborative* system whose interactions with other MEP systems are limited to relaying information.

- An *integral* and *rigid* system which *grows* over generations.

- A system with a six wheel rocker-bogie locomotion system and a centralized body.

NASA Mars rover design choices

The list of design alternatives that have been implemented on NASA Mars rovers is shown in Table 2-2. This list helps identify the trade-offs inherent to rover design, for example the use of a solar power system as opposed to a RPS. The list also helps select design variables that should be the inputs to a rover system design model. Except for mission duration and autonomy, all the design variables of the Mars Surface Exploration (MSE) rover design tool, described in Chapter 3, belong to the list of Table 2-2:

- Wheel diameter

- Power system

- Computational capability

- Telecommunication link

2.2 The Next Decade of Rovers

Figure 2-9 shows an illustration of the current plan for the next decade of Mars robotic exploration. Three rover missions are among the candidates for the 2016 and 2018 opportunities (MSL-clone option is not represented in the illustration) [MAPG, 2006 and 2006b]:

- *Astrobiology Field Laboratory (AFL)*: the AFL rover is based closely on MSL heritage but with an astrobiology-focused payload, the next-generation of sample processing system, and the capability to land in more difficult regions of Mars. The mission relies on the heritage of MSL's cruise stage, entry descent and landing (EDL) system and rover design. Current plans estimate the AFL science payload to be 35 kilograms heavier than that of MSL [Schmidt, 2006].

- *Mid-rovers:* this mission concept involves two MER-derived rovers directed to different sites to explore the geologic diversity on Mars.

- *MSL-clone:* this mission concept is an exact copy of MSL, or a mission that is identical to MSL in all respects except that the payload is re-competed. The MSL-clone concept is a cost-driven mission but would still be quite valuable in evaluating habitability in a different location and possibly with more advanced instrumentation than MSL [MAPG, 2006b].

Figure 2-9 Proposed next decade MEP flight architecture [MAPG, 2006b]

All three candidate rover missions depart from the paradigm of rover of increasing scale and science capabilities (Figure 2-6). Although, the AFL concept still follows the trend of larger and more sophisticated scientific payloads, it does so at a lower pace such that it plans to benefit from MSL reuse strategies. All three concepts apply some aspects of platform strategy which is one of the architectural alternatives considered in the next section and which is also the subject of detailed analysis in Chapter 5.

2.3 Exploration of Mars Surface Mission Concepts

The comparison of Sojourner, MER and MSL has highlighted the fact that a large spectrum of the rover design space has been covered in terms of scale and science capabilities (Figure 2-6) but not in terms of physical design alternatives. In the second part of the concept formulation process (Figure 2-1), a qualitative investigation of Mars surface exploration architectures is developed in order to compare NASA rover designs with alternative vehicle concepts. Figure 1-9 shows the pictures of four Mars surface vehicle concepts that illustrate the wide spectrum of surface exploration alternatives. A functional decomposition is employed to explore and organize the trade space of surface exploration concepts.

A top-level concept of a Mars mission's required functions is broken down into sub-functions, and, at the same time, the most abstract version of its physical form, called surface probe, is broken down into sub-elements capable of performing the sub-functions [Crawley, 2004]. The parallel process is illustrated in Figure 2-10; the conjunction of the functional and physical decompositions generates numerous surface exploration concepts which are organized in a concept tree and a figure of merit tree. *Function partitioning* and *vehicle interfacing* are two approaches used to allocate surface exploration functions to surface probes.
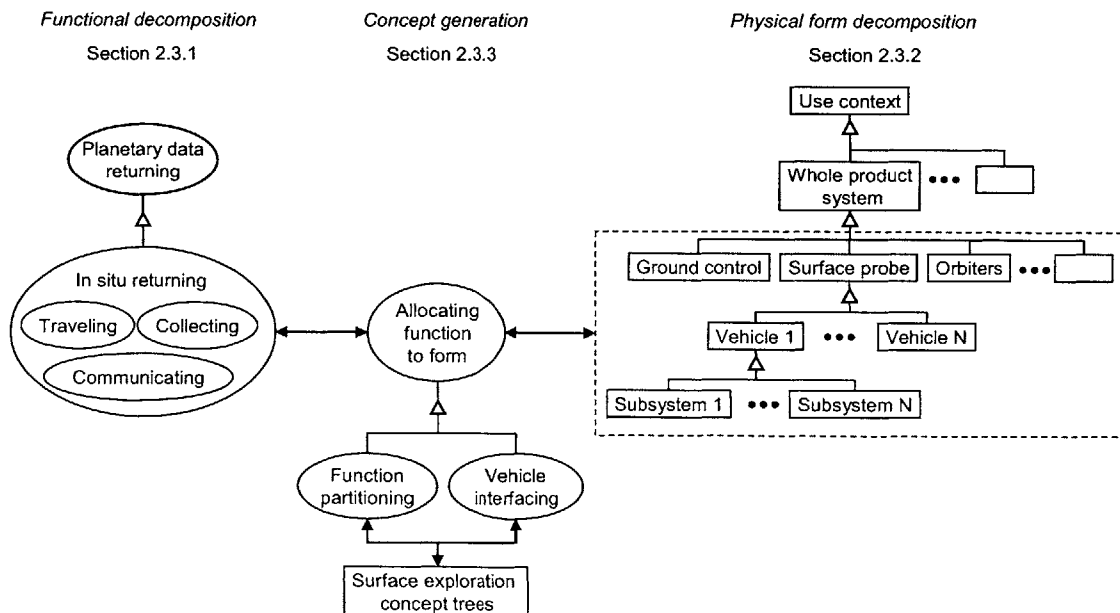
Figure 2-10 Diagram of the approach for exploring Mars surface mission concepts

2.3.1 Functional Decomposition of Mars Mission Concepts

The decomposition process is an adaptation of that proposed by Crawley [Crawley, 2005]; it starts with a characterization of MEP goals and stakeholders based on which figures of merit are subsequently derived.

Mars Exploration Program Goals

The MEP encompasses all NASA Mars robotic mission activities and data analyses to understand Mars and its evolution, and directly supports NASA's Vision for Space Exploration (VSE). It is a *science-driven*, *technology-enabled* effort to characterize and understand Mars [Li, 2006].

Mars exploration scientific goals

The Mars Exploration Program Analysis Group (MEPAG) is charged by NASA with the role of maintaining an up-to-date analysis of the scientific investigations and measurements that would contribute to achieving the high-level scientific goals of the MEP [MAPG, 2006b]. MEPAG regularly evaluates Mars exploration goals, objectives, investigations and required measurements and produces a *Mars Scientific Goals, Objectives, Investigations, and Priorities* document [MEPAG, 2006]. This document summarizes the desired *scientific* and *exploration range* of measurements that should be covered by Mars missions. Water is central to the planet's history and to the four overarching goals of Mars exploration:

1) *To determine if life ever arose on Mars,*

2) *To understand the processes and history of climate on Mars,*

3) *To determine the evolution of the surface and interior of Mars,*

4) *To prepare for human exploration.*

Goals one to three address the needs of the Mars scientific community while the fourth goal addresses the needs of the human exploration community.

Mars exploration programmatic goals

To enable the accomplishment of the scientific goals, the current overarching programmatic goals of the MEP are [Li 2006 and MAPG 2006b]:

1) *To maintain a continuous operations presence on Mars,*

2) *To launch at least one mission to Mars at each 26-month opportunity,*

3) *To provide continuing improvements in technical capabilities of Mars missions by investments in technology development,*

4) *To capitalize on measurement opportunities that contribute to the advancement of knowledge for future human exploration of Mars, in collaboration with ESMD,*

1) *To ensure that Mars exploration activities are publicly engaging and incorporate current Mars mission science and technological achievements into a long-term portfolio and informal education and public outreach activities.*

The first and second goals are purely programmatic; they defined the *schedule* of the MEP. The third goal addresses the need for *innovation* of the scientific and technological communities; the fourth goal addresses the need for knowledge *feed forward* to the VSE; the fifth goal addresses the need for outreach activities targeted to the American public.

Vision for Space Exploration goals

The fundamental goal of the 2004 Presidential Vision for Space Exploration [VSE, 2004] is to advance U.S. scientific, security, and economic interests through a *robust* space exploration program. This vision is supported by:

- *The implementation of a sustained and affordable human and robotic program to explore the solar system and beyond*

- *The extension of human presence across the solar system, starting with a human return to the moon by the year 2020, in preparation for human exploration of Mars and other destinations*

- *The development of innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration*

- *The promotion of international and commercial participation in exploration to further U.S. scientific, security, and economic interests*

Accordingly, NASA's administrator Sean O'Keefe defined the aim of NASA as leading an exploration in a *sustainable, affordable,* and *flexible* manner [VSE, 2004].

Mars exploration stakeholders

The VSE goals address the needs of a wide range of societal sectors. Using a stakeholder analysis, Rebentisch et al. [Rebentisch, 2005] have aggregated societal sectors into five stakeholder groups; the groups are listed by column in Table 2-3.

Table 2-3 Societal interest groups for space exploration [Rebentisch, 2005]

Exploration	Science	Economic	Security	Public
Explorers, Engineers, NASA	Scientists, NASA, Other US government agencies	Commercial enterprises, Other government agencies, Engineers	Dep. Of Defense, Intelligence, International partners	US public, Media, Educators, Executive branch Congress, NASA

Even though the MEP program plan [Li, 2006] identifies *all societal sectors* as beneficiaries of its activities, it recognizes that the scientific and exploration stakeholder groups are its prime customers [Hubbard, 2004]. The economic and security groups play a more influential role in the definition of human exploration activities than in the robotic exploration of Mars. For this reason, this study is limited to the formulation of mission concepts whose objectives contribute to the MEP scientific and exploration goals.

Figures of merit

The process of deriving form from function generates a vast array of potential concepts which all serve the same primary functions. Figures of merit and architecting principles guide the selection of concepts that best satisfy stakeholders [Crawley, 2004]. The IEEE dictionary [IEEE, 1997] defines a figure of merit as a measure of effectiveness through which quantitative system requirement and characteristics can be related to mission objectives in optimizing the system design.

The previous characterization of MEP and VSE goals has already highlighted some figures of merit including: scientific and exploration range, innovation, schedule, knowledge feed forward, robustness, sustainability, affordability, and flexibility. The VSE puts a particular

emphasis on sustainability; variations of the word *sustainable* appear 17 times in the 32-page document describing the VSE [VSE, 2004]. Crawley et al. have adopted the view that sustainability of the exploration effort is the primary organizational principle of the architectural concept [Rebentisch 2005 and Cameron 2006]. They propose that four key factors contribute to sustainability: value delivery, affordability, policy robustness, and mission success.

Value delivery

The notion of value delivery is related the value outputs delivered to the prime beneficiaries of the exploration, the science and exploration groups. Howard et al. [Howard, 2003] use three figures of merit to qualify the scientific return of a mission: *scientific productivity*, *scientific quality*, and *scientific and exploration range*. Scientific range refers to the notion scientific diversity in the kinds of experiments that are performed on a given sample.

The figures of merit of *knowledge feed forward* and *innovation*, previously mentioned, measure other scientific and technological aspects of value delivery to the scientific and exploration communities. The MEP program commitment PC-06 [Li, 2006] states that each mission within the MEP shall be designed to feed forward scientific knowledge, key technologies, and lessons learned to future missions. The program commitment PC-08, states that the MEP Technology Program shall develop low-TRL, high risk, high return technologies that address the long-term goals of the program as well as critical enabling technologies for upcoming missions.

Affordability

To be affordable, the multiple elements of a campaign must be acquired and operated within a realistic budget. The program requirement MEP-R01 [Li, 2006] specifies that the MEP shall be conducted within the funding profile defined in the MEP Program Commitment Agreement. Related to the notion of affordability is the notion of *resource efficiency*. Resource efficiency measures the amount of resources a system consumes in order to produce a given set of valuable outputs. It is crucial for Mars surface probes to exhibit high resource efficiency because they suffer from severe mass and power constraints [Schilling, 1996].

Policy robustness

A policy-robust campaign is capable of adapting to shifting and modified government policies without failing to meet the needs of the critical stakeholders [Singleton, 2005]. Policy robustness is enhanced by a sound stakeholder satisfaction strategy and architectural flexibility. Singleton et al. propose that in a campaign there should be at least one aspect that addresses a need or desire of each of the important stakeholders. This recommendation is particularly important during the selection of the scientific payload of a mission. The selected instruments must address the needs of all planetary science fields (e.g. climate science) represented in the MEPAG document. The MEP must also deal with policy regulations related to the planetary protection regulations in the case of in-situ exploration and public safety regulations in the case of Mars sample return missions (program requirement MEP-R16 in [Li, 2006].

Mission Success

Mission success is achieved by managing of risk over all design phases. The MEP program commitment MEP-PC03 [Li, 2006] highlights safety and mission success as higher priorities than cost and schedule. During formulation and development, *technology readiness* [Shishko, 1995] is a major driver of the selection of mission technologies [Caffrey, 2004]. System *reliability* is a measure of mission success in the operations phase. Reliability is defined as the ability of a system to perform its required functions under stated conditions for a specified period of time [INCOSE, 1998]. In practice, redundancy is often implemented to improve the reliability of system through graceful degradation of its capabilities [Wertz, 2005]. Because the EDL phase is one of the riskiest phases of Mars mission, the MER mission implemented redundancy at the system level by developing two rovers that have been independently launched, landed and operated. Mission success required the successful operations of only one of the two rovers. Because of its increased mission duration, the MSL mission is expected to implement redundancy at the subsystem level by implementing a double-string architecture, instead of a single-string one, for its avionics.

Figures of merit of Mars exploration architectures are summarized in Table 2-4. Although these figures of merit have been derived from MEP goals and stakeholders, their definitions are broad enough to be applied to other fields of planetary exploration.

Table 2-4 Figures of merit of Mars exploration architectures

Stakeholders		Figures of merit
Science and exploration	Value delivery	scientific quality scientific productivity scientific range exploration range flexibility scientific feed-forward scientific robustness
MEP, NASA	Value delivery	technology feed-forward technological innovation
	Affordability	campaign affordability mission cost resource efficiency
	Mission success	schedule technology readiness reliability simplicity robustness
	Policy robustness	stakeholder range public safety planetary protection

Solution-neutral definition of a robotic planetary mission

For a given system, an operand is an object which the system operates on. The value related operand is the operand which is associated with system value delivery; the value related operand is operated on by changing a system attribute. In this sense, the value-related operand of a planetary mission for science and exploration is planetary data. Indeed, by returning planetary data, a mission satisfies the need of the scientific and exploration stakeholder groups for a better understanding of the planet. All the elements of a solution-neutral statement of a planetary mission's function have been identified: the beneficiaries are the scientific and exploration groups; their broad need is to better understand a planet; a mission addresses this need by acting on planetary data; the process involved in this action is *returning*. In the remainder of this chapter, processes, as opposed to objects, are written in italic font in the text.

The value delivery process is illustrated in Figure 2-11 using an OPM representation [Dori, 2003]. The OPM representation is well suited to highlight the stakeholders, operand and value delivery process.
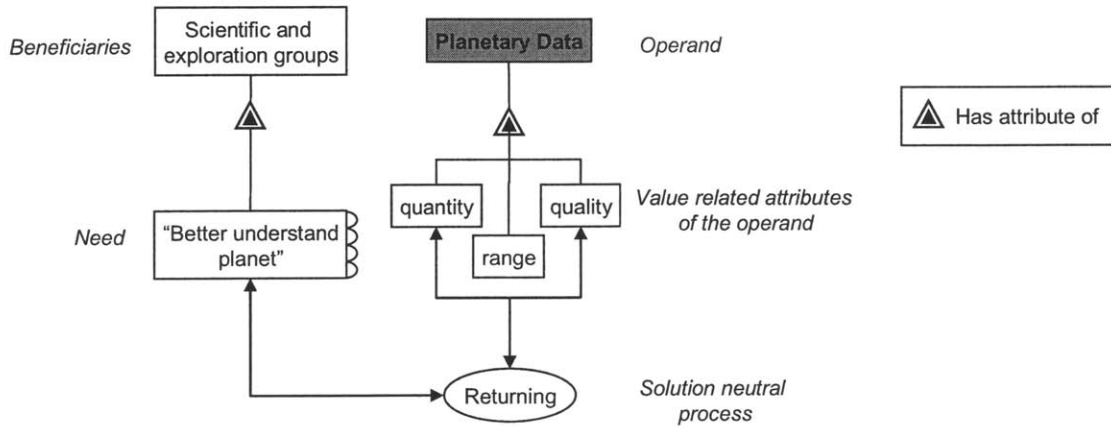
Figure 2-11 Solution-neutral formulation of the value delivery process for a planetary mission

The value delivery process as expressed in Figure 2-11 applies to all types of planetary observations. The subsequent decomposition of this solution-neutral expression introduces a first layer of specialization which differentiates various processes of *returning*.

Concept process and instrument object

In order to complete all MEPAG objectives, three types of observation are necessary: remote sensing, in situ measurements, and sample analysis in Earth laboratories [SSE, 2003]. Accordingly, Figure 2-12 shows the decomposition of *returning* planetary data into three specialized processes: *remotely observing*, *in situ measuring*, and *sample returning*.
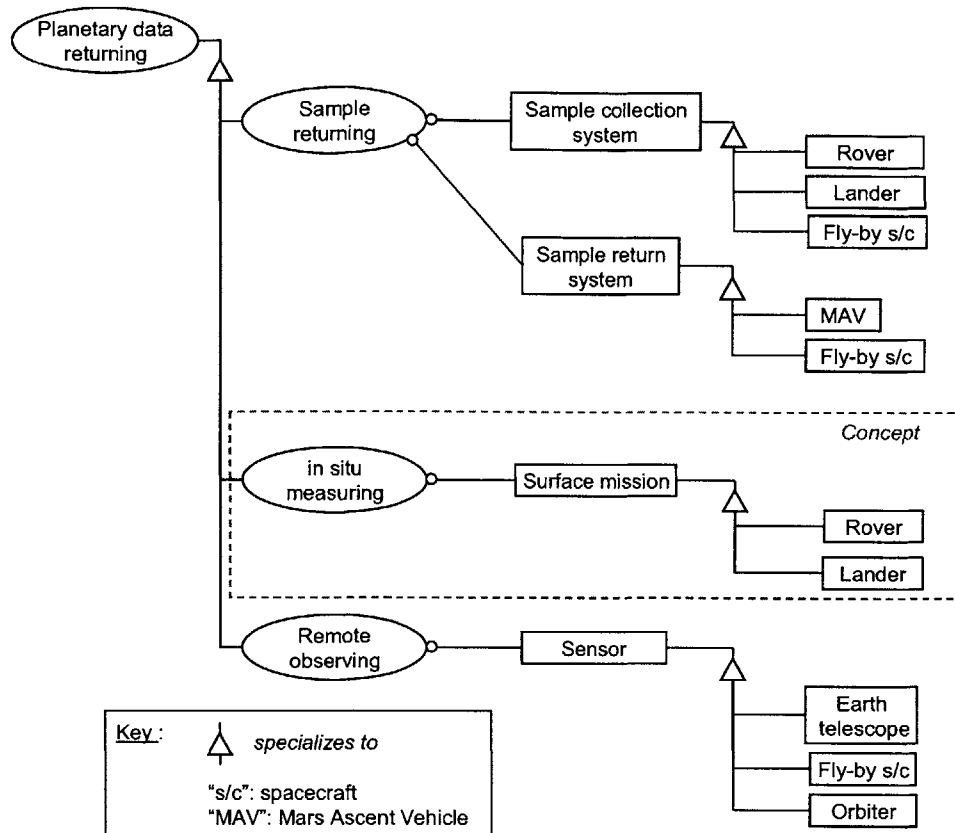
Figure 2-12 Specialization of the *planetary data returning* process

The MEP campaign of missions has maintained a balance between remote observing and in situ measuring missions, but it does not yet have confirmed plans for a sample returning mission (Figure 2-9). A closer examination of the planning of Mars sample return (MSR) missions provides insights about the factors influencing the decision of planning a surface mission as opposed to a sample return one. The Solar System Exploration (SSE) decadal survey emphasized the scientific value of a MSR mission compared to remote and in situ observation missions; MSR is required in order to perform definitive measurements to test for the presence of life, or for extinct life, as well as to address Mars's geochemical and thermal evolution [SSE, 2003]. The survey recommended that MEP begin its planning for MSR so that its implementation can occur early in the decade 2013-2023 [NRC 2003, p7]. Under current program funding levels and priorities, the mission queue does not include MSR before the 2020's nor a focused technology development starting before 2014 [MAPG,

2006b]. The MEP has been criticized by the National Research Council (NRC) for not following SSE's recommendation [NRC, 2006].

While the SSE and NRC arguments for an early MSR mission are primarily based on scientific considerations, the MEP is forced to balance scientific priorities with other figures of merit: MSR has high scientific and technical risks; it is not financially possible with current MEP funding; its focused technology development needs to start 10 years prior to launch; and the mission has policy and safety implications related to the collection and return to Earth of extra-terrestrial samples. The advantages of flying in-situ missions are that they are relatively low cost compared to MSR and there are no issues of sample degradation, sample amount, sterilization, quarantine or off nominal delivery to Earth [Steele, 2006]. Figure 2-14 illustrates the effects of the figures of merit on the decision regarding the planning of a MSR mission. Figure 2-13 shows the generic format used in the remainder of this study is to represent decisions and influencing factors.
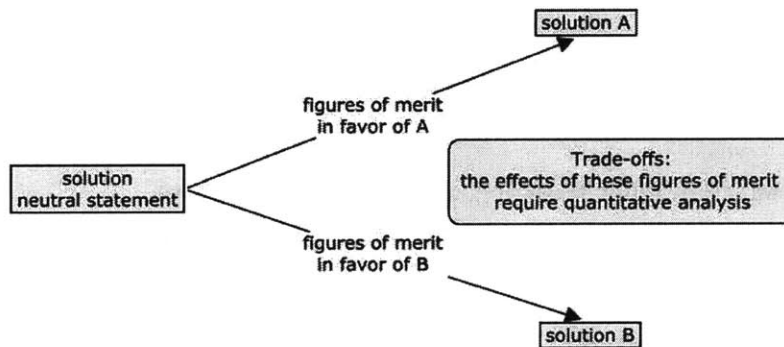
Figure 2-13 Generic representation of figures of merit that influence specific implementations of a solution neutral statement
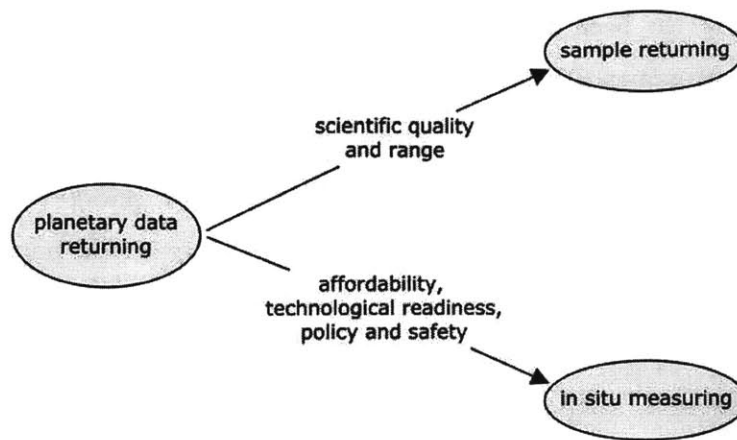
Figure 2-14 Figures of merit that influence the selection of mission type

The selection of a mission type is the first decision leading to the implementation of a rover mission. Abstract systems involved in the physical implementation of *planetary data in situ measuring* are described in the next step.

Internal processes

Crawley [Crawley, 2005] categorizes internal processes into four groups:

1) *supporting*: connecting, powering, and controlling processes

2) *other value related*: other processes linked to other necessary externally-delivered processes.

3) *interfacing*: interfacing processes

4) *primary value related*: processes which support the primary externally-delivered process linked to value.

The *planetary data in situ measuring* process involves three major solution-neutral sub-processes: *traveling* to the data, *collecting* the data, and *communicating* the data to Earth (Figure 2-15).
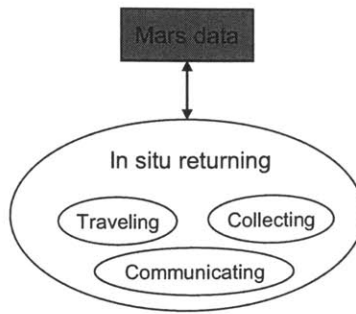
Figure 2-15 Functional decomposition of data in situ returning

The three sub-processes are further decomposed as follows (adapted from [Lincoln, 2003] and [Howard, 2003]):

- *Moving* : changing the probe's location on the surface to a target position

- *Sensing* : sensing of the terrain over which the probe expects to move

- *Mapping* : creating map of the terrain based on the sensing data

- *Planning* : planning a safe trajectory through the terrain

- *Locating* : locating the position of the probe on the surface

- *Imaging* : taking panoramic pictures of the surface or close-ups of rocks

- *Targeting* : selecting targets based on imaging data

- *Approaching* : positioning of the rover with respect to the desired sample

- *Acquiring* : acquiring the sample

- *Handling* : preparing the sample for subsequent measurement, disposing of the sample and cleaning sample handling equipment

- *Measuring* : measuring the sample
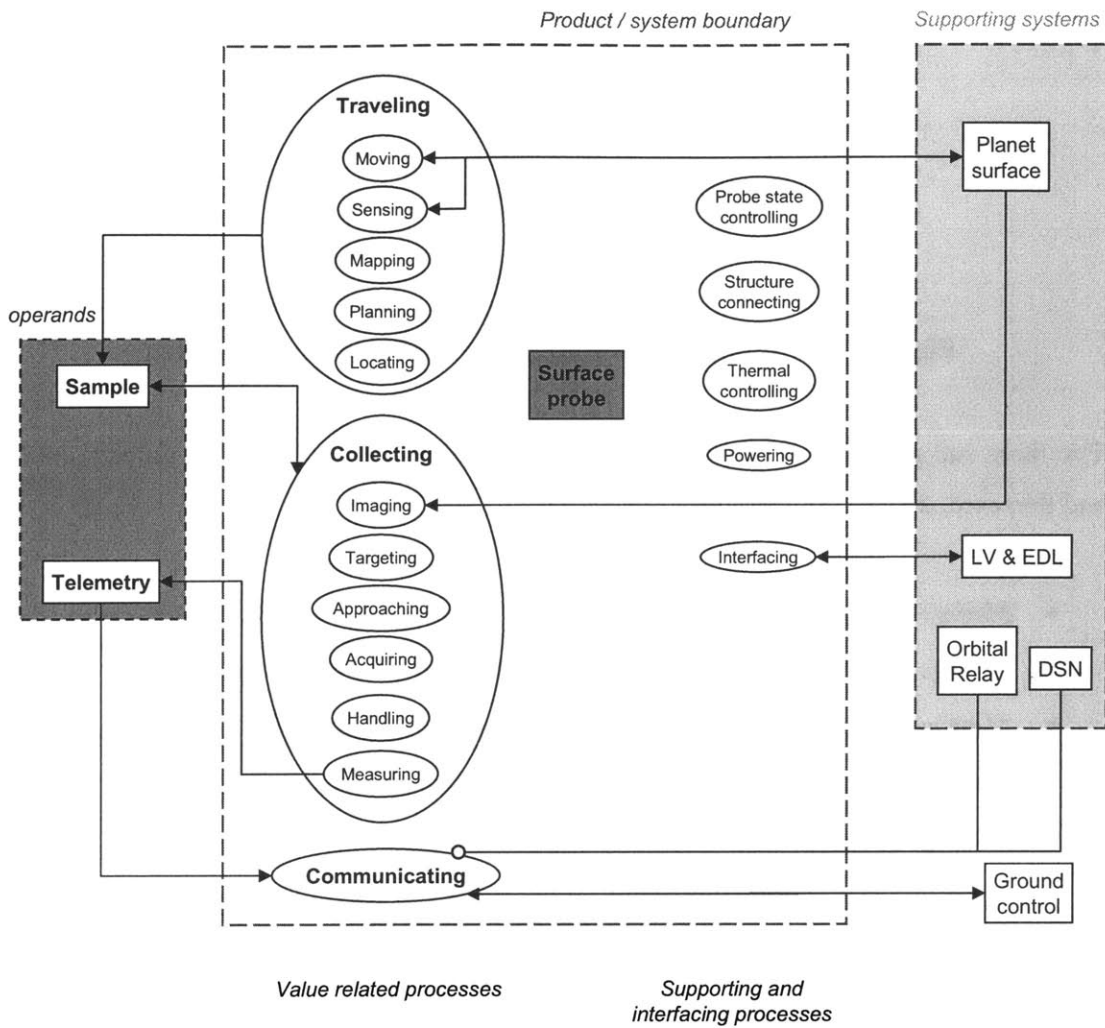
Figure 2-16 OPM diagram of the functional decomposition of *planetary data in situ returning*

Figure 2-16 shows value related, supporting, and interfacing processes. At this stage, processes are detailed enough for some to be associated with particular elements of the whole product system discussed in the next section. The remaining processes are associated with vehicles and vehicle subsystems of the surface probe.

2.3.2 Physical Form Decomposition

In this section, the notion of surface probe is described in the broader background of the whole product system and use context (Figure 2-10) and options for the implementation of surface probe concepts are discussed.

Whole product system and use context

At this stage, the notion of surface probe is very broad; in Figure 2-12, a surface probe is shown as an abstract physical implementation of *planetary data in situ returning*. In this study, a surface probe is any kind of vehicle or collection of vehicles (network) that perform the function of *planetary data in situ measuring* (Figure 2-12). Surface vehicles are said to belong to the same surface probe concept when they are operated together and either collaborate or share strong physical and technical design similarities (e.g. MER). According to this definition, the Pathfinder lander and Sojourner belonged to the same surface probe concept because they collaborated in their surface exploration activities.

A surface probe system alone cannot return planetary data; it requires, in fact, the support of a number of systems. A launch vehicle (LV), cruise stage, and EDL system are elements necessary to bring a probe to the planetary surface; relays (e.g. orbiters) and the deep space network (DSN) are elements that help a probe's communications with its operators and beneficiaries. The system (surface probe) and supporting elements constitute the *whole product system* (Figure 2-17).
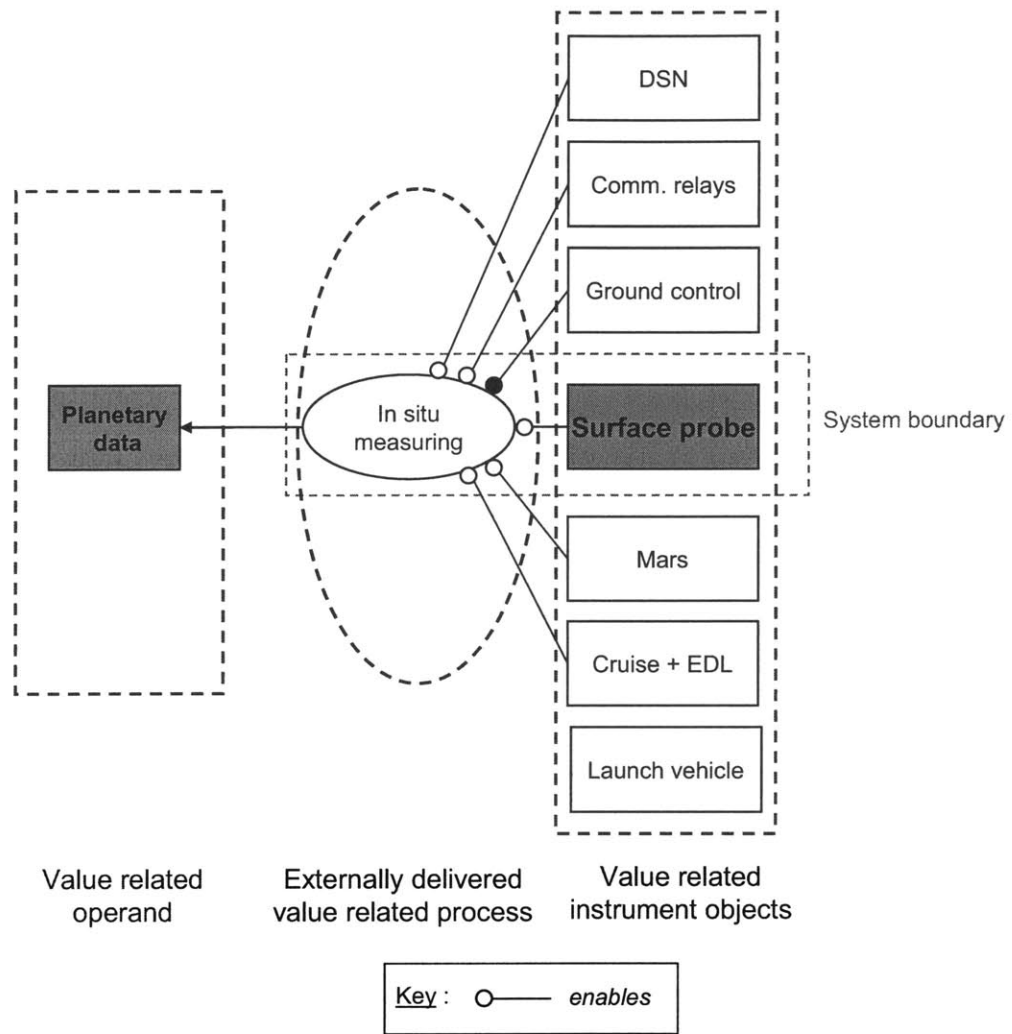
Figure 2-17 Rover whole product system

(adapted from [Crawley, 2005])

The whole product system is itself part of the use context (Figure 2-18). The use context includes other systems that do not directly support the surface probe but are present in its operational context.
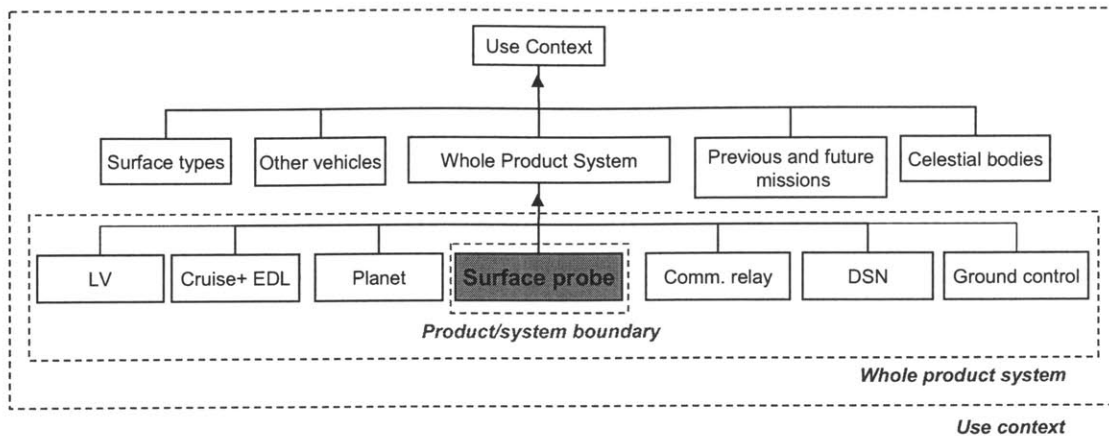
**Figure 2-18 Rover system whole product system and use context
(adapted from [Crawley, 2005])**

Figure 2-18 illustrates the fact that the use of a surface probe can involve operating on various types of surfaces (e.g. crater, dune), interacting with other vehicles (e.g. an ascent vehicle), and playing a role within the integrated planetary exploration campaign. The participation of the surface probe in an exploration campaign is an interaction that takes place over time. It needs to be highlighted because time interactions are not easily captured in OPM representations of architectures. Mars missions form an integrated set in three aspects [Li, 2006] : a) the scientific discoveries from one mission inform the formulation of the scientific focus of future missions, and, in certain cases, provide crucial data for their execution; b) a mission can provide engineering capability or demonstration of technological advances that enable future missions (feed-forward); and c) a mission serves as a telecommunication relay for other missions.

Physical implementation options

In the subsequent paragraphs, modularity, reconfigurability, and platform strategies are described as physical properties of a concept which improve its performance with respect to specific figures of merit. Principles and guidelines regarding the implementation of these physical properties are also provided. Figure 2-19 shows where modularity, reconfigurability, and platform strategies act in a system.
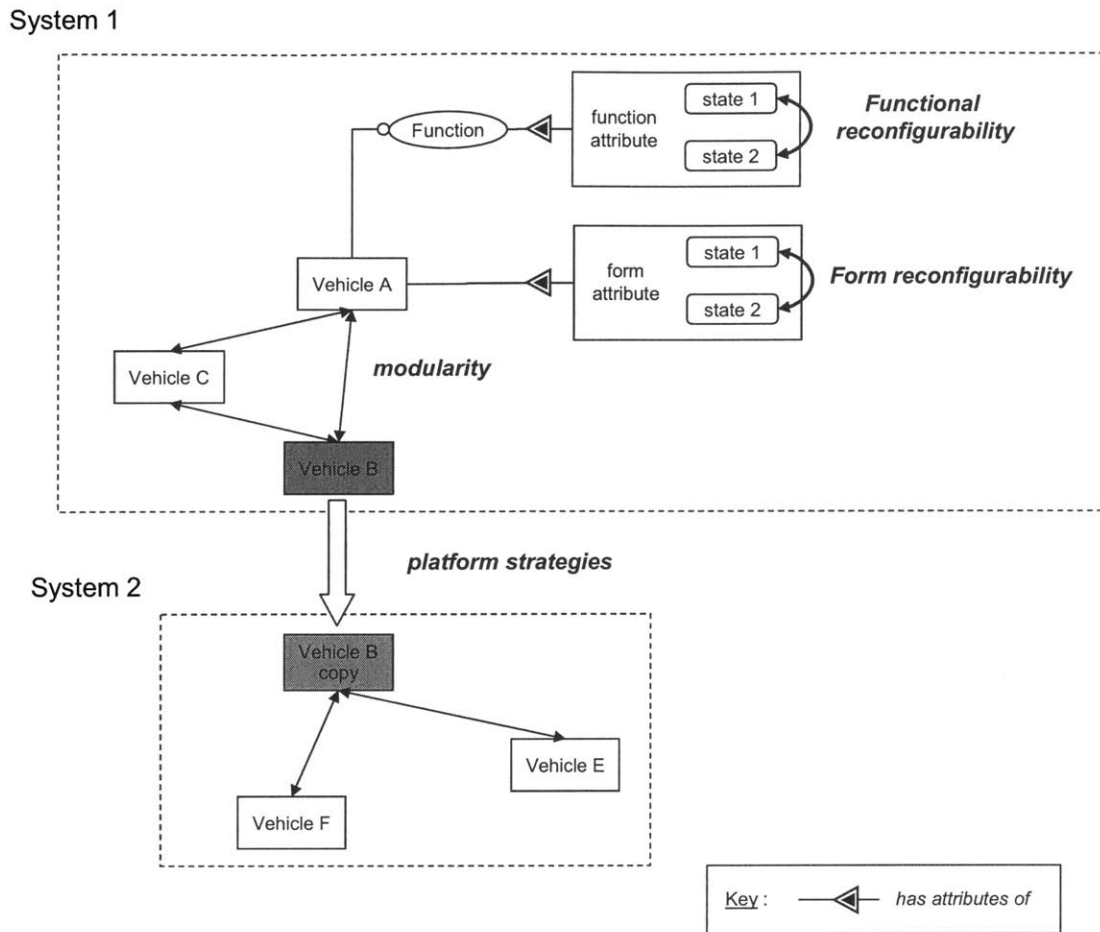
System 1

Figure 2-19 Illustration of the application area of modularity, reconfigurability, and platform strategies in the conception of a system and families of systems (adapted from [Siddiqi, 2006b])

On the one hand, reconfigurability is employed at the vehicle level; it provides a vehicle with the ability to partially change form or function. On the other hand, a platform strategy is employed at the family level (system 1 *and* system 2); it enables several systems to be based on common vehicles. The implementation of reconfigurability and platform strategies is facilitated by modularity which acts at the system level; modularity improves the interface between two vehicles.

Modularity

A definition of modularity is the degree to which a system is composed of discrete components such that a change to one component has minimal impact on other

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components [INCOSE, 1998]. Miller [Miller, 2006] breaks down the benefits of modularity in terms of hardware, software and mission phases (Table 2-5).

Table 2-5 Benefits of modularity in space missions [Miller, 2006]

	Development	Operations
Hardware	• Customize at assembly • Inventory subsystem modules for rapid deployment • Simplified integration and verification • Exploit design heritage	• Reconfigure to optimize team productivity or perform different tasks • Discard and replace failed or obsolete modules • Upgrade obsolete sub-systems
Software	• Re-use design & test processes • Re-use design templates to insert new technology through proven processes • New sub-system testing through S/W emulation	• Adapt planner and executive to changing environment • Adapt planner to reconfigured rover • Adapt S/C operation to accommodate failed components

According to Table 2-5, modularity provides similar benefits to hardware and software design. During development, modularity helps integration and testing, shortens development schedule, and enables feed-forward of modules to future missions. During operations, modularity improves flexibility, extensibility and maintainability. It is, however, striking that modular software architectures have been widely accepted in planetary missions [Biesiadecki & Maimone, 2005], whereas, to the best of the author's knowledge, no deep space robotic probe has yet been designed with modular hardware. The MER mobility software has been organized in a modular architecture made of software objects, each with their own task, state variables, and memory. Biesiadecki et al. argue that this solution greatly simplified rapid development of robust software [Biesiadecki & Maimone, 2005]. Furthermore, the ability to reconfigure the mobility software during MER operations, in order to adapt to the surface environment, proved very useful. It also enables the development of new autonomy technologies that will likely be used by MSL.

All of the operational benefits of hardware modularity listed in Table 2-5 assume that the system is interacting with other modules and other modular systems. Because NASA Mars

rovers have traditionally been operated independently, there has been no need for infusing modularity. The sustainability objective and operational context of the Vision for Space Exploration offer real opportunities for modular robots, notably with the prospect of human-robot collaboration. Astronauts could perform reconfiguration and module exchange tasks and thereby greatly improve the lifecycle value of modular robots as opposed to integral ones. Zakrajsek et al. [Zakrajsek, 2005] judge that design "modularity will be the single most important factor in the development of a truly viable surface mobility vehicle" to achieve the goals of the VSE.

The fact that NASA has designed only integral rovers also suggests that NASA has judged the benefits of modularity development not worth its costs. Modularity adds interfaces between modules which add weight and occupy space that can be used to accomplish other goals in an integral system [Crawley, 2004]. Therefore, the resource efficiency of a modular rover is less than that of integral rovers. It is debatable whether modularity improves mission and campaign affordability. To answer this question, a real options analysis would be required in which the initial design overhead of a modular system is balanced with the potential lifecycle savings enabled through easier maintenance, repair, and evolution.

Figure 2-20 illustrates the figures of merit that influence the decision for modularizing a planetary surface exploration probe.
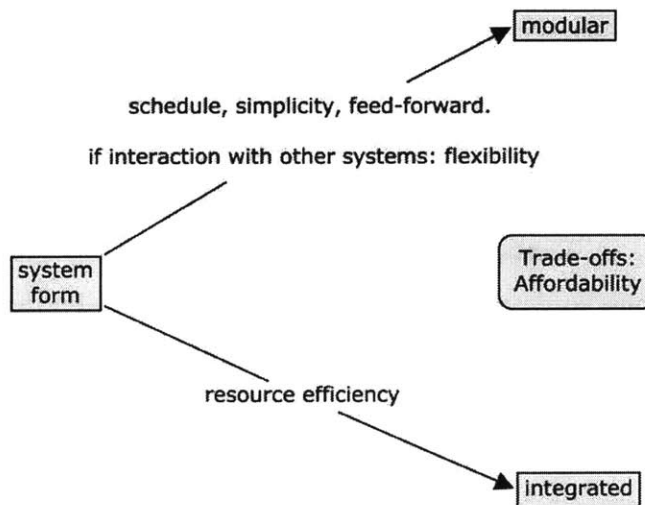
Figure 2-20 Figures of merit that influence the decision to implement of hardware modularity

In addition to the figures of merit, two principles guide the implementation of modularity. Both principles, provided by Maier and Rechtin [Maier, 2002], express the same guideline; the first one is for partitioning tasks, the other one is for aggregating tasks.

Do not slice through regions where high rates of information exchange are required.
and

Choose a configuration with minimal communications between subsystems

Both principles originate from the field of computer networks but have relevant and useful applications to the design of modular surface exploration architectures as shown in the subsequent concept formulation exercise. Because it promotes the creation of numerous architectures by decomposing and re-assembling systems, modularity is a catalyst in the formulation of concepts.

Reconfigurability

Reconfigurable systems can be defined as systems that can reversely achieve distinct physical configurations (or states) through alterations of system form or function, in order to achieve a desired outcome within acceptable reconfiguration time and cost [Siddiqi, 2005]. Reconfigurable systems are robust and flexible because they can advantageously adapt to changes in use context either functional (system must execute new function) or operational (system operates in new environment) [Siddiqi, 2006]. Furthermore, reconfigurable systems can potentially exhibit good resource efficiency and affordability because they combine several functions in one system. However, reconfigurability has also a cost in design overhead (more mechanisms) and in the effort spent for each reconfiguration. There is a resource efficiency and affordability trade-off for reconfigurable systems. The main advantage of single-state systems is that they are more simple to design than reconfigurable systems.
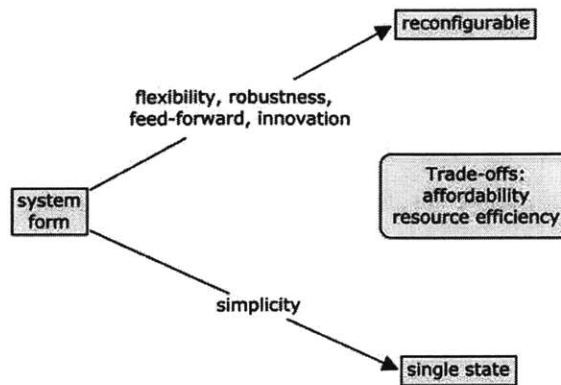
Figure 2-21 Figures of merit that influence the implementation of reconfigurability

Siddiqi et al. [Siddiqi 2006] have developed two frameworks to assess the benefits reconfigurability and optimize the performance of reconfigurable architectures. This work has also contributed three principles related to reconfigurable systems [Siddiqi, , 2006b].

- Principle of reconfigurability:

For every configuration of a reconfigurable system there exists a corresponding

dedicated system that is at least equal in performance.

A good reconfigurable design is one in which the performance of each configuration approaches that of the corresponding dedicated system.

- Principle of self-similarity:

Systems with self-similar modules have the highest degree of reconfigurability.

Systems composed of identical or very similar modules are the easiest to reconfigure radically. The corresponding prescriptive principle is that common modules should be maximized across configurations.

- Principle of information reconfiguration

Maximize the informational nature of the element under frequent reconfiguration

Maximizing the informational nature of reconfigured elements is desirable since it is easier to change information than physical hardware..

Platform strategy

A platform strategy acts on a *family* of systems as opposed to a single system. A product platform is a set of parameters, features, and components that remain constant from product to product, within a given product family [Simpson, 2001]. Platform strategies are appealing because they can potentially improve the affordability of a product family by taking advantage of economies of scale across the family [de Weck, 2004]. Furthermore, the re-use of proven components enables platform-based systems to have shortened development schedules [McCoy, 2005] and reduced development and operational risk [Gonzalez, 2000]. Accordingly, the MEP program commitment PC-07 [Li, 2006] states that the program shall apply a systems approach to exploit, where appropriate, project-to-project reuse of flight and ground hardware, software and development tools such that program cost and risk are minimized.

However, the desire to test new technologies and to optimize each mission makes the reuse of large portions of a system unattractive. Furthermore, platform strategies tend to diminish some aspects of policy robustness; over time, the design of platforms favors a subset of beneficiaries (e.g. one entity related to the development of a platform component) at the expense of other potential beneficiaries [McCoy, 2005].

In the case of Mars exploration, several characteristics of the Mars rover program suggest that it could benefit from platform strategies [de Weck, 2004]:

- The Mars rover exploration architecture has a common set of basic attributes. Section 2.1 shows that rover missions of the MEP exhibit a high level of commonality at the functional, physical, technical, and operational levels.

- The Mars rover exploration architecture has highly interconnected systems (e.g. surface vehicles and orbiters) with a need for future growth and a constant update of technologies.

- The Mars rover exploration architecture has a stable core functionality but has variability in secondary functions. For example, the primary functions of the rover vehicle (e.g. *traveling*, Section 2.3.1) are the same for all rover missions. However, the functions of the scientific payload depend on mission-specific objectives.

Figure 2-22 summarizes the factors that influence the implementation of platform strategies in space exploration systems.
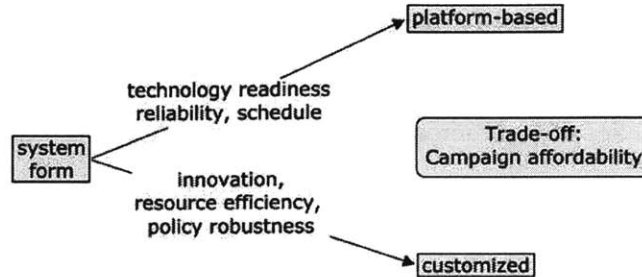
Figure 2-22 Figures of merit that influence the implementation of platforms

It is debatable whether a space exploration platform strategy would sufficiently improve affordability the level of the space exploration campaign (product family) to offset non-optimality and resource inefficiency at the mission level. The following is a list of principles which guide the implementation of platform strategies.

- Principle of platform strategy

The principle of reconfigurability stated above has a derivative in platform strategies.

For every platform-based system there exists a corresponding customized system that is at least equal in performance.

A product family is optimized at the family level and, in the general case, optimality of a family does not imply optimality of each of its products.

- Principle of platform component identification [Crawley, 2005]

Customize where it is hot, platform where it is not

Based on this principle, good platform components should exhibit low sensitivity to the variety of requirements and uses specific to each system on which they are implemented. Components that are sensitive to requirements should be customized for each system implementation.

2.3.3 Concept Generation

As mentioned previously, the notion of surface probe refers in this study to a vehicle or a collection of vehicles (network) performing the function of *planetary data in situ measuring* (Figure 2-12). During the physical implementation of a concept, the designer chooses the number of robotic elements that comprise the surface probe and allocates functions to these elements and their subsystems.

Further decomposition of the surface probe and functions illustrated in Figure 2-16 is accomplished only by choosing particular concepts or instantiations of the probe [Crawley, 2004]. A concept is a product or system vision, idea, notion or mental image which maps function to form [Crawley, 2005]. The mapping of functions to objects is done at three levels (Figure 2-10 and Figure 2-23). First, functions are assigned to agents of the whole product system, including surface probe, ground control and other MEP systems. Second, functions are associated to vehicles that constitute the surface probe; this step produces multi-vehicle mission concepts. Third, functions are assigned to subsystems of each vehicle.
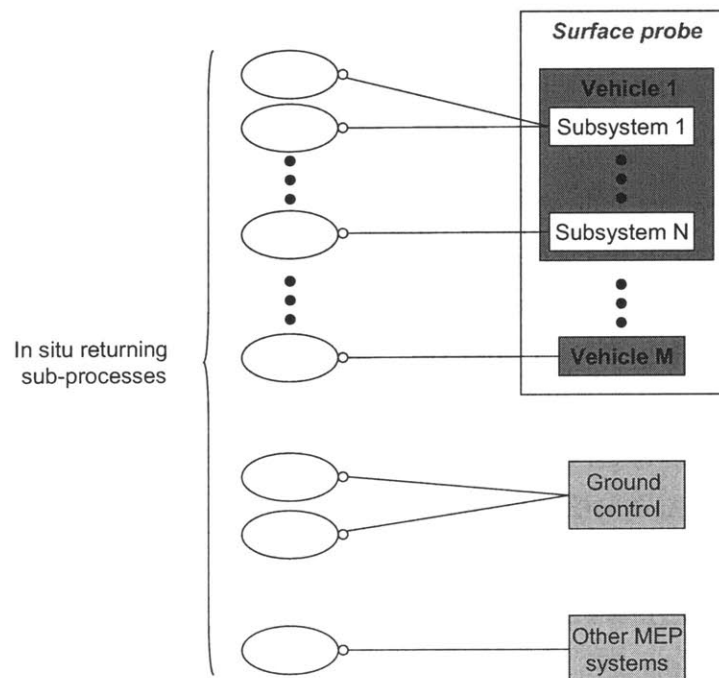
Figure 2-23 Illustration of surface probe concept as a mapping of function to form

The first two allocation steps define a concept's physical implementation, while the last allocation step defines its technical implementation. In this approach, the number of vehicles in the surface probe is not considered a design variable, but rather, it is a result of the function allocation process. At this stage emphasis is on completeness of the decompositions and concept creativity; a priori judgments about concept feasibility should not limit the mapping of function to objects.

Allocation of Processes to Agents

In this study, an agent is defined as a system, automated or human, which is able to perform a value related function (Figure 2-16). A typical robotic mission involves three categories of agents: a surface probe, other MEP systems (e.g. orbiters) and ground control. Most functions are performed by a combination of operator and probe agents. The degree to which the surface probe is involved defines the level of automation for the given function. In general, development cost and schedule are two figures of merit that tend to limit the development of new software and autonomy technologies and favor instead software heritage from previous missions [Reeves 2005 and Kurien 2004]. The next two sections examine the influence of the remaining figures of merit on the *traversing* and *collecting* sub-processes.

Traversing sub-processes

Moving is an in situ function exclusive to the surface probe. The remaining sub-processes can involve several agents. In MER operations, processes related to surface navigation (*mapping, planning,* and *locating*) currently involve a combination of operator-generated commands (blind drive) and probe autonomy (autonomous drive) [Biesiadecki, 2005b] (*Autonomy,* Chapter 3). During a blind drive, the rover follows a trajectory planned and commanded by the operations team based on panoramic images the rover sent at the end of the previous sol; this type of drive is referred to as blind because the rover follows the commands of the operations team without using its on-board navigation capabilities. During a site-to-site traverse, a rover executes a blind drive on a daily basis. Once the rover has finished the blind drive, and if it has the time and energy to do so, it continues in an autonomous drive mode. During the autonomous drive the rover uses its on-board navigation sensors to plan a path on its own; as a consequence, it moves at a slower speed than during a blind drive.

The visual odometry capability of MER's autonomous navigation has improved safety by enhancing autonomous wheel slippage detection [Cheng, 2006]. The partial automation of navigation processes has also increased daily traverse capability and therefore rover science productivity. The move toward a full automation of navigation processes would alleviate the need for daily operations and thereby reduce operations cost; if the savings offset the cost of autonomy development, full automation would improve affordability. Because, with current technology, the execution of autonomous drives is slower than that of blind drives, autonomous navigation would, however, decrease scientific productivity. Therefore, automation does not always improve scientific productivity.

Orbiters can also play various roles in the execution of *traversing* sub-processes. Improvements in orbital imagery resolution could enable orbiter-based surface hazard *sensing* and probe *locating* with sufficient accuracy and thus retire the need for such functions on-board the probe. Furthermore, orbiters could act as computer units for *mapping* and *planning* processes of several surface missions. Because orbiters are in general less power limited than surface probes, computationally expensive and power demanding functions could be performed by orbiters and the results sent back to surface probes for execution. The frequency and duration of communication windows between orbiters and probes are factors influencing the feasibility of this concept. Savings in computational cost should be traded against increased communications cost. Figure 2-24 is an illustration of concept paths emerging from the allocation of the mapping and planning sub-processes to operators, orbiters and surface probe.
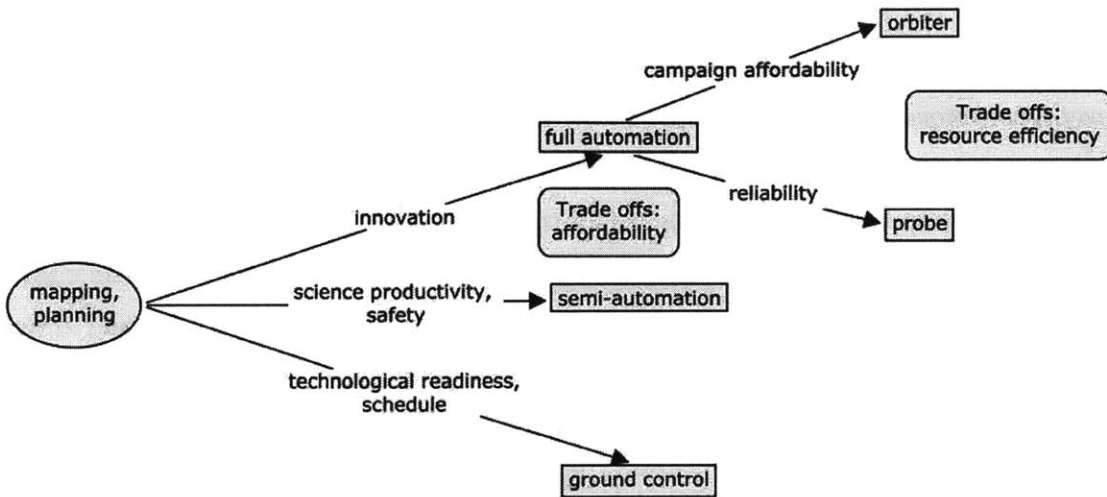
Figure 2-24 Concept paths emerging from the allocation of *mapping* and *planning* to agents.

Collecting sub-processes: imaging, targeting, approaching, acquiring, handling, and measuring

Orbiter agents are not involved in the execution of collecting sub-processes. Even though some orbital imaging of the surface is useful to outline the broad scientific features of the planet's surface, imaging from the surface provides a different perspective and the higher level of detail necessary to identify specific scientific samples.

Currently in MER, the collecting sub-processes are executed under close supervision of the science and operations team. However, current technology developments [Smith, 2005] may enable autonomous sample operation capabilities for future missions; probes would be able to autonomously identify and acquire scientific targets from site imaging data and from navigation images, which would increase the likelihood of finding valuable samples (science of opportunity). If such autonomous capabilities become technically feasible, they can potentially improve the productivity of surface missions by reducing interactions with ground control. The implementation of science-related autonomous capabilities may run against cultural factors; the scientific community may feel reluctant to lose oversight of critical scientific steps and question the quality of autonomous scientific experiments. A quantitative analysis is needed to determine whether increased science productivity and reduced ground processing would offset autonomy development costs and thereby improve mission affordability. An analysis of the value of autonomous sample *approaching* is provided

in Chapter 4. Figure 2-25 is an illustration of concept paths emerging from the allocation of the collecting sub-processes to automation and ground control agents.
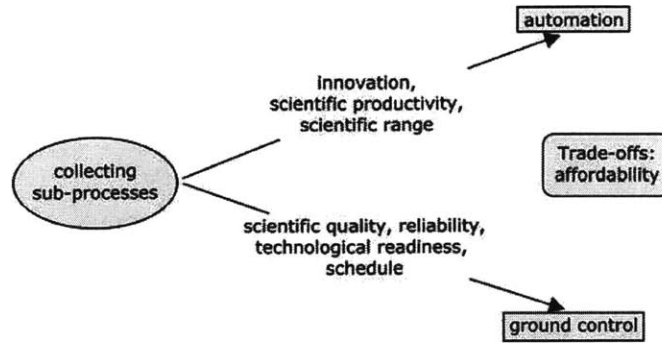
Figure 2-25 **Figures of merit that influence the function allocation between gound control and automation**

The rationalization of function allocation to human and automated agents is the subject of on-going research with a particular focus on missions involving both human and robotic explorers [Rodriguez 2003 and Lamamy 2005].

Allocation of processes to vehicles – Generation of multi-vehicle concepts

The task of allocating functions to vehicles of a surface probe defines, in fact, the vehicle-level modularity of the probe concept. Crawley defines an architecture as the allocation of physical and informational functions to elements of form, and the definition of structural interfaces among the elements and with the surrounding context [Crawley, 2005]. Based on this description, the task of allocating functions among vehicles and subsystems is approached from two perspectives: function partitioning and vehicle interfacing (Figure 2-10). From one perspective, a network is a map of function-vehicle allocations; network concepts are generated by partitioning the list of processes and assigning a vehicle to each subset of processes. From another perspective, a network is a map of vehicle-vehicle interactions (Figure 2-26).
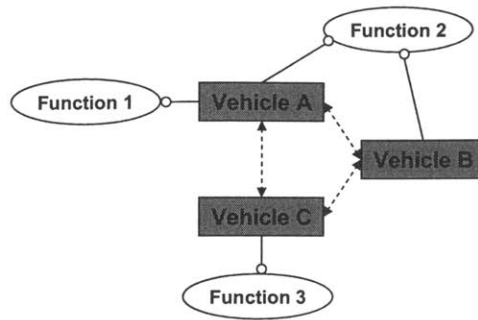
Figure 2-26 Robotic network

Function-vehicle allocations are represented with solid lines; vehicle-vehicle interactions are represented with dash lines.

Functionality partitioning and interface evaluation are also two steps in the similar process of allocating requirements to computer systems [Larson, 1992 section 16.1]. Information networks provide practical analogies that help conceive vehicle network architectures.

Function partitioning: approach

The set of processes listed in Figure 2-16 can be partitioned in numerous ways; in theory, there are four million possible partitions of the twelve value related processes. A traditional approach to function partitioning is to compare functions and group those that share similar requirements and attributes (e.g. execution time, resource needs) [Larson, 1992 section 16.1]. Maier and Rechtin [Maier, 2002] propose a comparable rationale for aggregating elements:

Group elements that are strongly related to each other, separate elements that are unrelated.

While this approach is well founded, it does not stimulate the creation of innovative concepts. An alternative capability-driven approach is proposed in this study to supplement the traditional one; the approach relies on an established analogy with information networks to promote concepts which optimize certain aspects of network performance.

The attributes of scientific performance (productivity, quality, and range) defined previously are traditional metrics to measure the performance of one system. Other factors must be considered to characterize the performance of a collection of systems. Shaw et al. have established a parallel between information networks and satellite constellations [Shaw, 2001]. The Generalized Information Network Analysis (GINA) framework is based on the assertion that most satellite systems are information disseminators that can be represented as information transfer networks [Jilla, 2004]. Based on this analogy, the performance of a

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given satellite constellation architecture is measured with respect to four capability metrics [Shaw 2001, Jilla 2002]: rate, integrity, isolation, and availability (Table 2-6).

Surface exploration probes are also information disseminators and therefore it is appropriate to describe a network of surface probes with the same information network analogy. Table 2-6 shows the parallel between information network capability metrics and surface exploration metrics. Isolation and availability do not have equivalent metrics in the original set of surface exploration metrics (productivity, quality and range); therefore, the notions of scientific isolation and scientific activity time fraction have been introduced. Bandwidth is added to information network capability metrics as an equivalent to scientific measurement range. The constellation architectures analyzed by Shaw et al. are designed to transmit one type of information; in this situation, bandwidth is not a discriminating factor. Bandwidth is an important measure of a network's ability to carry several types of valuable information; in this sense, it is equivalent to scientific measurement range.

Table 2-6 Parallel between capability quality of service metrics for information systems and their equivalent for surface exploration systems. Information network definitions come from [Jilla 2002 and IEEE 1997]

Capability metric	Information network	Surface exploration network	Scientific metric
Rate	measure of the speed at which the system transfers information between nodes in the network.	number of valuable measurements made per unit time	Scientific measurement productivity
Integrity	measure of the quality of the information being transferred through the network (e.g. signal to noise ratio)	measure of the quality of scientific measurements	Scientific measurement quality
Isolation	ability of the system to isolate and identify signals from different sources	ability of the system to identify and acquire the scientific targets desired by the science team	**Scientific measurement isolation**
Availability	fraction of time within which a system is actually capable of performing its mission	fraction of time dedicated to performing scientific activities as opposed to servicing activities (e.g. driving, charging batteries)	**Scientific activity time fraction**
Bandwidth	range of frequencies within which performance, with respect to some characteristics, falls within specific limits	variety of different measurements that can be made on a specific sample and variety of samples that can be analyzed	Scientific and exploration range

The five capability metrics are used as drivers to generate surface exploration concepts.

Function partitioning: application

Concept implementations are derived from the desire to optimize each of the five capability metrics (Table 2-6). The resulting concept implementations are summarized in Table 2-7. For each capability metric, the column labeled *concept implementation* lists a general implementation guideline, an implementation guideline for single-system probes (1) and one for multi-system probes (N).

Table 2-7 Physical implementations optimizing each capability quality of service parameter.

Capability metric	Concept physical implementation	Example
Productivity	*Redudancy and parallel tasking*	
	1) redundant instruments on an element working in parallel	Viking, MER
	N) redundant elements working in parallel	Microbots
Quality	*Cross-check*	
	1) distinct instruments supporting the same measurement	
	N) Several elements in distinct locations supporting the same measurement	
Isolation	*Multi-view:*	
	1) combination of remote, contact, and analytical instruments	MSL, ExoMars
	N) elements with identical instruments in distinct locations	MER, Microbots, seismological network
Availability	*Decoupling location and function*	
	1) scientific activities on the fly	
	N-b) elements performing value related functions on opposite sides of the planet	Viking, MER
	N-a) allocation of value related functions and supporting functions to distinct elements	Scout-Laboratory concept
Range	*Multi-field:*	
	1-a) combination of geological, environmental, biological, and human preparation related instruments	MSL
	1-b) reconfigurable moblity system for access to wide range of terrains	ExoMars, MoRETA
	N) elements with distinct mobility systems and terrain access capabilities	MoRSE

Table 2-7 shows that redundancy of instruments and vehicles is a simple implementation strategy to improve the productivity of surface probes; the MER mission which operates two rovers in parallel is a recent example of this approach. Another example is the *microbots*

concept [Dubowsky, 2005]. It consists of small, identical spherical vehicles deployed in large number to survey vast areas of the Martian surface.

In addition, multi-system concepts exhibit improved isolation because they have an increased probability of finding valuable scientific samples and they can collaborate to isolate scientific sources (e.g. seismic waves, fume vent). Some scientific experiments require more than one vehicle; for example, seismology triangulation relies on signals being detected by at least three stations to localize a seismic event; with a fourth station, seismic waves transmitted through the planet core can be detected leading to core size estimations [Marsal, 1999].

Integrity also improves with the number of vehicles [Chien, 2006]; the magnitude of improvement depends on the instruments and types of measurements being made. In general, if the noise is uncorrelated, additional measurements can help; for many measurements, this improvement is related to the square root of the number of measurements. However, noise correlation, due to instrument design and calibration, diminishes the improvements that can be made. In the extreme case of complete noise correlation, there is no gain. Other sources of noise are related to environmental conditions, such as radiation and atmospheric distortion.

The notion of range (bandwidth) has two aspects: scientific range (number of distinct scientific measurements addressed) and exploration range (sample diversity). Instrument payloads are composed in order to maximize measurement diversity and satisfy the needs of all of the Mars science communities. Sample diversity improves with the number of topographic features a probe is able to access. In the case of a single-vehicle concept, a reconfigurable mobility device would be able to access a wider variety of terrains. The Modular Rover for Extreme Terrain Access (MoRETA) [Massie, 2007] is an example of a mobility mechanism which has can roll and walk; rolling is used on flat terrain with low rock abundance whereas walking is used on steep and rocky terrain. In the case of a multi-vehicle concept, reconfigurability is implemented at the vehicle level. Vehicles are equipped with distinct mobility capabilities and, as a whole, the vehicle team is able to access multiple terrain types.

The Modular Rover for Surface Exploration (MoRSE) concept [Miller, 2006] described in the last section of this chapter is based on this implementation strategy. The MoRSE team is

composed of a large wheeled vehicle which carries a smaller, specialized vehicle on traverses over flat terrain; the mobility system of the specialized module is designed for accessing extreme terrains. In this study, drilling is considered a form of mobility which enables access to underground planetary layers. ExoMars is expected to be the first Martian rover equipped with a drilling capability.

Williams provides another example of a cooperative robotic network [Williams, 2003], in which robotic systems act together to achieve elaborate missions within uncertain environments. In Williams' concept, a scout rover, with a tethered blimp, creates a high resolution map of local regions and performs initial evaluation of the scientific sites. A laboratory rover then performs detailed evaluation of scientifically promising sites. A concept with heterogeneous vehicles performing specific functions exhibits good scientific robustness because vehicles are able to adapt to environment uncertainties. However, depending on how different the systems are, the concept's affordability may not benefit from economies of scale. Furthermore, reliability is low, without redundancy, since the concept relies on all vehicles to be working to achieve the mission.

The availability of a surface vehicle is the ratio of time dedicated to valuable (scientific) activities over the total mission time. In a traditional rover mission, traversing, collecting and communicating processes are sequential. In this situation, the availability A_I of a surface vehicle is given by:

$$A_1 = \frac{T_{imaging} + T_{measuring}}{T_{traversing} + T_{collecting} + T_{comm}} \tag{2-1}$$

where

$$T_{traversing} = T_{moving} + T_{sensing} + T_{mapping} + T_{planning} + T_{locating} \tag{2-2}$$

$$T_{collecting} = T_{imaging} + T_{targeting} + T_{approaching} + T_{acquiring} + T_{handling} + T_{measuring}$$

The notation $T_{process}$ is used to refer to the duration required to perform the *process* task. For given instrumentation and communications technologies, the imaging, measuring and communicating processes have set durations which do not change, regardless of the surface probe design. In this situation, increased availability is achieved by performing processes in

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parallel. The implementation of parallel processing in a single-vehicle concept is difficult because of power constraints.

There are two implementation modes for parallel processing in a multi-vehicle concept. In the first mode, the surface probes work in parallel but in distinct locations and independently from each other; this is the implementation mode of the MER and Viking missions. In this mode, the availability A_{team} of a team of two vehicles is the probability that at least one vehicle is still productive.

$$A_{team} = 1 - (1 - A_1)(1 - A_2)$$ (2-3)

where A_1 and A_2 are the availabilities of the first and second vehicles.

In the second mode, the two surface vehicles form a collaborative team; each vehicle is assigned a share of functions in order to maximize the availability of the team as a whole. William proposes the association of a scout vehicle working with a laboratory vehicle [Williams, 2003]. *Traversing* and *imaging* are assigned to a scout, *collecting* and *communicating* are assigned to a laboratory. More precisely, the scout vehicle drives ahead of the laboratory vehicle, scouts the terrain, identifies and marks safe paths, and performs imaging of sites. In parallel, the laboratory vehicle performs scientific analyses of samples at previously visited sites; when complete, the vehicle travels to the next site following the safe path marked by the scout. Because the path has already been scouted, the laboratory vehicle does not need to perform local path planning activities and is able to travel at high speeds between sites. The imaging of sites by the scout prior to the laboratory arrival enables the science team to select scientific targets ahead of time. Thus, the processes have in fact to be partitioned and assigned to three entities working in parallel: two surface vehicles and a science team. The availabilities A_{scout} and A_{lab} of the scout and laboratory, respectively, are provided in the equations below.

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$$A_{scout} = \frac{T_{imaging}}{T_{traversing} + T_{imaging} + T_{comm}}$$

$$A_{lab} = \frac{T_{measuring}}{T_{moving} + T_{collecing} + T_{comm} - T_{imaging}}$$

(2-4)

In the expression of A_{scout}, the second term of the denominator is $T_{imaging}$ only instead of $T_{collecting}$ as in Equation (2-1). This is because the scout only performs the *imaging* sub-process of the *collecting* process. Similarly, in the expression of A_{lab}, the $T_{traversing}$ is reduced to T_{moving} because the laboratory does not perform the remaining path planning processes included in *traversing*. The combination of Equations (2-3) and (2-4) provides the expression of the availability of the team.

$$A_{team} = 1 - (1 - A_{scout})(1 - A_{lab})$$

(2-5)

A rigorous performance comparison of a single-vehicle mission and a scout-laboratory mission would require an analysis of productivity which combines availability, reliability and rate.

All capability parameters increase with the number of vehicles involved in the surface exploration concept. However, adding surface vehicles has heavy consequences on non-scientific figures of merit. Figure 2-27 is an illustration summarizing the physical implementations mentioned in this section; it combines Figure 2-21 and Figure 2-22 with the cases described in Table 2-7.
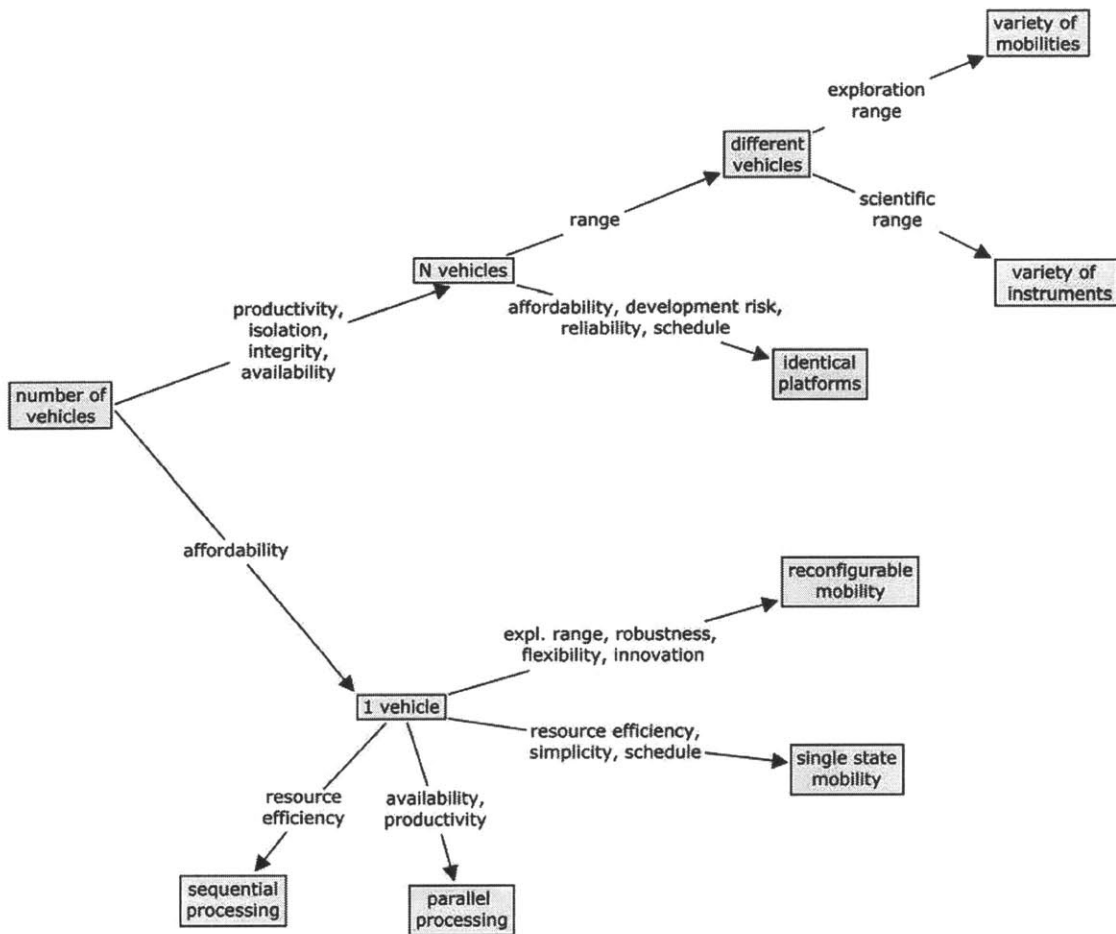
Figure 2-27 Set of physical implementation concept paths

Vehicle interfacing: approach

In this section, the second perspective on multi-vehicle missions, the vehicle-to-vehicle interaction perspective, is discussed. Network concepts are created by enumerating interface schemes. An interface is defined by the nature of the property exchanged and by the interface structure. The content of an exchange between two vehicles can be either energy, matter, information, or value [Crawley, 2004]. Drawing on another analogy with computer systems, interface structures fall into two main categories: centralized and distributed (hybrid structures are created by combining aspects of the two). Illustrations of the two structure types are provided in Figure 2-28 and Figure 2-29.
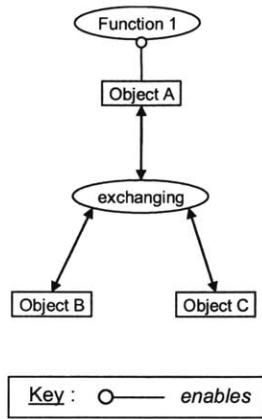
Figure 2-28 General representation of a centralized structure
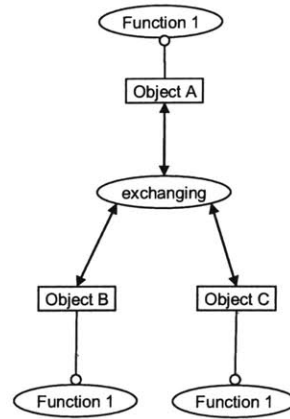
Figure 2-29 General representation of a distributed structure

In general, centralized structures are resource efficient solutions while distributed structures are easily modified, enable parallel execution of tasks, and do not have single point failures. Figure 2-30 provides an illustration of the structure's properties with respect to figures of merit.
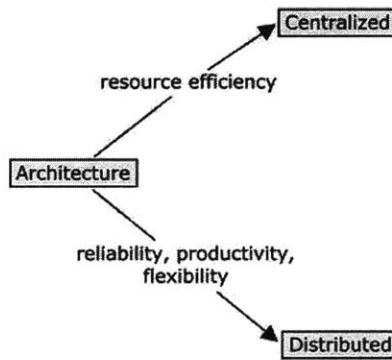
Figure 2-30 Figures of merit that influence the choice between centralized and distributed architectures

In the next section, concepts are created by enumerating combinations of exchange content and interface structure.

Vehicle interfacing: application

In this formulation approach, vehicle network concepts are created by exploring ways vehicles can interface with each other. The subsequent paragraphs develop concepts for exchanges of energy, matter, and information. In each case, the resulting concept paths are illustrated using Figure 2-31 as a template.
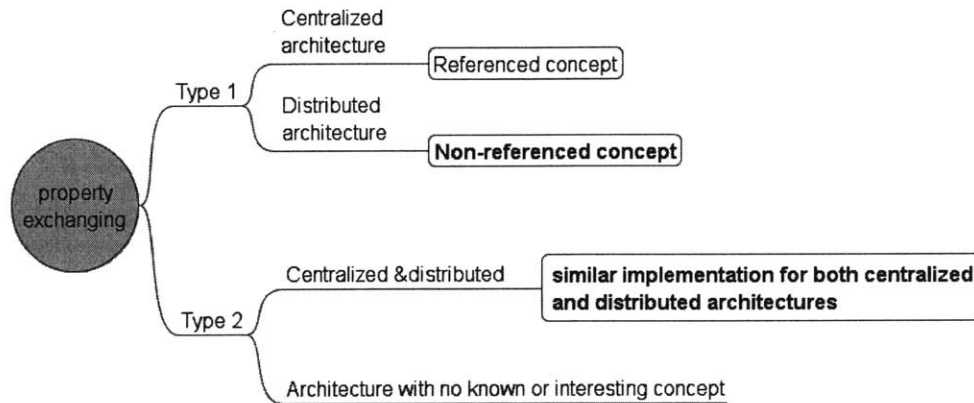
Figure 2-31 Template for representing concept paths derived from the vehicle interfacing approach

- Energy exchange

Energy exchange is subdivided into exchange of electrical, electromagnetic, thermal, mechanical, chemical, and nuclear energy. Figure 2-32 is a graphical representation of the concept paths developed in the subsequent paragraphs.

    o Electrical energy

In a centralized concept, electrical energy flows from one energy source to several energy users. The Prop-M rover was designed to receive power from the Mars lander via a cable. In another centralized concept, one vehicle equipped with several RPS's could serve as an energy-recharge plant to other vehicles equipped with either solar panels and batteries or just batteries. In a distributed concept, vehicles with equal amounts of energy collaborate to perform tasks that one vehicle could not perform by itself. A vehicle could benefit from an extra supply of energy coming from another similar vehicle to perform a specific activity, such as communicating or acquiring a sample.

Electrical energy
- Centralized — Prop-M : Lander serves as electrical power source to rover (cable transmission)
- Distributed — Vehicles connect to each other in order to perform power demanding tasks (e.g. drilling)

Electromagnetic energy (energy beam)
- Centralized — Snow White : Reflector concentrates sunlight on a small region where solar-powered rovers work
- Distributed — Distributed reflectors on several vehicles

Energy exchanging

Thermal energy
- Centralized — MoRSE : Base rover provides thermal energy to specialized vehicles
- Distributed — Huddle of vehicles

Mechanical energy
- Kinetic
  - Translational energy
    - Centralized — MoRSE : base rover carries specialized vehicle for site-to-site traverse)
    - Distributed — Two vehicles with specific mobility types. Based on the terrain, the most able vehicle carries the other one
  - Rotational energy — Centralized & distributed — Driveshaft transmission between vehicles
  - Potential
    - Centralized — Cliffbot
    - Distributed — Schenker's concept : collective climb concept

Chemical energy
- Centralized — ISRU plant provides fuel to vehicles
- Distributed

Nulcear energy

Figure 2-32 Concept paths involving exchange of energy

o Electromagnetic energy

This relationship is similar to the previous one except that power is beamed from one vehicle to another instead of being transmitted through electrical wiring. Weisbin and Rodriguez have proposed an original concept, called Snow White, which involves a solar concentrator deployed from a mast that concentrates sunlight onto a small region on the ground where solar powered rovers are then able to work [Weisbin, 2000].

o Thermal energy

Similar to the power plant example discussed in the previous paragraph, a rover could serve as a thermal power source or sink to other vehicles. A distributed architecture suggests the idea of a group of vehicles in tight formation that share their warmth during cold periods as in a huddle of penguins.

o Mechanical energy

The transfer of mechanical energy from one vehicle to another can either be a transfer of kinetic energy or potential energy. The transfer of kinetic energy is decomposed into translational energy and rotational energy. An exchange of translational kinetic energy means that one vehicle acts on another vehicle's position on the surface; some processes which involve kinetic transfer are carrying, pulling, pushing, and throwing. In a centralized concept like MoRSE, a large mother vehicle designed for traverse (e.g. with good clearance and speed) serves as a taxi to vehicles specialized for other types of terrain. An exchange of rotational energy evokes the idea of a driveshaft transmission from one vehicle equipped with an engine to another vehicle which uses the energy for useful work, such as drilling.

A transfer of gravitational potential energy implies one vehicle acting on the altitude of another vehicle. In an example of a centralized architecture, a vehicle could be used for the specific purpose of carrying other vehicles up and down a slope or cliff (Cliffbot concept in Figure 1-9). In a distributed architecture, several wheeled vehicles could connect to each other in order to perform collective climbs [Schenker, 2000].

o   Chemical energy

The exchange of chemical energy suggests a transfer of fuel between vehicles. An example of a centralized architecture has one vehicle, with In Situ Resource Utilization (ISRU) capabilities, providing fuel to several other vehicles.

o   Nuclear energy

Concepts based on the exchange of nuclear energy are similar those mentioned in the previous Electrical energy section.

The MoRSE concept described in the last section of this chapter is an example of a base module providing kinetic, thermal, and electrical power to smaller specialized mobile payloads.

- Matter exchange

The transfer of matter among surface probes is subdivided into transfer of external matter (e.g. Mars sample) and transfer of internal matter (e.g. vehicle module). Figure 2-33 is a graphical representation of the concept paths developed in the subsequent paragraphs.
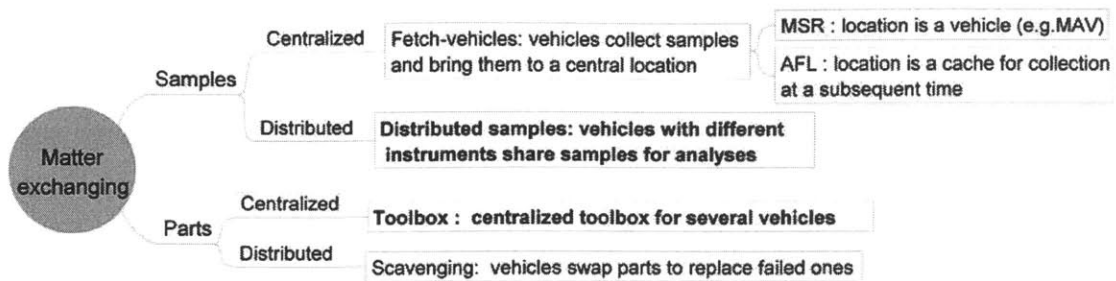
Figure 2-33 Concept paths involving exchange of mass

     o   Sample exchange

MSR is an example of a mission which involves sample transfer between vehicles, for example between a rover and a Mars Ascent Vehicle (MAV). In a centralized concept, a team of fetch-rovers collects samples and brings them to a stationary laboratory for analysis or to a MAV for launch. In a distributed concept, several rovers, with different scientific payloads, share samples in order to perform more comprehensive analyses using all available instruments. The addition of a temporal attribute to this relationship evokes concepts where samples are shared across several generations of surface probes. For example, a surface probe (e.g. AFL) could cache interesting samples which would be analyzed are retrieved by a subsequent mission (e.g. MSR) [MAPG, 2006b].

In the context of surface exploration, Mars samples are carriers of scientific information. A principle stated in the previous *Modularity* section indicates that the modularity of an architecture should not slice through regions where high rates of information exchange are required. Based on this principle, the exchange of samples between vehicles should be avoided. Furthermore, the exchange of samples between vehicles increases the risk of sample contamination and, transfer technologies are complex (Figure 2-34). Based on these considerations, it appears that sample exchange is not recommended unless it is mandatory (e.g sample return mission).
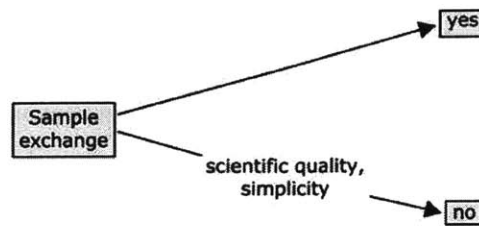
Figure 2-34 Figures of merit that influence the decision to implement a sample exchange between vehicles

 o Part exchange

The exchange of parts (modules) between vehicles has been discussed in the previous section on modularity. The replacement of failed modules, mentioned in Table 2-5, suggests a scenario where failed vehicles are scavenged for parts by partially degraded ones (scavenging concept). The exchange of parts could also involve two working vehicles that share tools, such drill bits.

• Information exchange

The transfer of information among vehicles is subdivided into transfer of logical information and transfer of valuable information. In an exchange of logical information, the recipient does not benefit from the information it receives; for example, a relay orbiter does not benefit from the information it receives from surface vehicles. In an exchange of valuable information, the recipient benefits from the information transferred; valuable information can be, for example, the location of a scientific target. Figure 2-35 is a graphical representation of the concept paths developed in the subsequent paragraphs.

 o Logical information exchange

The exchange of logical information among surface vehicles is similar to computer networks on Earth. In a centralized architecture, a vehicle acts as the calculating unit for other vehicles with less computing capability. In a distributed architecture, computationally intensive tasks, such as surface mapping and path planning, are processed in parallel on several vehicles in a fashion similar to distributed computing (e.g. Berkeley Open Infrastructure for Network Computing [Anderson, 2004]).
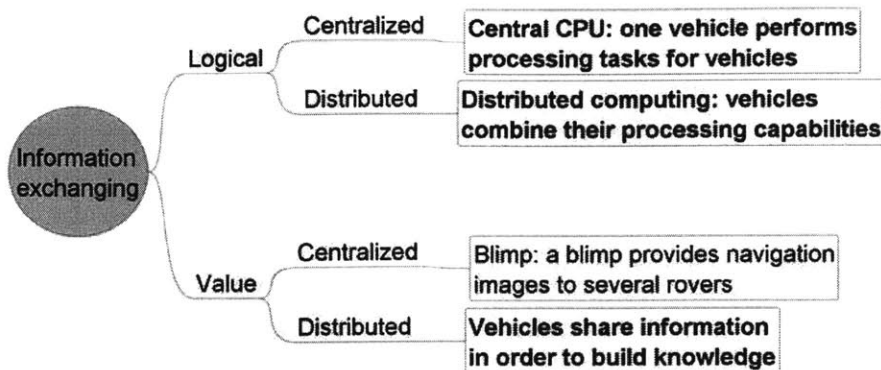
Figure 2-35 Concept paths involving exchange of information

     o   Valuable information exchange

In the centralized architecture, a vehicle provides information to other vehicles; for example, a blimp could provide a family of rovers with navigation images. In a distributed architecture, vehicles share pieces of information to build up collective knowledge. A network of stations performing seismic experiments is an example of a distributed, valuable information network. This configuration improves the isolation and integrity previously discussed.

Allocation of processes to vehicle subsystems

Until this stage, the notion of surface vehicle has referred to any exploration system ranging from a blimp to a microbot. Vehicle types are distinguished by the technologies they implement to perform the functions assigned in the previous step. The subsequent paragraphs discuss technical solutions for the two main functions: *moving* and *powering*.

Technical solutions for the moving function

The technical implementation of the *moving* process is a defining characteristic of a surface probe concept. For example, NASA rovers can be defined as *rolling* vehicles. Hirose [Hirose, 1991] categorized the locomotion of surface robots into three basic types: 1) *rolling*, using rotational devices, 2) *walking*, using legs, and 3) *slithering*, using articulated bodies similar to the body of a snake. Another process, *sliding* is added to this list to capture ski-based locomotion modes used by vehicles such as Prop-M (Figure 1-1). The current list of processes focuses on locomotion *on* a surface; it is complemented with processes moving *over* a surface (e.g. *flying*, *hopping*) and *under* a surface (e.g. *digging*). Figure 2-36 develops a tree of

concept paths for each of these processes; the *rolling* process is developed further in the subsequent paragraphs. At the end of each path, the objects that are encircled are concepts that have been either implemented or proposed in the literature.
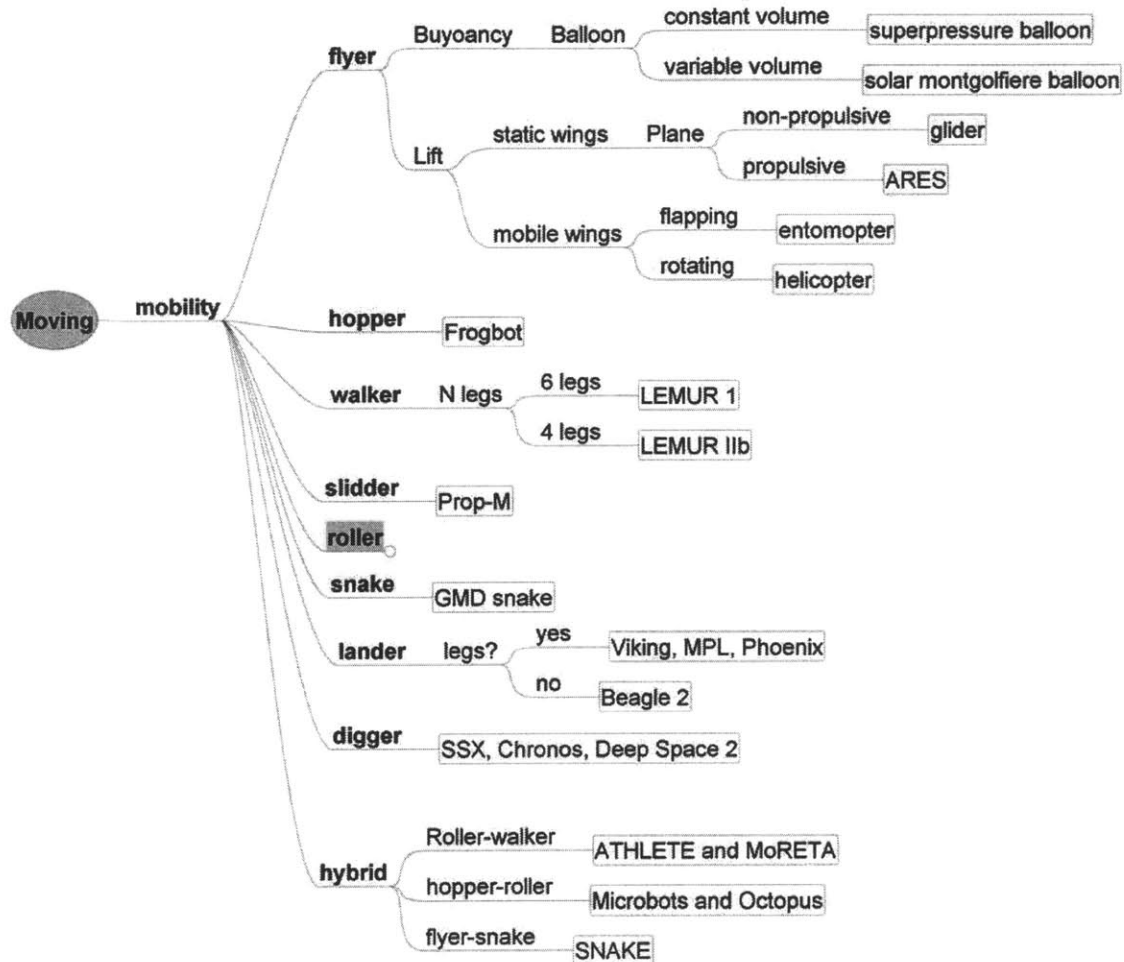
Figure 2-36 Concept paths for the *moving* function

ARES plane [Braun, 2006]; Frogbot [Konuk, 2003]; Prop-M [RMVEI, 2002]; LEMUR legged robot [Kennedy, 2001]; GMD snake [Worst, 1998]; Subsurface Explorer (SSX) [Weisbin, 2000];

The figure shows that a variety of hybrid concepts can be created by combining several types of *moving* processes in one mobility system. For example, the Modular Rover for Extreme Terrain Access (MoRETA) concept developed by MIT [Massie, 2007] combines *walking* and *rolling* processes, while the previously mentioned microbots combine *jumping* and *rolling*.

The *flying, hopping,* and *digging* processes are appealing because they provide access to regions of the surface and subsurface otherwise not easily reachable by processes moving on a surface. The major drawback, however, is the inherent risk associated with these modes of transportation. Flyers operate in an uncertain dynamic environment and must repeat risky operations, such as landing and take-off. Diggers require a lot of energy and also operate in an uncertain and hostile environment (e.g. uncertain layer composition and properties). Figure 2-37 illustrates the figures of merit which influence the implementation of *on-surface moving processes* as opposed to *over-the-surface* and *sub-surface moving processes.*
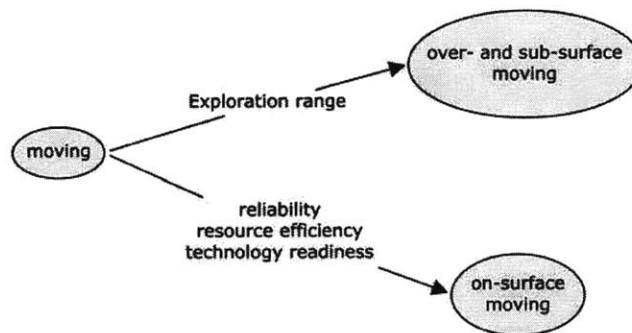
Figure 2-37 Figures of merit that influence the selection a specific mode of locomotion

The performance comparison of *on-surface moving* processes has been the subject of on-going research [McCloskey, 2007]. Hirose et al. [Hirose, 1995] characterized the main advantages and disadvantages of *rolling, walking,* and *slithering.* They note that *rolling* involves simple mechanisms (i.e. good reliability), manifests good adaptability to terrain (i.e. good flexibility), and is energy efficient (i.e. good resource efficiency). In comparison, *walking* exhibits higher adaptability to terrain. The higher terrain flexibility of walking systems enables them to access steep surfaces which are generally rich in geological features (i.e. improved exploration range). The chief drawback of *walking* is the need for a large number of mechanisms which entails a low payload mass fraction (i.e. low resource efficiency). Similarly, *slithering* exhibits good terrain adaptability and lends itself to modularity and reconfigurability; but crawlers have more degrees of freedom that necessary, many mechanisms and, therefore, a very low payload mass fraction. Figure 2-38 illustrates the

figures of merit which influence the implementation of *rolling* process as opposed to *walking* and *slithering* processes.
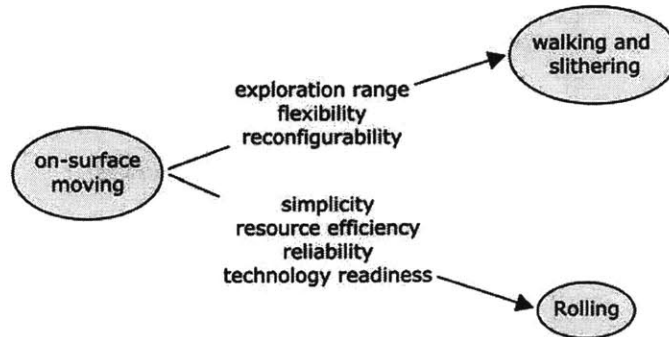
Figure 2-38 Figures of merit that influence the selection of a *rolling* mode of locomotion

Hirose et al. judge that the simplicity of the moving mechanism is the most important factor in the selection of a mode of planetary locomotion; as a consequence, they favor *rolling* over *walking* and *slithering*.

The *rolling* process itself has numerous technical implementations. A *rolling* mobility system is defined by such parameters as the number of wheels, structure of the wheels, drive architecture, and number of gears. Figure 2-39 develops a tree of concept paths for technical implementation of *rolling*. At this level of technical detail, it becomes difficult to capture all aspects of design information in a single representation. At the end of each path, the objects that are encircled are concepts that have been either implemented or proposed in the literature; the circles with a colored background highlight the technical solutions implemented on Sojourner, MER and MSL. The figure shows that NASA rovers represent only one of the many possible mobility configurations.

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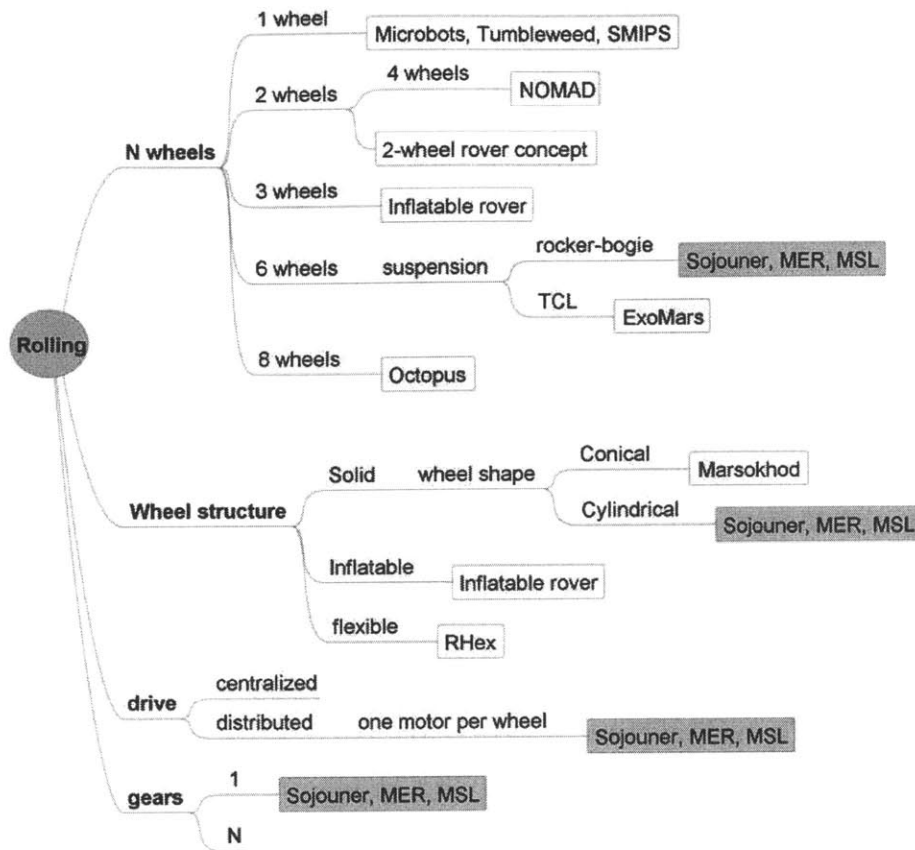
Figure 2-39 Concept paths for rolling vehicles

Microbots [Dubowsky, 2005]; Tumbleweed [Antol, 2003]; SMIPS [Bruhn, 2005]; 2-wheel rover [Tao, 2006]; NOMAD [Rollins, 1998]; ExoMars [ESA, 2002]; Octopus [Lauria, 2002]; Marsokhod [Carrier, 1992]; Inflatable rover [Jones, 2001]; RHex [Moore, 2002]

Technical solutions for the powering function

The Tumbleweed rover (Figure 1-9), which is an example of single-wheel rover in Figure 2-39, is an original concept which uses Martian wind power for *rolling*. The Tumbleweed shell acts as a wind machine which transfers mechanical energy from Martian wind to the rover. Figure 2-40 shows that the general *powering* process involves the conversion of an energy source into energy usable by recipients (vehicle systems and subsystems). Figure 2-41 lists the principal types of energy sources and transfers available to Mars surface probes. A

RPS uses several intermediate steps, which are not represented in the figure, to convert nuclear energy into electrical energy.
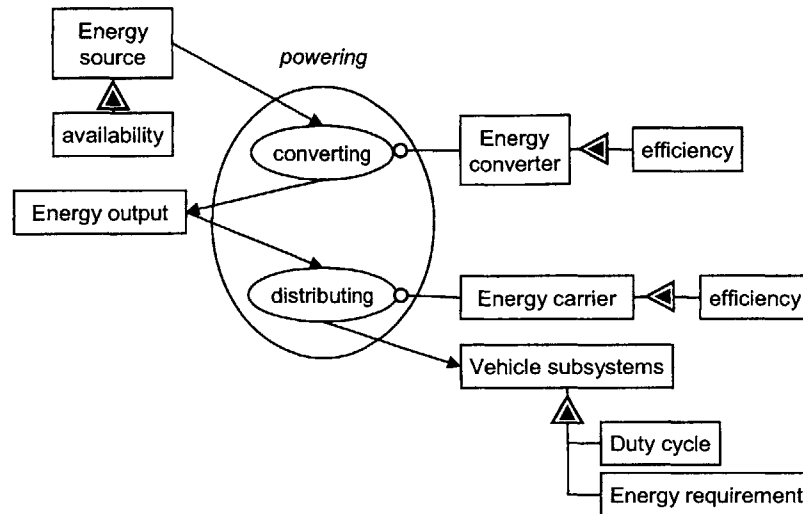
Figure 2-40 Decomposition of the *powering* process
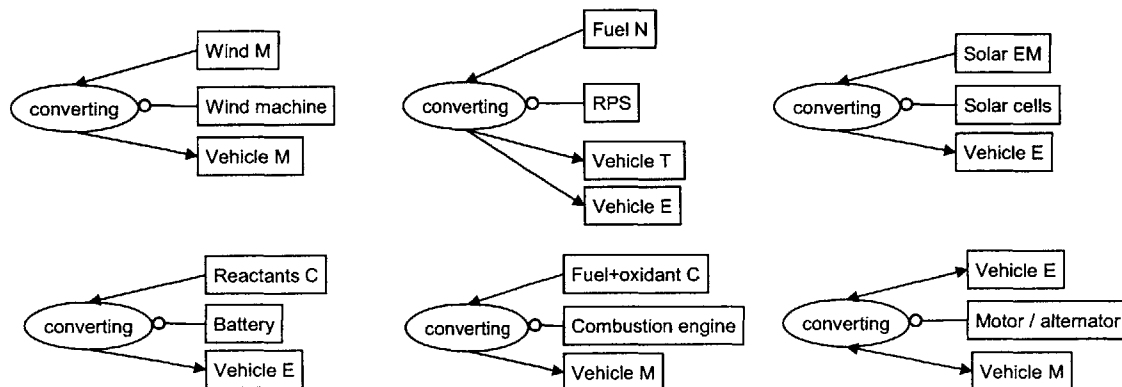
Figure 2-41 *Powering* processes for Mars surface vehicles

Energy types: C chemical; E electrical; EM electromagnetic; M mechanical; N nuclear; T thermal

In Figure 2-41, the energy types considered are the same as those considered in the previous *Vehicle interfacing* section (Figure 2-32).

The selection of a power system is based on considerations of feasibility, technology readiness, exploration range, and cost. The attributes of the energy source (availability),

converter and carrier (efficiency), and recipient (duration duty cycle and power demand) determine the feasibility of a given power system to meet the demand and constraints of a particular mission scenario. For example, the Lunar Rover Vehicle (LRV), used during the last three Apollo missions, could use non-rechargeable batteries as sole power source because it was designed for short mission durations. Combustion engines and wind machines have low readiness levels for Mars exploration applications. The selection of a solar power system as opposed to a RPS involves a trade-off in scientific productivity, exploration range and cost. RPS-powered and solar-powered MSL designs have been examined by NASA. On the one hand, in order to meet mission productivity goals, a solar-powered MSL design would be limited to landing sites located at 15° North latitude [Cleave, 2006]. RPS-powered designs, however, could land within 60° North and 60° South latitudes. On the other hand, the design of a RPS is more expensive than that of a solar power system and the use of radioisotope material has policy implications. The RPS fuel has significant cost contribution; for example, the fuel cost in a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), which uses plutonium Pu^{238}, is approximately \$8M [Balint, 2005]. Figure 2-42 shows the figure of merit branches for the solar-radioisotope power trade-off.
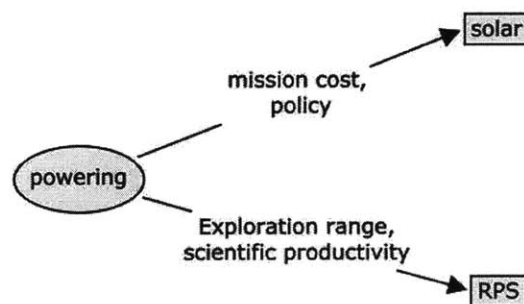
Figure 2-42 Figures of merit that influence the selection of a *powering* source

Operational alternatives

Some operational aspects of Mars surface exploration missions have already been addressed. The *Physical Form Decomposition* section discussed the operations of several vehicles collaborating in parallel (e.g. scout-laboratory concept) and over time (e.g. AFL and MSR in Figure 2-33). The section also discussed the role of ground control operators with respect to that of on-board probe autonomy. The next paragraph briefly discusses the potential of stand-by modes as operational options for surface vehicles.

Planetary surface vehicles have traditionally been operated continuously from the beginning of the surface mission to the end. One motivation for operating vehicles continuously is to maximize the mission's science return. The use of long duration power systems, such as a RPS, could make possible another mode of operations in which surface vehicles alternate between active and dormant modes. For example, a vehicle could enter a dormant mode after the end of its nominal mission and until the landing of a subsequent surface mission. Providing the AFL rover with a stand-by mode option could enable its use during a subsequent MSR mission. During its first active phase, the AFL rover would serve as traditional scientific rover; while, during its second active phase, it would serve as a sample collection rover for the MSR lander and MAV. A stand-by mode is an operational option which provides flexibility in the use of surface robotic assets. Operators would have the option but not the obligation to continue using a vehicle and the option but not the obligation to re-activate it.

2.4 Surface Exploration Concept Maps

The functional and physical decomposition exercise has enabled the qualitative exploration of the trade space of Mars surface mission concepts. In the third part of the concept formulation process (Figure 2-1), the results of the exploration are synthesized into two representations of the trade space. One representation, called concept tree, focuses on the enumeration of form solutions for the various functions involved in the mission. Figure 2-39 is an example of a concept tree. The second representation focuses on stakeholder figures of merit which influence the selection of a specific concept implementation. Figure 2-38 is an example of a map of figures of merit. The use, value and limitations of each representation is discussed in the next sections.

2.4.1 Concept Tree

The concept tree is a representation of surface mission concepts which focuses on objects; it provides an overview of the possible implementations of form (i.e. physical and technical aspects) of surface exploration functions. These exploration functions are not explicitly shown in the tree representation. The concept path tree shown in Figure 2-43 is an aggregate of the concept paths developed at each step of the concept generation process (Figure 2-32,

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Figure 2-33, Figure 2-35, Figure 2-36, and Figure 2-39). The tree has three parts. In the middle, is the main function, *surface exploring*. On the right, are the possible form implementations of a generic vehicle; Figure 2-44 provides a zoom on this section. On the left, are the different interactions that another vehicle, labeled *Vehicle N*, could have with the first vehicle; Figure 2-45 provides a zoom on this section.

The concept path tree structures the concept development process. It provides a visual representation of the extent of the trade space of surface exploration concepts. Furthermore, it highlights the particular concept paths that have been implemented in past and current NASA rovers. NASA Mars rover implementations are highlighted with colored backgrounds. The concept path tree shows that only a small number of design alternatives have been explored. Using this tree, one can generate surface probe concepts by selecting a number of vehicles, by choosing for each vehicle particular system and subsystem implementations (from the list on the right) and by choosing for each pair of vehicles types of interactions (from the list on the left).

Figure 2-43 Concept tree of Mars surface robotic missions

Figure 2-44 Overview of the possible technical implementations of a generic surface exploration vehicle

Central CPU: one vehicle performs processing tasks for vehicles — Centralized — **Logical**

Distributed computing: vehicles combine their processing capabilities — Distributed — **Information**

Blimp: a blimp provides navigation images to several rovers — Centralized — **Value**

Vehicles share information in order to build knowledge — Distributed

Prop-M : Lander serves as electrical power source to rover (cable transmission) — Centralized — **Electrical**

Vehicles connect to each other in order to perform power demanding tasks (e.g. drilling) — Distributed

Snow White : Reflector concentrates sunlight on a small region where solar-powered rovers work — Centralized — **EM**

Distributed reflectors on several vehicles — Distributed — **Energy**

MoRSE : Base rover provides thermal energy to specialized vehicles — Centralized — **Thermal**

Distributed

MoRSE : base rover carries specialized vehicle for site-to-site traverse) — Centralized — Translational energy — Kinetic — **Mechnanical**

Two vehicles with specific mobility types. Based on the terrain, the most able vehicle carries the other one — Distributed

Gear transmission between vehicles — Centralized & distributed — Rotational energy

Elevator : one vehicle specialized to carry others up and down a slope — Centralized — Potential

Schenker's concept : collective climb concept — Distributed

ISRU plant provides fuel to vehicles — Centralized — **Chemical**

Distributed

Nulcear

MSR : location is a vehicle (e.g.MAV) — Fetch-rover: rovers collect samples and bring them to a central location — Centralized — **Samples**

AFL : location is a cache for collection at a subsequent time

Distributed samples: vehicles with different instruments share samples for analysis — Distributed — **Matter**

Toolbox : centralized toolbox for several vehicles — Centralized & distributed — **Parts**

Scavenging: vehicles swap parts to replace failed ones

Vehicle N — **Vehicle interacting**

Figure 2-45 Overview of possible vehicle interactions

2.4.2 Figure of Merit Tree

At the beginning fo this chapter, Figure 2-2 illustrated the process of allocating function to form through a sequence of architectural and design decisions. The figure of merit tree conveys the same information; it establishes the connection between stakeholder needs and the selection of concept implementations enumerated in the concept path tree. At each step of the functional and physical decompositions (Section 2.3), architectural alternatives have been compared with respect to stakeholder figures of merit. The map shown in Figure 2-46 synthesizes the architectural alternatives discussed in Section 2.3 and their corresponding figures of merit (Figure 2-14, Figure 2-20, Figure 2-21, Figure 2-22, Figure 2-25, Figure 2-30, Figure 2-34, Figure 2-37, and Figure 2-38).
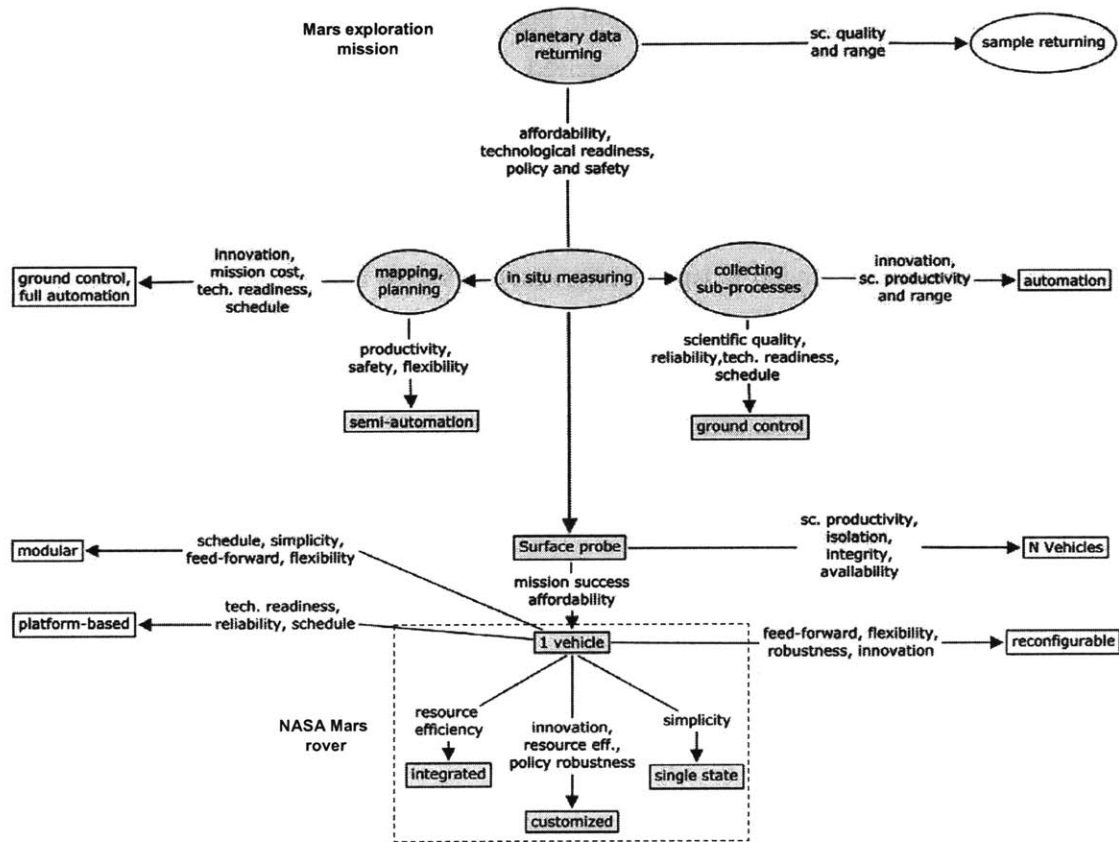
Figure 2-46 Map of figures of merit involved in the specialization of a Mars exploration mission into a NASA Mars rover mission

The figure makes explicit the sequence of decision steps that lead from the solution-neutral statement of a Mars mission function, *Planetary data returning*, to the solution-specific implementations of exploration concepts. In the figure, the chain of decisions which defines NASA rover missions is highlighted by ovals and boxes with shaded backgrounds (e.g. *in situ measuring* and customized). The alternative architectures not implemented in NASA rover missions are represented by ovals and boxes with white backgrounds. This tree enables to identify which figures of merit tend to drive the implementation of NASA rover missions. By examining the whole sequence of decisions defining a NASA Mars rover, affordability, technology readiness and resource efficiency appear more than others figures of merit and are, therefore, the drivers.

The representation also enables to understand the effect of changing stakeholder priorities. If another figure of merit becomes predominant, the examination of the tree can suggests what the impact is on the preferred exploration architecture. For example, a demand for increased scientific productivity, but with set EDL constraints on landed mass capability, would favor the implementation of multi-vehicle concepts. Large scientific payload, too massive to be landed one a single vehicle, could be distributed among several vehicles that would be landed independently. Another factor that could radically change the implementation of rover architectures is the potential of human-robot interactions. As mentioned in the *Modularity* section, human presence greatly increases the operational benefits of modularity; the same is true for reconfigurability

2.5 Modular Rover for Surface Exploration

In this section, the figures of merit and architecting principles guide the formulation a lunar rover concept in the context of the Vision for Space Exploration (VSE) [VSE, 2004].

2.5.1 Motivation

As stated in the previous *Figures of merit* section, sustainability is a major figure of merit for stakeholders of the VSE. In order to be sustainable, robotic surface exploration architectures must be affordable and able to adapt to the uncertainties of exploration in domains such as policy and science. As mentioned in the first section of this chapter, robotic surface explorers have traditionally been designed as single use integral systems meeting mostly rigid

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and predefined set of goals. A solution to improve the flexibility of robotic surface explorers is to implement modularity (Figure 2-20) and reconfigurability (Figure 2-21) into their architecture. In addition, platform strategies can potentially improve the affordability of the robotic exploration campaign (Figure 2-22).

The proposed MoRSE concept is a result of an implementation, guided by the system architecting principles, of modularity, reconfigurability, and platform strategies in a lunar rover architecture. MoRSE consists of two modules: a base module (BM) and a specialized module (SM). One platform BM provides the basic supporting functions (e.g. powering, thermal controlling) to several generations of SM's. The SM's address the dynamic aspects of lunar exploration, related to scientific discoveries and policy, while the BM addresses the know challenges of lunar exploration, such as lunar thermal environment cycles. Both aspects are discussed in the subsequent sections.

2.5.2 Dynamics of Lunar Exploration

As humans and robots explore the moon, the goals, context and capabilities of the lunar campaign will evolve. The policy context, the technological capabilities, and the knowledge of the lunar science, in-situ resources and environment are dynamics domains to which the surface exploration must be robust and flexible. Guidelines emerging from the consideration of sustainability and dynamic domains are discussed in the subsequent paragraphs and summarized in Table 2-8. These guidelines affect the design of SM's.

Table 2-8 Design guidelines emerging from considerations of architecture sustainability

			Uncertainty Domains		Design Guidelines
	robust		policy		delivering value early and being affordable
Sustainable surface	flexible		science objectives		supporting various instrument suites and mobility requirements
robotic systems	flexible	to	the search for resources	by	reconfiguring around a resource location or redeploying to other locations
must be	flexible		the environment		managing various slopes and soil properties
	timely		technology innovations		accepting technology upgrades

The policy robustness of an exploration architecture is improved by early value delivery (e.g. early scientific investigations of the moon). The technological capabilities of the architecture must be timely with innovations in order to increase productivity and remain relevant and competitive.

The robotic architecture must be flexible with respect to science objectives in two ways. First, the architecture must be able to support several types of science payloads, such as geological instruments, seismic stations and drills. Second, it must be capable of satisfying various mobility requirements, such as long distance traverse and extreme terrain access. Similar capabilities are required for the architecture to be flexible to the search for in-situ resources. If resources are discovered, the architecture must be able to reconfigure to exploit the resources.

The knowledge of the lunar environment is not currently adequate to confidently design extreme terrain access robots. Current maps of the lunar surface have an average resolution of 600 meters per pixel which is insufficient to assess local slopes that a robot might encounter. One camera of the 2008 Lunar Reconnaissance Orbiter is expected to improve the resolution to 100 meter per pixel [Robinson, 2005]. Surface exploration architectures will need to adapt themselves to uncertain local slopes and soil properties. The best elevation and slope data currently available is that of the Tycho crater [Margot, 1999]. This crater, considered representative of fresh and complex lunar craters, exhibits slopes as high as 40 degrees. Therefore, robots exploring craters may have to manage slopes of at least 40 degrees.

2.5.3 Known Functionalities of Lunar Exploration

The lunar environment exhibits several features that are known challenges to mission designers. These challenges are, for the most part, related to the illumination and thermal environments on the moon. Regions within 1.5 degrees from the lunar poles have an illumination cycle of six months. For these regions, night temperatures can be as low as 70 K and day temperatures as high as 150K. Outside of these regions, the lunar days and nights alternate every 14 Earth days, with night temperatures going below 100K. The resulting constraints on the design are twofold. First, the robot must be able to support cold temperatures in the range of 50K to 70K regardless of the region where it operates. Second,

the use of solar power outside of the polar regions, if viable, would most likely preclude night activities as the precious power stored during the lunar day will be used to keep the robot within satisfactory temperatures at night. In addition, lunar dust is expected be a major threat to the survivability of systems on the surface. The sensitive equipment on board the surface systems should therefore therefore be protected from levitating dust due to the vehicle moving. Other environmental effects, such as radiation and partial gravity, will affect the design of surface systems, but they are not considered major drivers in the subsequent analysis.

The topography of the moon, however, is to the advantage to the designers. Figure 2-47 shows a histogram of slope maps derived from the elevation models of Margot et al.
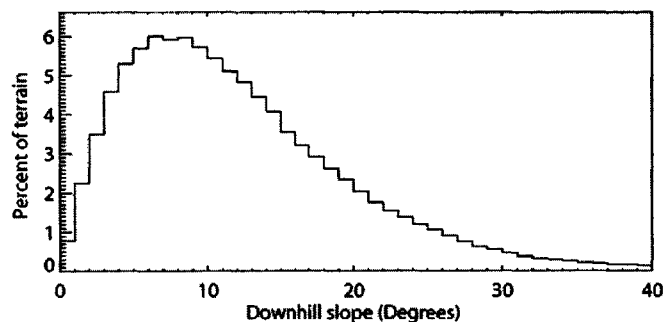
Figure 2-47 Lunar slope distribution at the South pole

Even though, as previously stated, the map is not accurate enough for precise design, the figure shows that most of the South polar area is easily accessible with slopes between 10 and 20 degrees. The scientifically interesting locations (e.g. craters) are likely to belong to the steeper regions with slopes larger than 20 degrees. This figure suggests that lunar exploration has two modes of locomotion; in the site-to-site (crater-to-crater) mode, vehicles traverse terrain with moderate slopes while, in the crater investigation mode, vehicles need extreme terrain access capabilities.

2.5.4 MoRSE concept

The MoRSE concept comprises two types of modules one base module (BM) and several specialized modules (SM's). The designs of the BM and SM match the known and dynamic aspects, respectively, of lunar exploration.

The Base and Specialized Modules

The two-vehicle implementation follows the system architecting principle, regarding platform strategies, stated in the *Physical implementation options* section. The principle recommends the use of customized components for systems with evolving requirements and operating in dynamic environments and of platform components for systems with baseline requirements. Following this principle, the MoRSE concept has SM's that are customized to meet specific mission objectives and to respond to the dynamic domains of lunar exploration (Table 2-8). The concept also has one BM which serves as a platform supporting several generations of SM's with known services, such as *powering, thermal controlling* and *site-to-site traveling*. In other words, the MoRSE concept is based on the allocation of value-related functions and supporting functions to two distinct vehicles (modules), which exchange electrical, thermal and mechanical energy (Figure 2-32). The MoRSE implementation also satisfies the principle of minimum communication between modules (*Physical implementation options* section). An illustration of the MoRSE concept is shown in Figure 2-48; in this illustration the BM is a rover which can accommodate small traditional rovers (e.g. Sojourner-class rovers), vehicles with extreme terrain access capability (e.g. legged vehicles), drills, stations (e.g. for a seismic network), and tanks for logistic purposes.
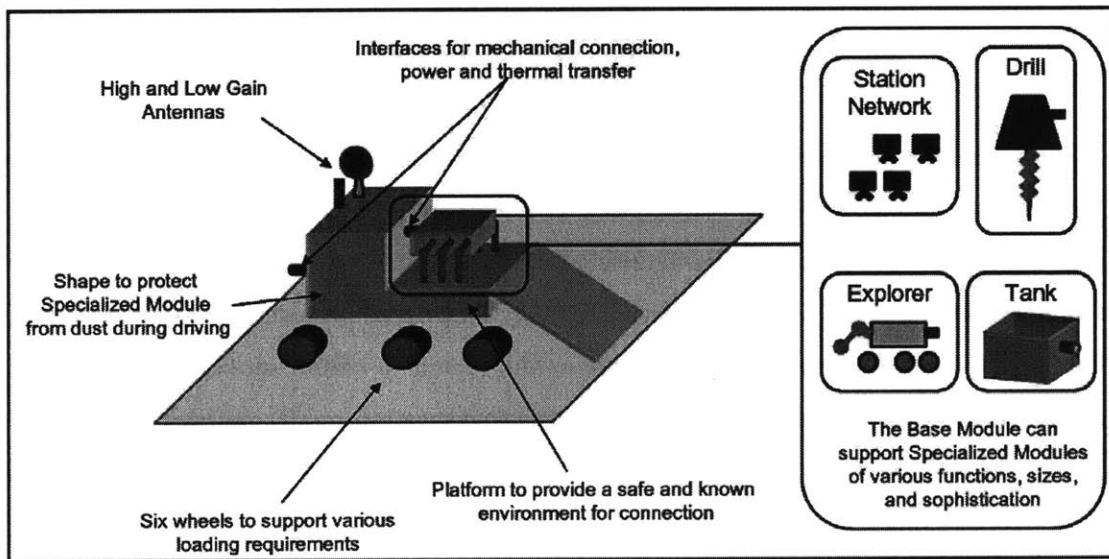
Figure 2-48 Illustration of the base module and specialized modules

Concept of operations

A low-cost Sojourner-like SM (working on batteries with a lifetime of a lunar day) could be sent to the moon the BM. Such a mission would deliver early value, generate support for the campaign and benefit the policy context. The BM is sent to the moon on a next mission, along with a new SM tailored for new mission objectives and with an extended lifetime because, with the support of the BM, the SM can survive lunar night.

Figure 2-32 shows an example of surface operations. If the SM is a robotic explorer, the BM carries the SM close to the location of investigation. During the day, the SM explores the sites for which its mobility system and autonomy software have been tailored. At night, the SM reconnects with the BM to receive electrical energy (e.g. recharge batteries) and thermal energy. The BM could be powered by several RPS's. The BM can also be used solely for transport, for example, to deploy stations for a seismic network or for logistic purposes when equipped with a tank. The same BM can reused over several missions and mission planners have the option of keeping the same SM for multiple missions or upgrading the SM based on new knowledge of the environment.

2.6 Conclusions

The examination of the functional, physical, technical, operational aspects of NASA Mars rover missions characterized NASA's approach to Mars exploration and led to the distinctions of class attributes and design choices. A method was proposed to perform a qualitative exploration of the design space of surface exploration concepts. With this method, the functional and physical aspects of planetary exploration architectures were decomposed in parallel, and then, bridged to generate a vast array of concepts. In the concept generation stage, analogies between exploration systems and information networks proved useful to think about multi-rover missions and create original concepts.

The proposed method has two characteristics. First, each decomposition step aims at providing a complete understanding of all the possible solutions (functional or physical) available. For example, the decomposition of the *moving* function considered all types of locomotion without screening the solutions based on a priori judgments of feasibility or cost. Second, each solution is assessed with respect to a defined set of figures of merit. These two features led to the creation of the concept tree and figure of merit tree. The

concept tree can be used to create surface exploration concepts and the figure of merit tree to compare concepts with respect to stakeholder figures of merit. In Chapter 5, inputs from the figure of merit tree impact the decision to implement customized rover missions as opposed to platform-based rover missions. In the same chapter, the Mars Surface Exploration (MSE) tool (Chapter 3) is used to analyze the affordability trade-off, between customized and platform-based systems, identified in Figure 2-22.

Although the proposed method is applicable to any field of space exploration, this thesis focused on Mars rover exploration. Following this same method, the same work could be reproduced for another area of exploration (e.g. Titan exploration with blimps) within a few months. The process of solution-neutral decomposition forces designers to be creative and holistic; it is, therefore, a valuable learning experience in early conceptual design stages.

Chapter 3

Evaluation of Rover Mission Concepts

The first part of this chapter is dedicated to the presentation of the Mars Surface Exploration rover modeling tool. The tool's conception, models, and unique capabilities are described. In the second part, the tool is used to evaluate a scout-laboratory, multi-rover mission concept formulated in the previous chapter.

3.1 Mars Surface Exploration Rover Modeling Tool

In this section, the purpose, scope and approach of the Mars Surface Exploration (MSE) tool are presented.

3.1.1 A Systems Engineering Tool for Early Rover Design

MSE is a systems engineering tool for the design of Mars rover missions. MSE was originally developed in 2003 by the Space Systems Engineering graduate class at MIT [Marquez, 2003]. The tool has since been further enhanced by the MIT Space Systems Laboratory with support from the JPL Mars Program Office [Lamamy, 2004]. MSE is a science-driven, systems engineering design tool targeted for use, in pre-Phase A, by mission study engineers. The purpose of pre-Phase A is to uncover and create a broad spectrum of ideas and alternatives for missions from which new projects can be selected for further study [Shishko, 1995]. Accordingly, MSE is conceived to enable the *rapid* evaluation and exploration of a broad range of Mars rover mission concepts; it is intended to provide mission designers with a multidimensional view of the trade space for future missions in order to enhance their system-level decision making.

3.1.2 Scope and Approach

In MSE, 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. These tools are described in the subsequent benchmarking section. What these techniques generally gain in fidelity, they lose in scope and agility. MSE's approach is meant to complement point design modeling techniques which, in return, assist in the validation of MSE's models at various points of the design space.

The core modeling capability of MSE covers the engineering, science performance, and cost aspects of a rover system. The current version of the tool has models for only one type of locomotion system, the six-wheel rocker-bogie. In addition, first order models of lander and Entry Descent and Landing (EDL) systems are used in order to analyze surface exploration strategies for the Mars Sample Return (MSR) mission. Other elements supporting the rover, such as the launch vehicle and cruise stage, are not included in the functionality of MSE. Furthermore, MSE does not capture 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 is implemented with a science-driven approach to rover design. In MSE, a mission is defined by its science requirements regarding payload composition (science instruments and acquisition tools), landing location, and surface exploration strategy. Users are able to generate a wide range of rover variants by tuning several key engineering characteristics of rover design which are called *design variables*. These design variables were selected to capture the design trade-offs relevant to mission designers. Other chief qualities guarantee the usefulness of MSE as a rover design aide. 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 software modeling architecture that matches the morphology of a rover system (Figure 3-1).

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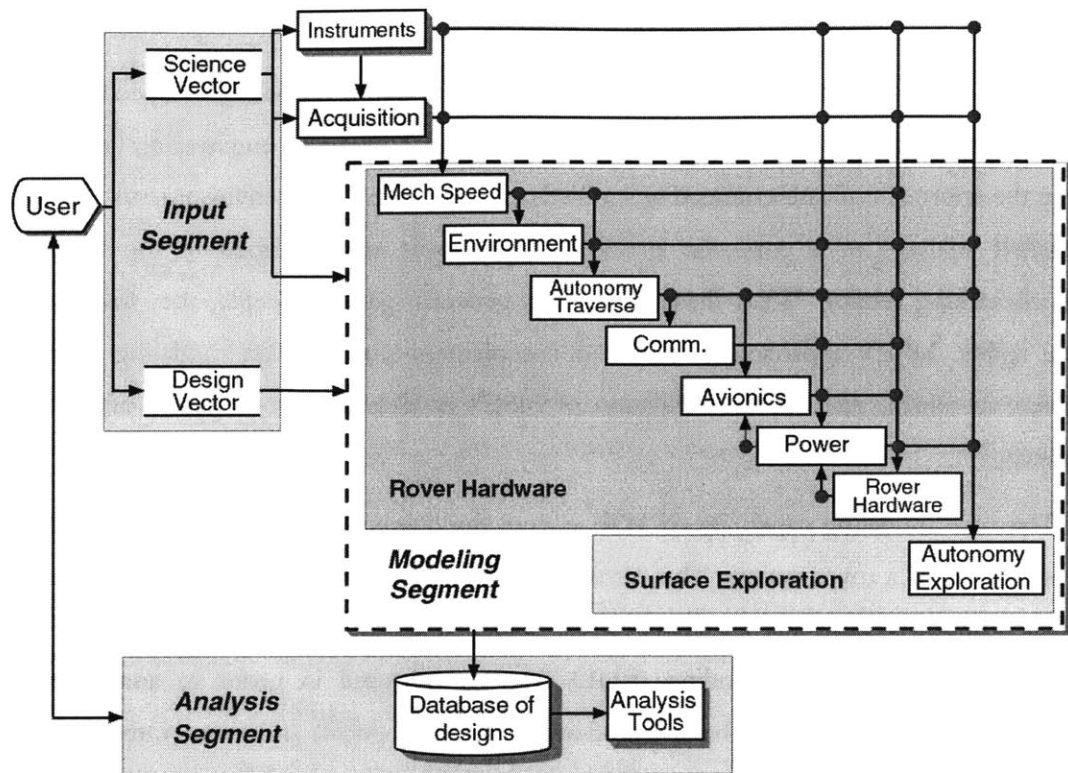
Figure 3-1 Illustration of MSE's model lay-out in the format of a design structure matrix.

A red disk at the intersection between a module's row and another module's column represents an input-output connection. The arrow indicates the direction in which design data flows.

Each rover subsystem is modeled in an independent MATLAB function. This allows easy access for review, update, and validation. The user interacts with MSE through a graphical user interface (GUI) which improves the tool's accessibility to users not familiar with MATLAB. 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 (e.g. MER, MSL and AFL) to that of Mars Sample Return (MSR) rover missions and Lunar rover missions.

3.2 Benchmarking MSE with Other Design Tools

In the subsequent paragraphs, the capabilities of MSE are compared with that of other existing tools which are grouped in three categories: concurrent engineering models, mission

scenario development models and subsystem models. Table 3-1 summarizes the performance of all tool categories, listed on the top, with respect to metrics of scope, fidelity, resources, and run time, listed on the left. The background color of a cell is a qualitative indicator of goodness of a tool with respect to a metric. A cell with light background indicates good performance; a cell with a dark background indicates better performance.

Table 3-1 Benchmarking of MSE's performance against that of other existing tools

	MSE	Concurrent engineering models	Mission scenario development models	Subsystem models
Scope	Rover design and operations	Rover, EDL, and cruise design	Rover operations	Rover subsystem
Fidelity	System-level	Higher-fidelity cost models	High-fidelity resource models	High-fidelity performance models
Resources	Matlab, 7MB	Subsystem experts	Subsystem experts	CAD software
Run time	sec - hours	week	sec - hours	sec - hours

Table 3-1 shows that there exists trade-offs between modeling scope and modeling fidelity and between modeling performance (scope and fidelity) and cost (resources and run time). For Mars rover modeling applications, MSE is shown to be a good complement of concurrent engineering models. The purpose, implementation and capabilities of every tool category are described in the subsequent sections.

3.2.1 Concurrent Engineering Models

In recent years, space agencies and industries have developed concurrent engineering facilities to improve their pre-Phase A and Phase A mission designs [Wall 2000, Zoppo 2005, Bandecchi 1999]. The JPL Advanced Projects Design Team and Model-Based Engineering Design tool development effort, presented in this section, are examples of tools relying on concurrent engineering.

JPL Advanced Projects Design Team [Wall, 1999]

JPL Advanced Projects Design Team (Team X) was one of the first concurrent engineering teams for space mission design. As implemented in Team X, "concurrent engineering is defined as the examination of design issues by teams that include all relevant disciplines in real time design sessions"; "the design teams examine design alternatives employing an

interconnected, distributed suite of tools" [Smith, 1998]. The purpose, implementation and capabilities of Team X are described extensively in [Wall, 1999].

Purpose

The Team X is environment was designed to improve the production process of conceptual studies of space missions [Wall, 1999]. Traditionally, conceptual studies had been produced by small, dedicated design teams that developed and implemented their own processes. This approach had two main disadvantages. First, it did not promote feed-forward of knowledge and tools from one design team to the next. Second, it made the cost and quality of the proposals highly dependent on team membership [Wall, 1999]. The creation of Team X addressed these two issues. Team X is a combination of a team of expert designers, connected and advanced modeling tools, visualization tools, and a specialized design facility. This environment enables real-time problem resolution. It enables the real-time exchange of information among experts of the design team; the exchange of design parameters among subsystem designers via a network of design tools; and the multidisciplinary optimization of design, with full consideration of schedule, mission operations and cost.

Implementation

The design team consists of an engineer and a backup for each subsystem of common space missions (*Physical Architecture*, Chapter 2), an engineer and a backup for cost calculations, a study leader, and documentarian [Wall, 1999]. Each subsystem engineer controls the model characteristics of its subsystem and shares them in real time with other subsystems engineers. By bringing all subsystem experts into one design room, and by developing a network of design tools, Team X has reduced the time of conceptual studies from several months to two weeks [Morse, 2006]. Mission cost is the metric used to iterate design requirements until the cost goal is met; each design iteration takes from minutes to hours. The Team X design process is described in [Morse, 2006]. A typical proposal performed by Team X costs $75,000 [Wall, 1999].

Capabilities

Team X environment combines powerful subsystem design tools with creative and flexible subsystem experts to transform a space mission concept into a converged point design [Morse, 2006]. The modular architecture of Team X, with independent but interconnected

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subsystem models, enables the modeling of many types of missions from Earth observation satellites to Mars rovers. Within a given mission, the team designs all critical systems, such as the cruise stage, entry descent and landing vehicle and surface probe. For this reason, Team X models have a wider scope of applications than MSE models. However, to the best of the author's knowledge, Team X does not have specific models for the subsystems that are characteristic of rover systems (as opposed to satellites), such as the mobility subsystem. These subsystem characteristics are evaluated based on expert judgement. Regarding cost, JPL has developed several cost models that use a variety of technical and system level parameters to generate cost estimates using only parametric analysis. For better accuracy, the cost estimation process in Team X consists of a "quasi-grassroots methodology" [Morse, 2006]. Some costs are based on grassroots estimates of labor costs or hardware costs, while other costs require parametric analysis based on previous detailed studies. Each subsystem expert spends time tailoring their cost to what they feel is representative [Morse, 2006]. This approach provides designs with a higher fidelity than MSE but it is not practical for the rapid exploration of numerous design alternatives.

Model-Based Engineering Design [Lamassoure 2004, Morse 2006, Wall 2004]

Purpose

The Model-Based Engineering Design (MBED) initiative at JPL stemmed from the belief that early modeling of the design can offer a solution to the problem of evolving requirements and constraints during the design process [Morse, 2006]. MBED was intended to expand the Team X process at the conceptual design phase by enabling more complete explorations of trade spaces [Wall, 2004]. The MBED effort has been discontinued.

Implementation

The implementation of MBED is described in [Lamassoure, 2004] and [Morse, 2006]. There are two main differences between MBED and Team X models. First, MBED uses system sensitivities models to represent the local trade space around a point design. Models share not only design results but also design equations to build sensitivity models. Second, MBED consists of rough-order-of-magnitude design models, based on rules of thumb from experts, for rapid exploration of the trade space, before selection of a point design.

Capabilities

MBED complements Team X with sensitivity calculations and enables faster trade space exploration, but with less fidelity. The MBED cost model uses parametric cost equations from JPL's Parametric Mission Cost Model (PMCM) and Assembly, Test, and Launch Operations Cost Model. As opposed to Team X grassroots cost model, the MBED cost model enables rapid, automated trade space analysis [Morse, 2006].

Comparison

Overall, tools in this category cover a wider scope and offer a higher modeling fidelity than MSE. Team X and MBED all aspects of missions (e.g. ground control, EDL system) whereas MSE tends to focus on the rover portion of a rover mission. The grassroot cost modeling approach, supported by expert inputs, implemented in Team X enables the design team to analyze the cost impact of subsystems trade-offs. The MSE cost estimating relationship, based on rover total mass, is less sensitive to subsystem variations, software architectural decisions, and decisions related to launch vehicles and trajectories. However, MSE has physics-based models for some of its subsystems which could complement the parametric models used by Team X. Moreover, compared to Team X and MBED, MSE has the unique capability of evaluating the exploration performance (number of samples collected, total distance traversed) of a rover design.

The main advantage of MSE compared to concurrent engineering facilities is that the evaluation of a rover design is automated, very quick (less than a second) and it requires only minimum resources (MATLAB software and 7MB of hard drive). In concurrent engineering facilities, the reliance on expert input provides great benefits, in creativity and problem solving capability, but it also makes the design process expensive, a Team X study costs approximately $75,000 [Wall, 1999], and long which prevents the exploration of a large trade space of design alternatives.

3.2.2 Operational Performance Evaluation Tools

This section describes two frameworks, intended for use in Phases A and B to assess the expected performance of a spacecraft. While these tools enable analyses that can help the design of particular spacecraft components, their main function is not to perform system design trade-offs.

Multi-Mission Analysis Tool [Kordon, 2003]

Purpose

The Multi-Mission Analysis Tool is a suite of subsystem simulation models, developed by JPL, that is used to predict the performance and resources of a spacecraft. The tool can be used to help size subsystem components, such as solar panels. Deep Impact and MER have used the tool to develop operation sequences.

Capabilities

The tool provides dynamic time and sequence-dependent outputs, as opposed to static point solutions produced by MSE. For example, it models the behavior of power sources and energy storage devices as they interact with the spacecraft loads over a mission timeline. The tool handles a range of power technologies similar to those captured in MSE (e.g. Li-Ion batteries, triple-junction solar cells, radioisotope power technologies).

Implementation

Models cover four main spacecraft subsystems: power, thermal, command and data handling (C&DH), and propulsion. These models have been validated with Pathfinder and MER data. Furthermore, the tool is equipped with a parameterized interface which enables it to support multiple types of space missions including, orbiters and landers.

The tool is easy to use; it runs on Windows, Solaris, and Linux as a stand-alone application equipped with a graphical user interface or as a linkable library package. The tool's average simulation run time is from seconds to minutes, which is commensurate with that of MSE.

Mission Scenario Development Workbench [Kordon, 2004]

Purpose

The Mission Scenario Development Workbench (MSDW) is a tool suite developed at JPL to evaluate spacecraft operational performance during Phase A. This data then informs the designers of the capabilities of the subsystems to meet payload, trajectory, communication, and activity requirements under prescribed mass, cost, and performance constraints. MSDW has been used to evaluate various MSL mission scenarios with respect to mission duration, number of science goals achieved, and power profiles.

Capabilities

MSDW generates detailed activity timelines which take into account science activities, relay orbiter passes, and ground processing. All three activities are modeled in MSDW with higher fidelity than in MSE; orbiter view times and data transmission rates are calculated based on site selection. In comparison to MSE, MSDW provides a better evaluation of rover performance but does not have the rover design trade-off capabilities of MSE.

Implementation

At the core of MSDW is the equipment list which is the flight system engineer's best estimate of the space vehicle design; the equipment list is organized in Excel spreadsheets. Interactions between components are simulated with separate computer programs, based on the Multi-Mission Analysis Tools described above. The process of creating a surface mission plan involves significant expert consultation in the domains of orbiter trajectories, instrument data volumes, and rover power profiles.

Rover Analysis, Modeling and Simulation [Jain, 2003]

Purpose

The Rover Analysis, Modeling and Simulation (ROAMS) is a physics-based simulator for planetary surface exploration rover vehicles. ROAMS addresses the need to develop validated modeling and simulation capability for surface systems to allow missions to carry out detailed surface system trade studies, develop and test new rover technologies, support the development of onboard flight software architectures, and develop mission operations concepts.

Implementation

ROAMS includes models for various subsystems and components of the robotic vehicle including its mechanical subsystem, an electrical subsystem, internal and external sensors, on-board resources, on-board control software, the terrain environment and the terrain-vehicle interactions. The rover vehicle modeled in ROAMS is the rocker-bogey class of 6-wheeled rovers used for planetary surface exploration. There are several variations on the basic design in terms of the location of the differential, the number of steerable wheels and the various

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mechanical dimensions of the rover. The underlying Dynamics And Real-Time Simulation (DARTS) models simulate the rover-terrain interactions.

Capabilities

ROAMS can satisfy a variety of uses: algorithm development, when used within a Matlab/Simulink environment; sequence building and testing during mission operations; design performance evaluation, when used for Monte Carlo studies of a rover design under different environment conditions and scenarios.

Comparison

Overall, tools in this category provide better modeling fidelity in the area of rover operations. The tools provide a more precise assessment of rover resource consumption and interactions with the environment, upon which designers are able to build exploration scenarios. MSE energy consumption calculations are based on averaged subsystem power demands and worst-case environmental conditions (end-of-life power and minimum illumination). The tools in this category are, however, not conceived to explore system-level design trade-offs. MSE provides more emphasis on the rover design; with MSE, designers are able to quickly grasp the effects of selecting particular scientific instruments, of changing design variables (e.g. wheel diameter, power system) on the rover design cost, mass and performance.

3.2.3 Subsystem Models

This section describes models which focus on the optimization of the rover mobility subsystem and of its terrain interactions.

Purpose

Mobility models are developed to create virtual proving grounds for vehicle designs [Michaud, 2004]. Mobility models enable the characterization of a concept and the analysis of trade-offs without relying on prototyping, which lowers the cost and risk of the vehicle design process.

Implementation

Lamon et al. [Lamon, 2004] distinguish three types of rover mobility modeling tools: three-dimensional simulation using finite element method; full mathematical and mechanical models; and constraint-based simulation models. The three types are compared with respect to metrics, such as simulation speed, processing power, fidelity, level of automation, and need for expert knowledge. Lamon et al. found that models of the first provide the best fidelity but perform badly with respect to the remaining metrics; models of the second type perform very well in terms of simulation speed and processing power but still require significant manual work and require expert knowledge; and models of the third type do not rely on expert knowledge and perform relatively well with respect to the remaining metrics.

Capabilities

Lamon et al. created a quasi-static mechanical model used to optimize the mobility configuration of the SOLERO rover [Lamon, 2004]. Blessing et al. [Blessing, 2005] developed a physics-based tool for modeling rover-terrain interactions to predict the performance of rover designs on a variety of terrain conditions. The tool relies on the use of a sophisticated software engine (Arachi Dynamics Engine) which computes interactions of objects, with a real-time three-dimensional visualization capability, based on Newtonian physics. Michaud et al. [Michaud, 2004] and Patel et al. [Patel, 2004] developed a Rover Chassis Evaluation Tool (RCET). The tool is based on Bekker theory and it is able to model several types of locomotion including wheeled, tracked and legged systems.

Comparison

Models in this category are able to optimize the mobility subsystem with a high level of fidelity by evaluating design performance on a variety of terrains. In comparison, the MSE mobility model has a lower fidelity. Only one mobility design parameter, the wheel diameter, is optimized and considerations of wheel-soil interactions are limited to the verification that the ground pressure of a given rover design is less than the assumed Martian soil bearing strength. New capabilities have recently been added to the mobility model of MSE; models for legged and hybrid legged-wheeled systems have been developed by McCloskey [McCloskey, 2007]. Compared to the subsystem models reviewed in this section, MSE

models, which cover the whole rover system, have a broader scope and can be used to perform system-level trade-offs.

3.3 Tool Structure

When generating models with broad applicability, model flexibility is the number one priority; the choices of model architecture and design are very important [Lamassoure, 2005]. MSE was conceived with a modular architecture to perform the following functions: receive inputs from the user; search the trade space; assess designs; and return information to the user. Accordingly, the tool is composed of three segments (*Input, Modeling,* and *Analysis*) and a trade space search engine (Figure 3-1).

3.3.1 Modular Segments

The *Input* segment is a front end which enables the user to set values for the mission science parameters (*Science vector*) and for the design variables (*Design vector*). By doing so, the user defines the nature and extent of the rover design trade space. The *Modeling* segment contains the models employed to size the rover's hardware components and assess its surface exploration performance. The *Analysis* segment provides the user with tools to visualize the trade space and to perform tailored analyses. Figure 3-1 shows the decomposition of the Modeling segment into calculation modules arranged in a design structure matrix. The usefulness of the design structure matrix representation is discussed in the subsequent *Rover System Modeling* section.

3.3.2 Full-Factorial Search

Optimizing designs in the early stages of the trade space exploration is not a necessity and could be premature [Lamassoure, 2004]. The purpose of MSE is not only to help uncover high performance rover designs for a given scenario but also to provide the user with a global and unbiased understanding of a mission trade space. For this reason, a simple full-factorial trade space search method was implemented in MSE. A full-factorial search is an exhaustive computation of all the possible designs that are parameterized by the design vector; therefore, it provides a complete view on the nature of the trade space. A full-factorial search method is more computationally expensive than intelligent search

algorithms, such as heuristic optimization methods. However, once the full-factorial search is complete and saved, users are able to optimize the trade space *a posteriori* for any set of objectives and figures of merit. On the other hand, intelligent search algorithms require users to explicitly state their optimization objectives *a priori*; therefore, with intelligent algorithms, a new search must be computed for each set of user objectives, which vary widely in early design phases.

3.3.3 Trade Space Search

The definition and the search of a mission trade space is facilitated by the MSE Graphical User Interface (GUI). Figure 3-2 provides a screenshot of the GUI. It is composed of a main window which contains, in the upper left corner, the controls for the definition of the science vector, the definition of the design vector, the initiation of the trade space search, and the analysis of the trade space. In addition, the GUI has a plot window, in the lower left corner, for creating two- and three-dimensional visualizations of the trade-space and of the geometry of a given rover (as shown). Another section, in the upper right corner, displays the characteristics of each subsystem for a given design.

The *Science vector* and *Design vector* buttons open two other GUIs, where the user inputs the vector entries. The user then initiates the search of the trade space by clicking on the *Create designs* button. The evaluation of one design point takes on average less than one second with a 1.6GHz workstation; the full-factorial search of large trade spaces is therefore feasible. Once the search is complete, all valid designs are saved in a MATLAB file and duplicated in an Excel file. The Excel spreadsheet format helps to facilitate the exchange of information with other users. The database of rover designs is available for analysis at any subsequent time.
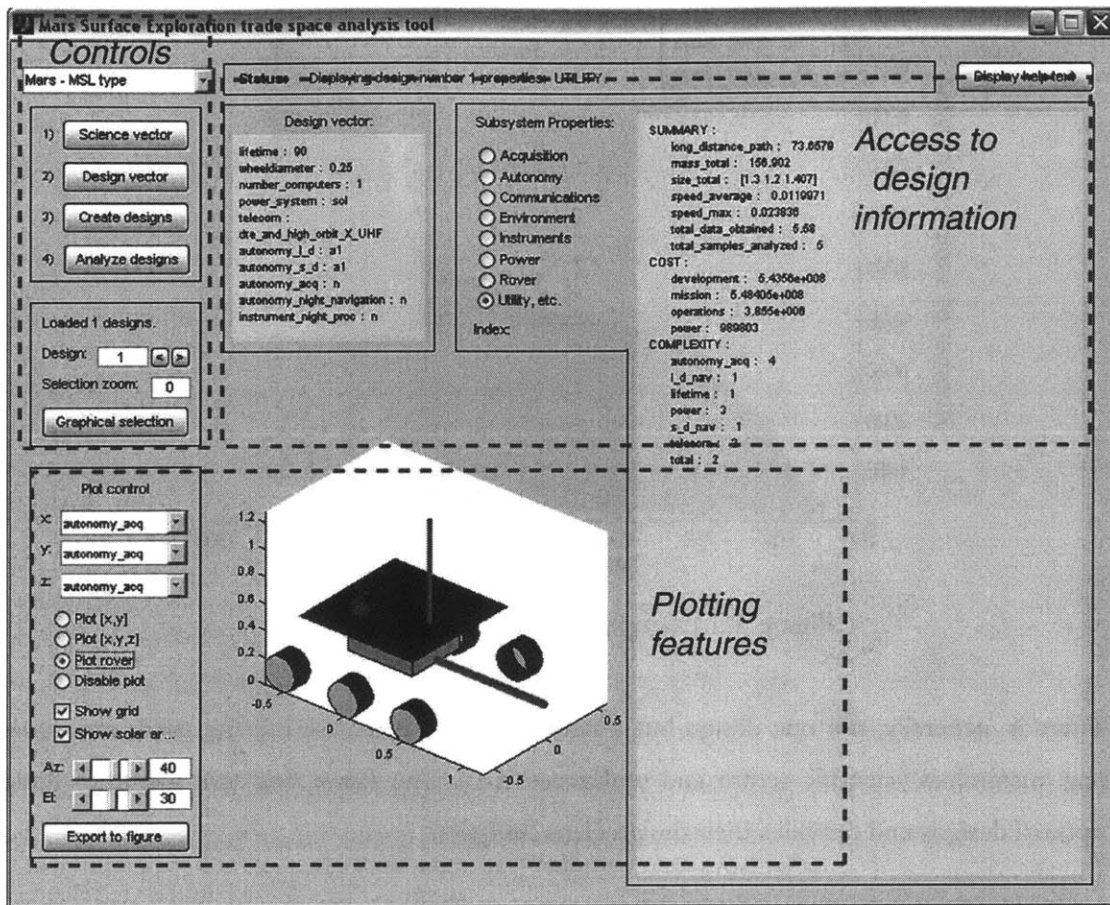
Figure 3-2 MSE main graphical user interface.

3.3.4 Trade Space Analysis

Through its GUI, MSE offers a suite of analytical features that extract and display data and insights from the trade space of designs. The user chooses, from pull-down menus in the *Plot control* area of the GUI, which design properties to visualize in the plot window. A common trade space visualization shows the *number of scientific samples analyzed* by each mission (proximate metric for science return) as a function of *mission cost*. Figure 3-3 shows an example of a trade space representation. In this visualization, solar-powered rovers are represented by squares and rovers powered by a radioisotope power system (RPS) are represented by dots. A function in MSE is used to represent by a shaded area the extent of the trade space covered by solar-powered rovers.
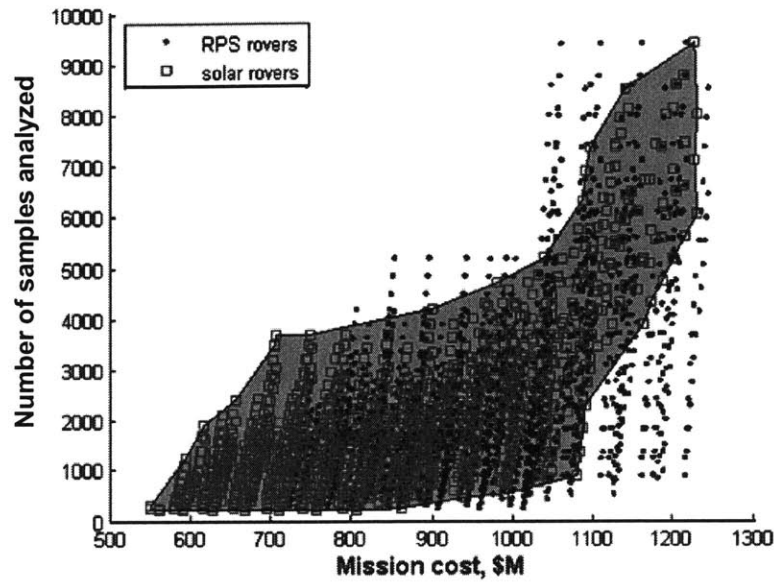
Figure 3-3 Example of rover design trade space

There is, generally, not one design but a family of designs that satisfy the user's objectives (e.g. maximizes scientific return and minimizes cost). The *Pareto front* tool identifies those optimal designs and provides their design characteristics.

3.4 Science Scenario and Technology Options Parameterization

As previously mentioned, MSE is a tool to explore technology options that improve rover performance for a user-defined science scenario. The science and technology aspects of the trade space are parameterized by two vectors, the *Science vector* and the *Design vector*, respectively.

3.4.1 Science Vector

For the science vector, the user defines a science scenario which includes instrument suite composition, landing site characteristics, and exploration strategy. Science instruments, navigation instruments, and acquisition tools are selected from a database which currently includes all instruments used on Sojourner and MER, and those which have been selected

for MSL and ExoMars. Other instruments and tools can be added to the list by providing values for mass, power demand, measurement time, and expected lifetime.

Landing site parameters include landing date, latitude of the landing site, and rock abundance of the area surrounding the site [Golombek, 2005]. Date and latitude influence solar flux calculations, which in turn determine the feasibility of solar-powered rovers. Rock abundance affects the trafficability of the terrain around the landing site; in MSE, it is assumed that a rover is operated on a flat terrain covered by rocks whose abundance and sizes are derived with Golombek's model [Golombek, 2005]. In its current version, the terrain model does not differentiate soil types and does not include terrain slopes.

Rover operations are modeled after that of MER; rovers linearly explore the surface, investigating scientific sites one after the other. A generic itinerary is created in order to compare the surface exploration performance of various rovers. The user parameterizes an itinerary by defining a *site-to-site distance*, a *site diameter* and a *number of samples analyzed per site*. The number of sites a rover is able to visit, and the number of samples analyzed, depend on the rover's technological capabilities (determines by MSE models).

3.4.2 Design Vector

The design variables are the rover properties that vary among rover designs; the variables are gathered in the design vector. During the creation of a system design tool, developers select which system variables are design variables with the intent to capture the engineering trade-offs of interest of the stakeholders. The following design variables were selected for MSE: mission lifetime, wheel diameter, processing efficiency, power source type, approach autonomy, and communications link (Table 3-2).

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Table 3-2 MSE design variables

Name	Unit	Description	Levels
lifetime	sol	mission duration	continuous, positive values
wheel diameter	m	diameter of the rover wheels	continuous, values between 0 and 1 meter
processing efficiency	-	measure of processing speed and algorithm efficiency	continuous, positive values
power source	-	type of power system on the rover	either solar power and batteries or RPS and batteries
approach autonomy	-	level of autonomy for the sample approach activity	either state-of-the-art or advanced
communications link	-	type of communications link used by the rover	seven combinations of DTE, low-orbit and high orbit links with X-band and UHF

The power source design variable has two possible values (also called *levels*): a solar power system or a radioisotope power system (RPS) combined with batteries. Users are therefore able to compare the performance of RPS-powered rovers with solar-powered rovers in the conduct of a particular mission scenario. The approach autonomy design variable also has binary levels, *state of the art* autonomy and *advanced* autonomy (the approach autonomy and processing efficiency design variables are discussed in the *Autonomy* section). The communications link design variable has seven levels which are combinations of a direct-to-Earth (DTE) link with orbital relays in low and high orbit around Mars. The default communications architecture used in most analyses is a combination of DTE link using X-band and high-orbit relay link using UHF. The remaining design variables have continuous levels. The only restriction on the number of levels that the user can input for each design variable is the calculation time the user is ready to tolerate. The number of designs in the trade space (to which the calculation time is proportional) is the product of the number of levels of each design variable.

3.5 Measuring Scientific Return

In the previous chapter, the Mars science community has been identified as the primary beneficiary of Mars rover missions. Consequently, the most valuable contribution of a rover mission is its scientific return to the scientific community. A mission delivers value if the

instruments produce data, from Mars sample measurements, which meet the needs of the scientific community.

Table 3-3 illustrates the connections between investigations desired by the scientific community, the mission instruments and the Martian environment. The two rightmost columns of Table 3-3 list several factors that influence the value flow at level of the samples, instrument and scientific community and at the interfaces. The subsequent paragraphs go over these factors and their implementation in MSE starting with the needs of the scientific community.

Table 3-3 Illustration of the scientific value delivery process
An arrow connecting two elements illustrates a flow of information. A solid line indicates a strong connection; a dash line indicates a significant connection. List of abbreviations: *spl* sample; *instr* instrument; *inv* MEPAG investigation; and *#* number.
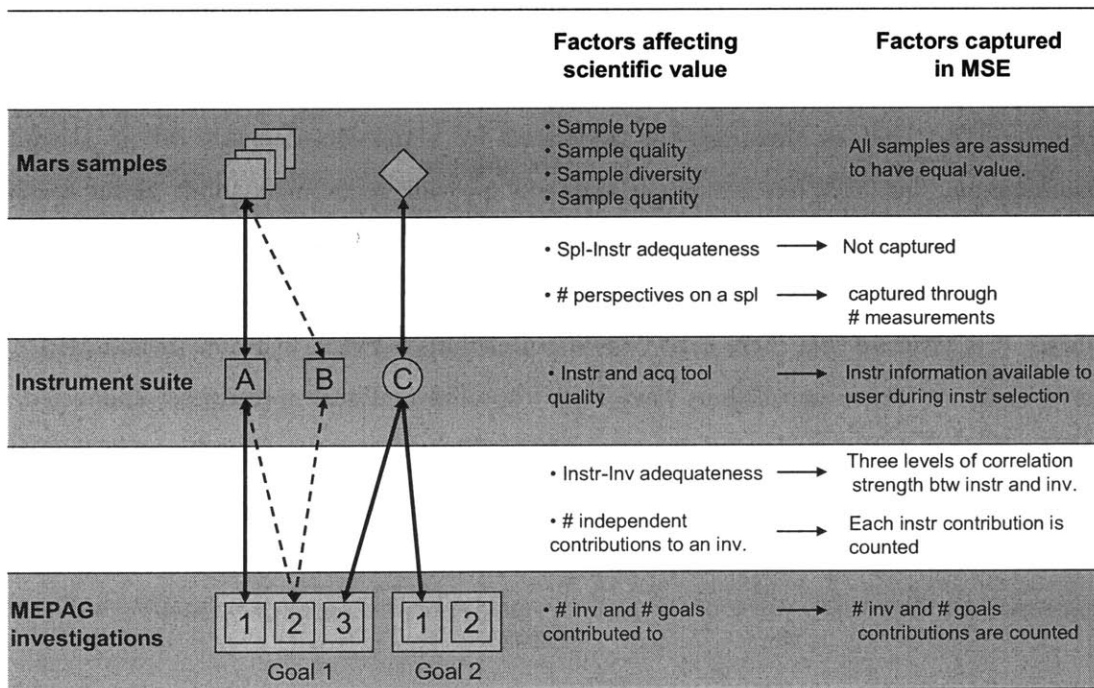
3.5.1 Scientific Investigations and Instrument Selection

In 2001, the Mars Exploration Program Analysis Group (MEPAG) was asked by NASA to work with the scientific community to establish consensus priorities for the future scientific exploration of Mars (*Mars Exploration Program Goals*, Chapter 2). The group has categorized the Mars science objectives into four science goals (the names used in this document to refer to each goal are included in parentheses):

5) To determine if life ever arose on Mars (*Life goal*),

6) To understand the processes and history of climate on Mars (*Climate goal*),

7) To determine the evolution of the surface and interior of Mars (*Geology goal*),

8) To prepare for human exploration (*Human goal*).

In addition, in its *Mars Scientific Goals, Objectives, Investigations, and Priorities* document [MEPAG, 2006], the MEPAG provides a hierarchical decomposition of each goal into objectives, investigations, and measurements. This document serves as a basis to identify the needs of the Mars scientific community and evaluate how well these needs are met by a mission. The kind of investigations addressed by a mission depends on its scientific instruments. The MEPAG document does not provide recommendations about specific instruments to carry out measurements. While some investigations can be achieved with a single instrument, others will require multiple instruments on multiple missions. In this thesis, it is assumed that there exist known correlations between instruments and MEPAG investigations. These correlations have been captured in Excel spreadsheet connected to MSE; Table 3-4 is a section of this table which shows the correlations between the MSL instruments and the Life goal.

Table 3-4 Correlation between scientific instruments and MEPAG investigations

Instrument	Life — Past and Present habitability of Mars				Life — Charact. Carbon Cycling in its geoche context				Life — Assess wether life is or was present on Mars			
	Establish the current distribution of water in all its forms on Mars	Determine the geological history of water on Mars (model proces.)	Identify and characterize phases containing C,H, O, N, P and S (minerals, ices, and gases)	Determine the array of potential energy sources available on Mars to sustain biological processes	Determine the distribution and composition of organic carbon	Characterize the distribution and composition of inorganic carbon reservoirs	Characterize links between C and H, O, N, O, and S	Preservation of reduced compounds on the near-surface through time	Characterize complex organics	Characterize the spatial distribution of chemical and/or isotopic signatures	Characterize the morphology of mineralogical signatures	Identify temporal chemical variations requiring life
APXS (MPF, MER, MSL)	1		2						1	2		
CheMin (MSL, AFL)		1	2		1				1	2	1	
MARDI (MSL)												
MAHLI (MSL)	1	1							1	1	1	
ChemCam (MSL)			2		1				1	2		
MastCam (MSL, AFL)	1	1									1	
SAM (MSL)	1		2		2		1	1	1	2		
REMS (MSL)	2											
Dynamic Albedo Neutrons (MSL)	2	1									1	
Radiation Assessment Detector (MSL)	1			2								

The instruments are listed in the left-most column and the decomposition of the MEPAG goals into investigations is listed in the top rows of the table. For example, *Establish the current distribution of water in all its forms on Mars* is the first investigation which improves the objective *Assess the past and present habitability of Mars*, which is one of the three objectives of the *Life* goal. In order to keep the table within a reasonable size, the MEPAG investigations are not decomposed into measurements – the MEPAG document lists a total of 49 investigations. A number at the intersection of an instrument row and investigation column means the instrument contributes to that investigation. The value of the number is a weight which represents the strength of that contribution. Some instruments are more suited than others to provide data for an investigation. In Table 3-3, a significant data contribution from an instrument to an investigation is illustrated by a dash line and a strong data contribution (current best) is illustrated by a solid line. In Table 3-4, a significant data contribution from an instrument to an investigation is represented by a weight of 1, a strong data contribution by a weight of 2. If an instrument does not contribute to an investigation, the weight is zero (zeros are replaced by blanks in Table 3-4). The creation of an investigation-instrument correlation map requires scientific expertise. The table currently used in MSE is based on the work of Dr. Ashwin Vasavada and Joanne Vozoff from JPL; it includes all instruments of Sojourner, MER, and MSL and those proposed for ExoMars and AFL.

Some investigations receive contributions from several instruments; instruments A and B both contribute to the second investigation 2 of Goal 1 in the illustration of Table 3-3. In the case of the MSL payload, the MastCam (remote instrument), the MAHLI (contact instrument), and the CheMin (analytical instrument) contribute to the second Life investigation *Determine the geological history of water on Mars, and model the processes that have caused water to move from one reservoir to another.* These three contributions illustrate a step-wise approach to science exploration which is the ability to conduct measurements at multiple scales: panoramic images from remote sensing instruments, close-up images from contact instruments, and analytical data from laboratory instruments [ESA, 2005]. With Table 3-4, it is easy to identify how many instruments of a science package contribute to a given investigation j. The sum W_j of the weights W_{ij}, connecting a given investigation j to an instrument i, is a measure of the number and strength of contributions to that investigation.

$$W_j = \sum_i W_{ij}$$

(3-1)

The weights W_j of various investigations can be compared to assess how a particular mission addresses each investigation. In conclusion, the selection of scientific instruments on-board a mission determines how science community needs are addressed by the mission.

3.5.2 Instruments and Mars Samples

Several factors at the instrument-sample interface affect the value of the scientific flow from the samples to the scientific community (Table 3-3). These factors are related to the operations of the rover on the surface. In the surface exploration scenario implemented in MSE, the rover drives to a site, acquires and analyzes a given number of samples, sequentially, and drives to the next site. In MSE, it is assumed that all sample acquisition tools and all instruments are used on every sample. In MSE exploration models, a *measurement* is considered to be an activity performed by an instrument which requires a given amount of time and power, and which produces data. A *sample* is a virtual entity on which acquisition tools and instruments operate.

All the samples collected, within a site and across several sites, are considered to have the same scientific value. In reality, the scientific value of a measurement would likely decrease as the number of similar measurements increases and the scientific data from the measurement becomes redundant. The depreciation rate is difficult to quantify because it

depends on the diversity of the samples measured; the value of ten similar measurements made at the same site is arguably less than that of ten measurements made at different sites. If the rate were quantified, for example through a Multi Attribute Utility Analysis (MAUA), it could easily be implemented in MSE to capture the trend of decreasing value. In the current version of MSE, the number of samples collected and the number and types measurements performed during a mission are recorded. Because some instrument can only perform a limited number of measurements, not all instruments analyze the same number of samples over a mission. In this thesis, the quantity *number of samples analyzed* by a mission is the maximum number of samples that are analyzed by a mission. In the equation below, S is the number of samples analyzed by a mission and, S_i is the number of samples analyzed by the instrument i.

$$S = \max\left(S_i\right) \tag{3-2}$$

Because an instrument only performs one measurement per sample, the total number of measurements (M) performed during a mission is the sum of the number of samples analyzed by each instruments (S_i).

$$M = \sum_i S_i \tag{3-3}$$

The weighted contribution over the mission of an instrument i to an investigation j is given by the equation below, using the same notations of Equation (3-1).

$$C_{ij} = W_{ij} S_i \tag{3-4}$$

The total contribution C_j to a given investigation j is the sum of the individual contributions of each instrument.

$$C_j = \sum_i C_{ij}$$
$$C_j = \sum_i W_{ij} S_i \tag{3-5}$$

The total contribution C to the MEPAG investigations is the sum of the individual contributions to each investigation.

$$C = \sum_j \sum_i W_{ij} S_i \tag{3-6}$$

The equation above highlights two components of the contribution. First, the weight, W_{ij}, is a measure of how well the instrument payload meets the scientific community needs; this component depends on the instrument selection by the user. Second, the number of samples

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analyzed S_i is a measure of the surface exploration performance of a rover; this component is calculated by MSE models. Figure 3-4 illustrates the two components of the scientific return. On the one hand, the spectrum the investigations addressed by a mission is determined by the composition of the science payload, which is defined by the user (in the Science vector). On the other hand, the number of contributions to a given investigation is determined by the correlations between instruments and the investigation (information stored in the MSE database) and by the number of samples analyzed by each instrument (performance calculated by MSE).

Calculated by MSE
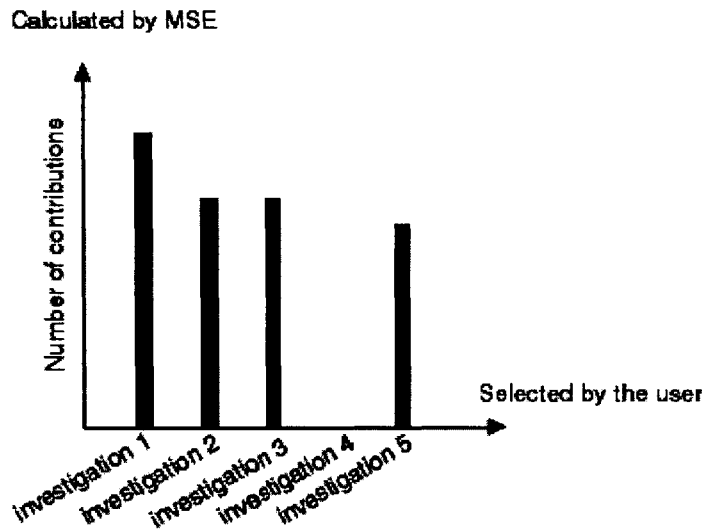
Figure 3-4 Illustration of the contribution of a mission to MEPAG investigations

3.5.3 Science Metrics

Based on the examination of the scientific value flow described in the previous section, there is a variety of parameters that can potentially serve as proximate metrics to measure the scientific value of a mission. On the one hand, the number of investigations and goals addressed by a mission indicates what share of scientific community needs is addressed. On the other hand, the number of samples analyzed is a measure of a rover's exploration capability. Two kinds of analyses are distinguished, each uses a specific proximate metric for science return. The first kind of analysis compares rover missions that carry the same instruments. In this case, the weights W_{ij} are the same for all rovers; the distribution of investigations addressed by rovers is independent from the technological solutions implemented on these rovers. In other words, value aspects related to stakeholder

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satisfaction do not depend on vehicle design. Therefore, value aspects related to exploration capability, which depends on vehicle design, are design performance discriminators. In this situation, the number of samples analyzed is the scientific metric used to compare and rank missions.

The second kind of analysis compares rover missions that carry the different instruments. In this case, each mission addresses specific needs of the scientific communities. The previous metric, number of samples analyzed, is not appropriate because it does not capture information about the needs addressed by a given mission. In this situation, the scientific metric used is called, in this thesis, *science score*; it is the sum of weighted contributions made to a given goal. The science score, V_K, for the goal K is derived from Equation (3-6).

$$V_K = \sum_{j \in K} C_j$$
$$V_K = \sum_{j \in K} \sum_i W_{ij} S_i$$

(3-7)

The weights W_{ij} summed over the instruments and the investigations of the goal K captures how well a mission (scientific payload) addresses the goal K. The number of sample, S_i, captures the exploration capability of the rover. Because developing an understanding of Mars as a system requires making progress toward meeting all four goals, MEPAG has not attempted to prioritize the goals, but rather represents them equally [MEPAG, 2006]. For the same reason, missions are compared on the basis of how well they meet each of the four MEPAG goals independently.

3.6 Rover System Modeling

In MSE, the complex rover system is subdivided into smaller disciplinary subsystems in each of the following areas: surface environment, science instruments, sample acquisition methods, rover vehicle (including structure, mobility and thermal hardware), autonomy, communication, and power. These seven subsystems are further subdivided into *calculation modules* in order to minimize calculation time. For example, the *mechanical speed* and *rover hardware* modules both belong to the *Vehicle* subsystem (Figure 3-1); they are separated to minimize the number of feedback loops during execution. The feedback loops are identified in the design structure matrix representation of the *Modeling* segment. For a given design, the modules are executed along the diagonal, starting at the upper left. A connection between

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two modules above the diagonal is a feed-forward flow of design data; a connection below the diagonal is a feedback flow of design data. Feedback loops remain unavoidable between the *avionics, power* and *rover hardware* modules. Subsystem modeling methods, assumptions and validation techniques are detailed in the following sections for *Rover Vehicle, Power, Autonomy,* and *Cost.* More information about the other is provided in [Lamamy, 2004].

3.6.1 Rover Vehicle Subsystem

The *Vehicle* subsystem includes the *mechanical speed* and *rover hardware* modules (Figure 3-1). t The *rover hardware* module has three components (Figure 3-5), namely structure, thermal and mobility, whose functionalities are described below. The *mechanical speed* module is discussed in the mobility section. Figure 3-5 illustrates the flow of variables within the *Vehicle* subsystem, and between *Vehicle* and other subsystems. The shared variables are represented using notations described in Table 3-5.
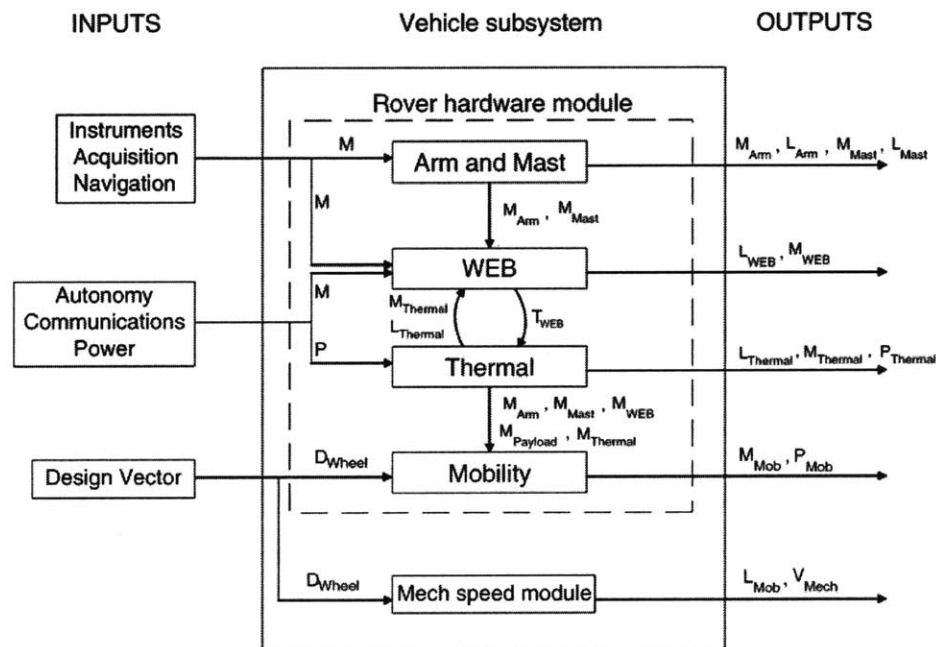
Figure 3-5 Program flow of the rover vehicle subsystem

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Table 3-5 Description of the notations used in Figure 3-5

Variable name	Units	Description
L_{sys}	m,m,m	system dimensions (lengh, width, height)
D_{wheel}	m	wheel diameter
M_{sys}	kg	system mass
P_{sys}	W	system power
T_{sys}	K	system temperature
V_{mech}	m/s	rover mechanical speed

Structure

The *structure* module sizes the arm, mast, and warm electronics box (WEB). The WEB is the body of the rover to which the arm, mast, and suspension are connected; it also isolates electronics and batteries located inside from the harsh Martian environment. In MSE, the WEB is designed to meet packaging and structural requirements. Its dimensions are driven by the payload volumes it must accommodate, both inside and outside. The thicknesses of its walls are sized to withstand bending and buckling under the most critical loads during generic launch and entry phases.

Thermal

The *thermal* module sizes the heating and cooling elements that maintain the temperature inside the WEB within the allowable temperatures of the components housed within. The allowable temperature range is typically from -40 degrees Celsius to +40 degrees Celsius [Stone, 1996 and Novak, 2003]. The thermal energy requirements for maintaining these temperatures, during day and night, are calculated based on heat transfer equations. The thermal control system implementation depends on the type of power source used. In the case of a solar-powered rover, the thermal elements are selected and designed to limit the power draw from the rover's batteries during the night. The thermal elements sized by the *thermal* module include an aerogel WEB insulation layer, radioisotope heating units (RHU) and, if necessary, extra heaters for extreme cold conditions. In the case of a RPS-powered rover, the *thermal* module mimics the strategy implemented in MSL; surplus heat generated by the RPS is transferred to the WEB through mechanically pumped fluid loops [Bhandari, 2005]. In this case, the sizable thermal elements include fluid loops, an integrated pump assembly, and hot and cold plates.

Mobility

The *mobility* module sizes the mobility hardware (including suspension, wheels, and motors), and performance (mechanical speed and ability to drive over rocks). The suspension model is currently limited to the rocker-bogie system patented by the Jet Propulsion Laboratory and used on Sojourner, MER, and MSL [Bickler, 1989]. The suspension of ESA's ExoMars rover is similar in design, such that ExoMars-type rovers can be simulated satisfactorily in MSE [ESA, 2002]. Other types of mobility systems are being added, including four wheel, legged, and hybrid legged-wheel systems [McCloskey, 2007]. The suspension is designed structurally as a truss supporting bending and buckling loads.

The largest diameter rock that a rocker-bogie rover can drive over is one to one and half times the wheel diameter. In this thesis, the rover mechanical speed is defined as the linear speed of a rover driving on a flat terrain at its maximum speed without using on-board navigation [MSL, 2006]. For real rovers, the mechanical speed is subject to trade-offs with other subsystems; it depends, for example, on the amount of power that designers are willing to allocate to driving as opposed to performing other activities, such as scientific analyses.

Figure 3-6 shows the speed of several rovers as a function of their wheel diameter. Rovers that have operated on or have been designed to operate on Mars are represented by squares. Testbed rovers operated on Earth are represented by circles. The solid line is a linear approximation of mechanical speed as a function of wheel size for Mars rovers; the dashed line is the same function for Earth testbeds. The comparison of the two speed laws shows that Mars rovers have been designed with conservative speeds. The main reason is that, as opposed to Earth testbeds, the power available to Mars rovers is very limited.
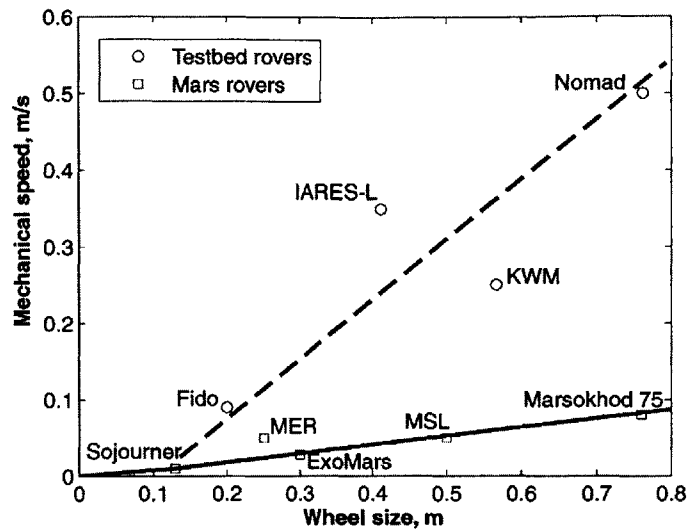
Figure 3-6 Mechanical speed as a function of wheel diameter for Mars rovers and

Earth testbeds

References: MER [Roncoli, 2002], Sojourner and MSL [Muirhead, 2004]; ExoMars

[van Winnendael, 2005]; Marsokhod 75 [CNES, 1992]; FIDO [Volpe, 2000]; Nomad

[Zakrajsek, 2005]; IARES-L and KWM [RMVEI, 2002]

The decision was made to model mechanical speed as a linear function of wheel diameter based on a curve fit to the Sojourner, MER, MSL, ExoMars, and Marsokhod 75 data points, as shown by the solid line in Figure 3-6. The first reason for this decision was that, in MSE, the wheel diameter is already the key scaling factor of the whole mobility system. The second reason was that this approach enables the calculation of the mechanical speed independently from the other rover system properties calculated in the *rover hardware* module (Figure 3-1); the early execution of the *mechanical speed* module greatly simplifies the input-output flow for the remaining modules. However, a consequence of this decision is that the power subsystem is sized to meet, if possible, the power demands of all other subsystems. Actual rovers are traditionally designed with the reverse approach; subsystems are sized according to the limited rover power available. The implementation of this latter approach would require a rationale for distributing the power budget among subsystems and would create more feedback loops in execution of the models. From a systems engineering perspective, the former approach is easier to implement.

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3.6.2 Power

As mentioned in the previous section, the *Power* subsystem is designed to satisfy the power demands of all other subsystems. The *Power* subsystem is composed of a power source and batteries. The type of power source is a design variable; the user chooses to power a rover either with solar panels or with a RPS. Both Sojourner and MER used solar panels, whereas the MSL current baseline uses a RPS. The type of RPS modeled in MSE is the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) used on MSL. One MMRTG provides 125 watts of continuous electrical power [Balint, 2005]. Contrary to a solar power system, the power output of a MMRTG is independent of latitude, season, and time of day. In both the solar and RPS cases, the power subsystem is sized using end-of-mission power output values.

In MSE, the peak and average power requirements are calculated for a typical *driving sol*. The underlying assumption is that a sol during which the rover is traversing imposes the largest demand on the power system. This assumption will need to be reviewed as acquisition tools and scientific instruments on future missions become more sophisticated and power demanding. In both the solar and RPS cases, a typical driving sol includes the following activities: sensing, path planning, driving, communicating, battery charging, heating, and nighttime stand-by. Energy and power requirements are calculated for each of these activities. The power source is sized to provide the energy required for the sol (i.e. the average power requirement); the batteries are sized to supplement the primary power source during peak power demands and, if needed, nighttime power.

3.6.3 Autonomy

In MSE, the *Autonomy* subsystem is the interface between the rover design and its exploration capabilities. The subsystem has two calculation modules, *autonomy traverse* and *autonomy exploration*. The *autonomy traverse* module uses rover hardware characteristics, such as mechanical speed and rock clearance, to calculate surface traverse capabilities. The *autonomy exploration* module uses this information to evaluate scientific and exploration performance based on the exploration itinerary defined by the user in the science vector. Exploration and scientific metrics calculated by the *autonomy exploration* module include total distance traversed and number of samples analyzed during the mission. The rover exploration of the surface is

decomposed into a four step routine: site reconnaissance, sample approach, sample acquisition and analysis, and site-to-site traverse (the activities performed by the operations team are not listed) [Erickson, 2002]. Site-to-site traverse and sample approach are activities related to the design variables processing efficiency and sample approach autonomy, respectively. The next paragraphs describe in detail these two activities and how they are modeled in MSE; Chapter 4 discusses the value of increasing processing efficiency and approach autonomy for future missions.

Site-to-Site Traverse

Site-to-site traverse is the activity of driving between sites selected by the Earth science team; site-to-site distances range from tens of meters to kilometers. The activity is modeled after MER operations [Biesiadecki, 2005b]; the traverse is modeled as a succession of two driving modes, a *blind drive* mode and an *autonomous drive* mode. During a blind drive, a rover follows a trajectory planned and commanded by the operations team based on the panoramic images the rover sent at the end of the previous sol; this type of drive is referred to as *blind* because the rover follows the commands of the operations team without using its on-board navigation capabilities. During a site-to-site traverse, a rover executes a blind drive on a daily basis. In MSE, the speed at which the blind drive is performed is the full mechanical speed, in real operations the rover would be operated at a lower speed for safety reasons. The distance over which the operations team can command a blind drive is limited by the horizon visible on pictures from navigation and panoramic cameras; the firm surfaces found on the plains of Gusev crater often allowed for blind drives of up to 70 meters [Biesiadecki, 2005b].

Once the rover has finished the blind drive, and if it has the time and energy to do so, it continues in an autonomous drive mode. During the autonomous drive the rover uses its on-board navigation sensors to plan a path on its own; as a consequence, it moves at a slower speed than during a blind drive. The autonomous drive is a succession of *plan-move cycles*. During terrain sensing and path planning phase, the rover does not move. In MSE, the path planning task is modeled after MER operations [Goldberg, 2002]. The duration of the planning task, T_{plan}, is the sum of the terrain image acquisition duration T_{acq}, and of the image and navigation map processing duration T_{proc}.

$$T_{plan} = T_{acq}^{MER} + T_{proc} \tag{3-8}$$

The image acquisition task takes approximately nine seconds for MER [Goldberg, 2002]. This duration is likely to stay the same for future rover missions, such as MSL, which use Hazard Avoidance Cameras (HazCam) similar to MER ones. The processing time, however, is sensitive to the rover *processing efficiency* (η_{proc}).

$$T_{proc} = \eta_{proc} T_{proc}^{MER}$$

$$\eta_{proc} = \frac{N_{MIPS}}{N_{MIPS}^{MER}} \frac{T_{alg}}{T_{alg}^{MER}} \tag{3-9}$$

In this thesis, a factor called processing efficiency captures improvements, relative to MER performance, in processing speed N_{MIPS} and algorithm execution time T_{alg}. At the beginning of MER operations, it took 18 seconds to process a terrain image and to create a navigation map with the MER RAD6000 processor [Goldberg, 2002]. Processing time will be shorter for MSL, which is equipped with a RAD750 processor; the processing speed of a RAD750 can be up to 10 times that of a RAD6000 if it is supported by appropriate data distribution architecture.

During the driving phase of the plan-move cycle, the rover drives forward the equivalent of half a rover length, D_{cyc}; the driving speed is the rover mechanical speed. The two-phase cycle is then repeated as long as the rover has the energy and time to do so during a sol. The autonomous speed, V_{auto}, is defined as the rover speed averaged over a cycle.

$$T_{moving} = \frac{D_{cycle}}{V_{mech}}$$

$$V_{auto} = \frac{D_{cycle}}{T_{moving} + T_{planning}} \tag{3-10}$$

The MER traverse activity also used a third type of driving mode involving visual odometry [Biesiadecki, 2005b]. In MSE, visual odometry is aggregated with the processing of the terrain image and navigation map; the rover is assumed to run visual odometry every 10 plan-move cycles in order to check for wheel slippage along the traverse. Visual odometry is a critical capability for the sample approach activity which requires accurate positioning of the rover with respect to a science target.

Sample Approach

The sample approach activity involves driving short distances, ten meters or less, and positioning the rover and its instruments correctly with respect to science targets (e.g. a rock) identified by the science team in the site reconnaissance pictures [Erickson, 2002]. In MSE, sample approach is simply modeled as an activity that takes either three sols with state-of-the-art autonomy, or one sol with advanced autonomy. Contrary to the traverse activity, the sample approach is not decomposed into sub-tasks.

The state-of-the-art sample approach autonomy is defined as that implemented in MER as of 2005. With this level of autonomy, MER uses at least three sols to approach and place an instrument on a pre-defined target [Huntsberger, 2005]. The first sol is used to traverse a path to a safe position using a path planned by the operations team on Earth. At the end of the traverse, an image of the science target is taken; this image is analyzed to determine if another short drive is needed to bring the target within the work-volume of the arm. The path is then uploaded to the rover and executed on the second sol. At the end of the second sol traverse, the target is imaged again and an arm trajectory is planned for the third sol to bring the instrument in contact with the science target. The advanced autonomy is defined as the improved autonomy that would enable sample approach in only one sol (by reducing human-in-the-loop decision points). The Jet Propulsion Laboratory is currently working on a project, Single Command Approach and Instrument Placement (SCAIP) [Huntsberger, 2005], to achieve this autonomy capability.

3.6.4 Cost

In this section, the MSE cost model is described and the mass-based cost estimating relationship for pricing the formulation and development of rover missions is derived.

Cost breakdown

The cost of a rover mission is decomposed into three components: formulation and development, power, and operations. The formulation and development cost includes all costs from pre-Phase A through Phase D including launch cost but without including costs related to the rover power system. Engineering trade-offs related to science payload capability, rover size and mass are captured in the formulation and development cost. The cost of the rover power subsystem is calculated independently from the development cost in

order to capture trade-offs related to the power source selection (RPS vs. solar). The operations cost covers mission Phase E but does not include scientific data analysis. The operations cost captures trade-offs related to mission duration and is calculated on a per-sol basis. The NASA budget request for the fiscal year 2005 [NASA, 2005] requested $26.6M for the operations of the two MERs during 2004, which is equivalent to $1.1M per rover per month. The five month extension announced in April 2004 was quoted as $15M, which is equivalent to $1.5M per rover per month [MER, 2004]. Accordingly, in MSE, the average operations cost per month of a rover is set to $1.25M.

Formulation and development cost

The formulation and development cost is estimated using a parametric cost model based on total rover mass. Other cost models use mass estimating cost. In JPL's Parametric Mission Cost Model, the spacecraft dry mass is the only parameter used to calculate spacecraft mechanical build-up cost [Morse, 2006]. The MSE parametric relationship is derived from cost and mass data from Sojourner, MSL, and that of designs studied at JPL by Team X [Wilson, 2005]. Table 3-6 provides the list of reference rover missions used to build the parametric cost relationship.

Table 3-6 Reference missions

Missions	Sources
Sojourner	[Shirley, 1995]
MSL 2007	NASA budget request for 2007
MSL 2008	NASA budget request for 2008
Small Rover, MER-C, MSL-M, AFL Option 2	[Wilson, 2005]

MER is not used as a reference because the cost of a single-rover MER mission is speculative. Wilson et al. [Wilson, 2005] provide data about two additional rover mission concepts called MSL MHP and AFL 2003 but they are not used as reference points because these missions assume a high level of reusability in hardware and software. Figure 3-7 shows the formulation and development cost of the reference missions as a function of rover mass, as well as the interpolated cost estimating function (Equation (3-11)). Figure 3-8 shows the divergence between the reference costs (x-axis) and costs modeled with the cost estimating

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function (y-axis). Equation (3-11) is the cost estimating relationship for mission formulation and development cost as a function of total rover mass; the cost is expressed in million dollars.

$$C_{mission}^{A-D} = 15.4\left(M_{rover}\right)^{0.67} + 85 \tag{3-11}$$

Several comments must be made regarding this cost estimating relationship. First, except for Sojourner whose cost is known, all other reference points used in Figure 3-7 were priced by JPL (Team X) cost models. Hence, the MSE cost estimating relationship is in fact a benchmark to Team X cost models. As mentioned in Section 3.2, Team X cost model does not use parametric relationships, but a grassroot approach enhanced with expert input. Second, the current formulation and development cost model only captures variations in rover hardware design; it does not capture variations in other aspects of mission design including software architecture, launch opportunities and transfer trajectories. The decision was made not to include a software cost component because of the difficulty involved in assessing software cost in pre-Phase A. Instead, the tool has been used to assess the appropriate budget that should be allocated to some aspects of software development (Chapter 4).

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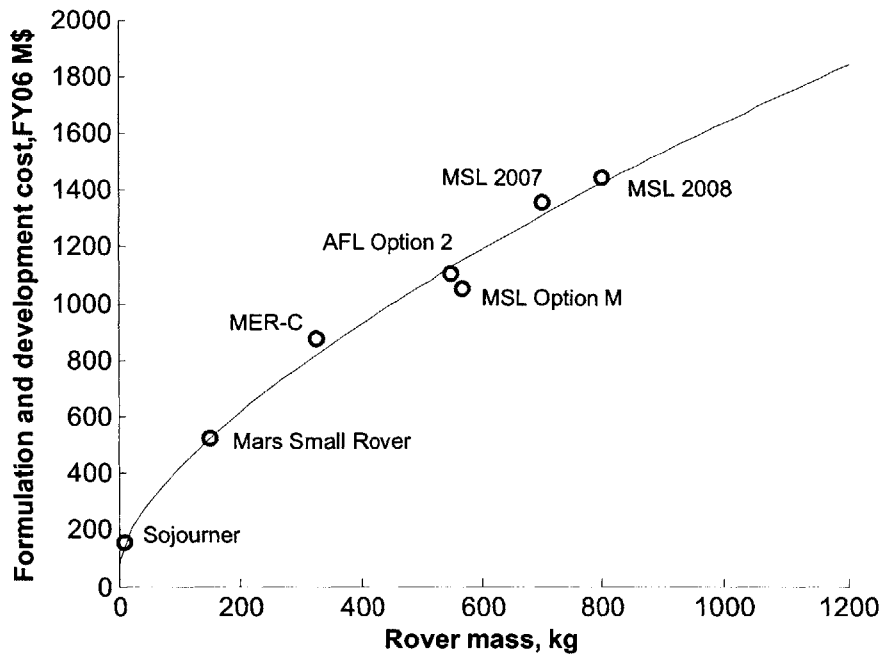
Figure 3-7 Cost estimating relationship for formulation and development cost
(without rover power cost) as a function of rover mass
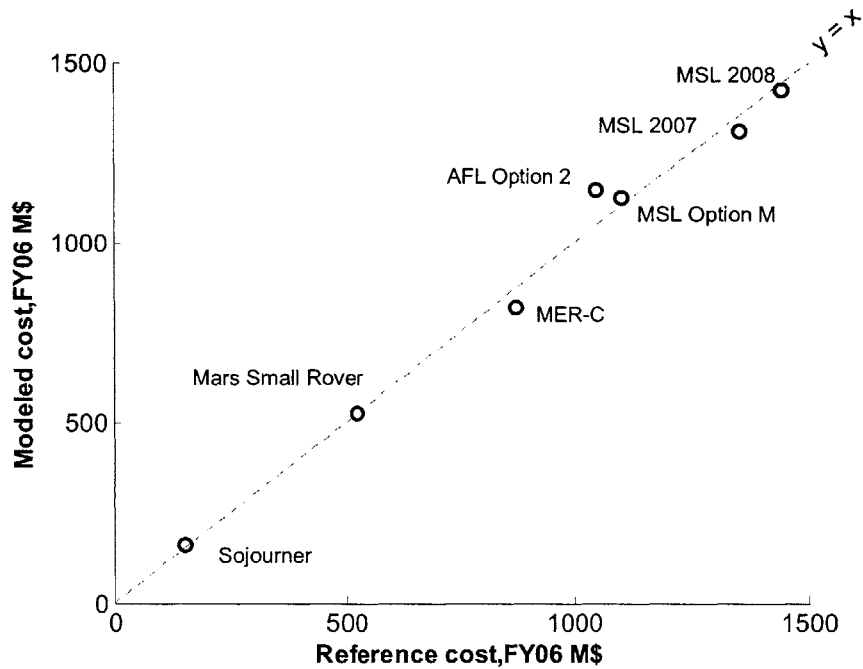
Figure 3-8 Comparison of reference and modeled formulation and development costs

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3.7 Validation

The engineering and exploration models were benchmarked against historical and Team X data. Engineering subsystem models were individually benchmarked with data from similar subsystems on existing rovers, and other spacecraft when applicable. The integrated engineering models are validated by comparing MSE simulations of Sojourner and MER with the actual designs, and by comparing MSE simulations of Team X mission concepts with Team X designs. The exploration model of MSE is benchmarked against MER operational data.

3.7.1 Engineering Models

Wilson et al. [Wilson, 2005] provided the science payload and rover mass of eight Mars mission concepts simulated in Team X. For each mission, the science payload was inputted into MSE to create a replicate rover design. The science payloads of Sojourner and MER were also used to create MSE replicas. Figure 3-9 and Figure 3-10 show a mass comparison of the MSE designs with the reference designs at the system and subsystem levels, respectively.

At the rover system level, the mass difference between the reference design masses and the MSE masses is on average 13%. At the subsystem level, the sizing of the thermal components of the MER-C and AFL Option 2 concepts leads to the largest discrepancies; the reason seems to be that MER-C and AFL Option 2 do not use the mechanically pumped fluid loops which are, in MSE, the baseline thermal control solution for RPS-powered rovers. Overall, the validation exercise shows satisfactory results across a wide range of mission concepts.
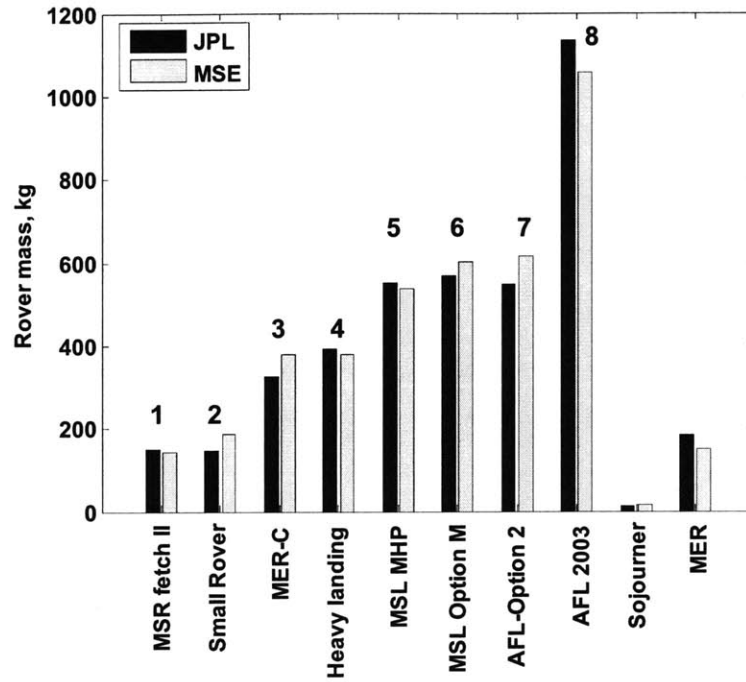
Figure 3-9 Benchmarking of MSE with Team X concepts and NASA missions. Comparison of rover system masses.
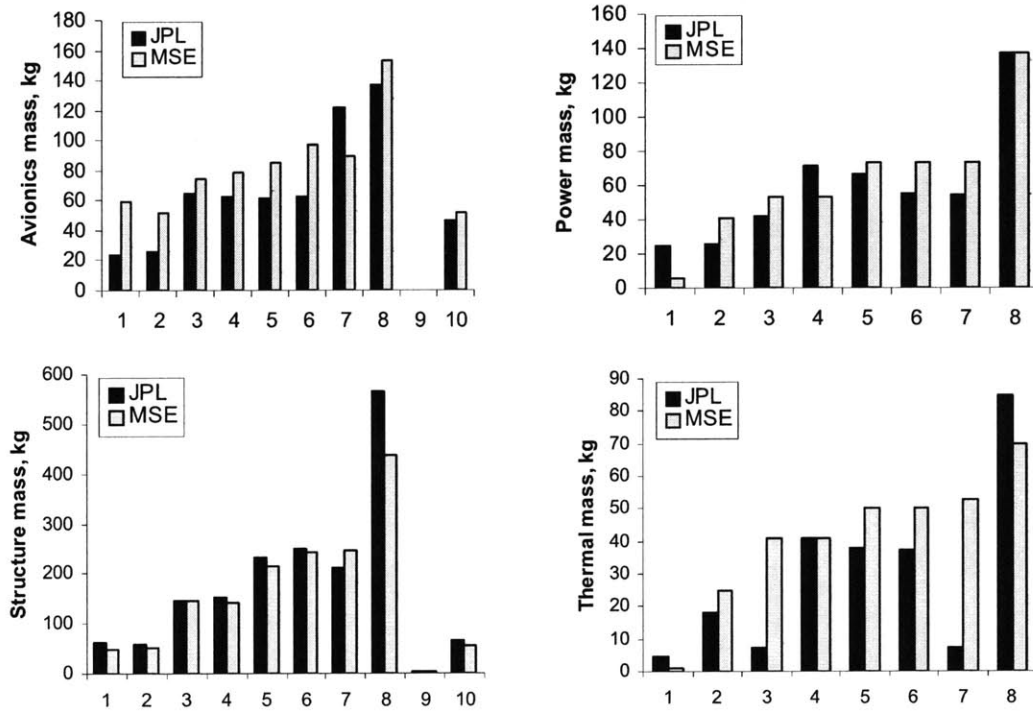
Figure 3-10 Comparison of rover subsystem masses

3.7.2 Exploration Model

Data from MER operations was used by McCloskey [McCloskey, 2007] to validate the MSE exploration model. The tool replicated the effects of rock coverage, drive modes, and speed on the odometry of the MER rovers (Spirit and Opportunity). The MSE tool also correctly reproduced the amount of time required to execute traverses and sample analyses. MER data was obtained from the MER Analyst's Notebook produced by the PDS Geosciences Node at Washington University [Stein, 2005]. The notebook provides four sets of operational data: rover motion counter, instrument usage, total odometry, and mission timeline. The first two data sets, which act as commands to the rover, were used to replicate the last two data sets, which are the operational outcomes. The rover motion counter and instrument usage data were used to estimate site-to-site traverse and number of samples per site parameters of the MSE science vector. The MSE exploration model was adapted to accept varying site-to-site distances, instead of a default one; it was then possible to capture the changing traverse commands sent to the MER rovers. A default assumption in MSE was that every sample is analyzed by the full instrument suite. In reality, not all MER instruments make measurements on every sample. To capture this effect, three instrument usage modes were introduced in MSE: panoramic instruments only; panoramic and contact instruments; and panoramic, contact instruments, and rock abrasion tool.

MER commands regarding site-to-site traverses, number of samples at each site, and instrument modes were inputted into the MSE tool to simulate MER operations. Simulation outputs were distance covered by each rover and mission timeline. The covered distance (odometry) and driving time were calculated based on terrain rock abundance, drive modes, and wheel slippage; sample analysis durations were calculated based on the instrument modes. Spirit's and Opportunity's operational and simulated profiles of odometry, as a function of time, are shown in Figure 3-11 and Figure 3-12. The match between the actual and simulated profiles is very satisfactory for both Spirit and Opportunity. Spirit's operational timeline shows a time lag with respect to that modeled in MSE; the reason is that MSE does not capture anomalies, such as the one that happened early in Spirit's operations and lasted 15 sols. Opportunity's example shows a good match in both odometry and time. This exercise has validated MSE's ability to correctly assess the effects of rock abundance, drive modes, wheel slippage, and instrument usage on mission operations.
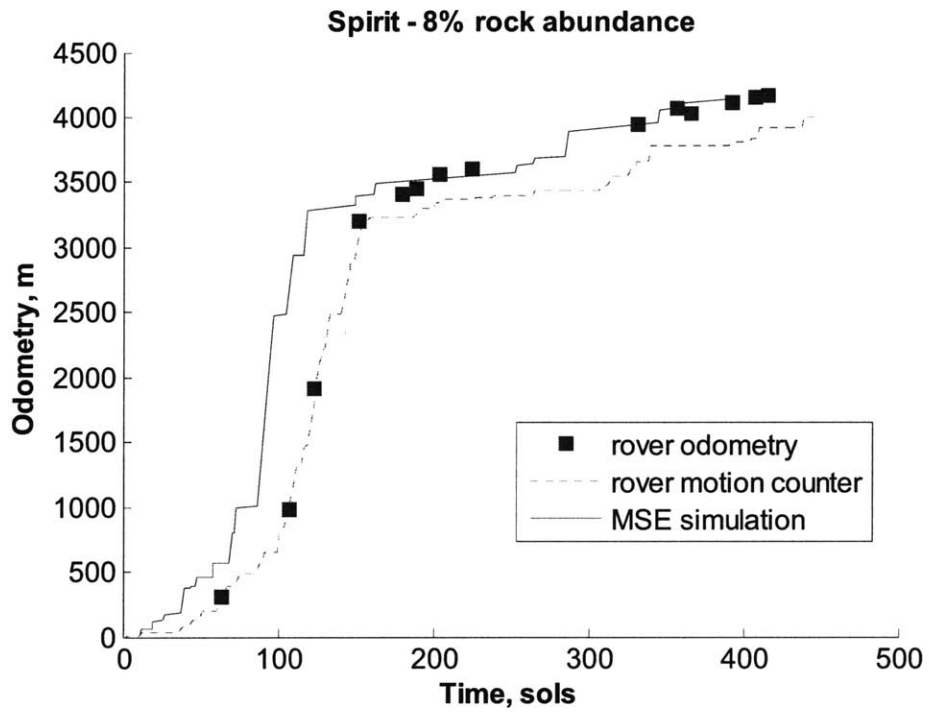
Figure 3-11 Spirit's profile of odometry and mission time
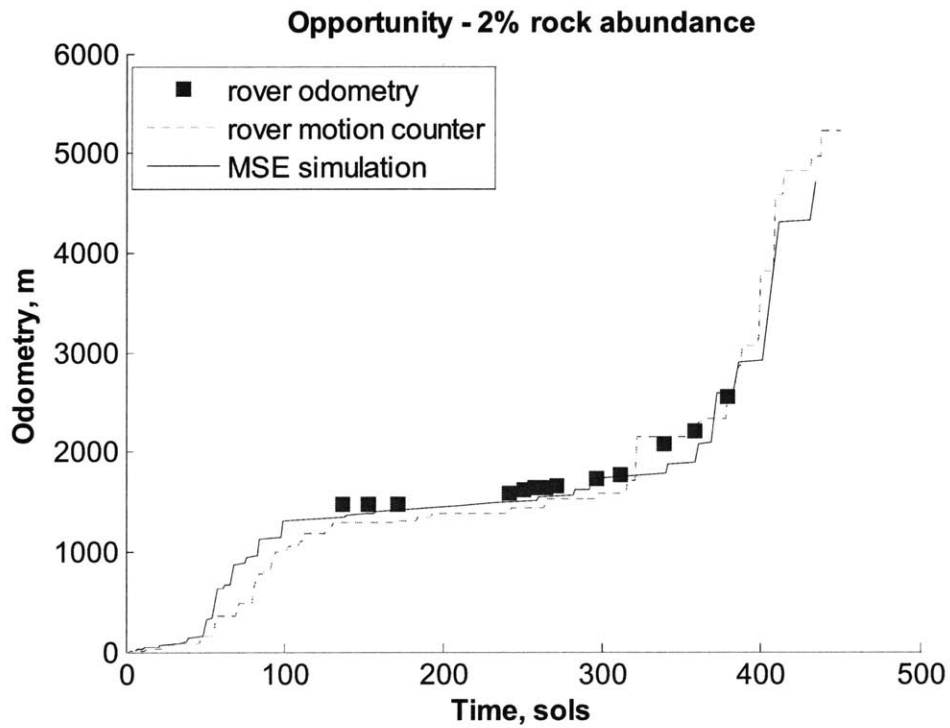
Figure 3-12 Opportunity's profile of odometry and mission time

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3.8 Rapid Evaluation of Mission Concepts

In this section, the modeling capabilities of MSE are demonstrated on the evaluation and analysis of a multi-rover mission concept, the scout-laboratory, which was formulated in Chapter 2 (*Concept Generation*). Using MSE, this evaluation exercise was completed by the author in less than two hours.

3.8.1 Concept Definition

In the scout-laboratory concept, *path planning* and *imaging* functions are assigned to a scout rover while science *measuring* functions are assigned to a laboratory rover (Section 2.3). In the example, it is assume the mission carries the MSL scientific payload. This function distribution results in a relatively small scout rover, carrying only navigation cameras and a panoramic camera, and a larger laboratory rover carrying all remaining instrumentation. In this study, the concept is modified in order to keep a balance between the two rovers.

In addition to path planning and imaging functions, the scout rover is assigned some measuring functions; in other words, the scientific instrumentation of the mission is split between the two rovers. The distribution of instruments between the two rovers is made according to the principle provided by Maier and Rechtin [Maier, 2002] and discussed in the *Modularity* section of Chapter 2:

Do not slice through regions where high rates of information exchange are required.

The equivalent of information in surface exploration is a scientific sample (e.g. rock sample). According to this principle, sample transfer from one rover to another should be avoided; instruments that share samples should be assigned to the same rover. In MSL, for example, the Sample Processing and Handling (SPAH) tool feeds processed samples to analytical instruments which include the Sample Analysis at Mars (SAM) instrument and the Chemistry & Mineralogy X-Ray Diffraction/X-Ray Fluorescence (CheMin) instrument. Therefore, in order to avoid sample transfer from one rover to another, the three instruments are allocated to the same rover. The downside of this decision is that it concentrates most of the instrumentation mass on one rover. Indeed, the SPAH, SAM, and CheMin represent almost three fourth of MSL's instrumentation mass; analytical instruments are in general a lot heavier and power consuming than remote and contact instruments. For this reason, the

SPAH, SAM, and CheMin are assigned to the laboratory rover and all remaining instruments to the scout.

During operations, while the laboratory rover analyzes samples at a site, the scout rover identifies a path that leads to the next site. Once there, the scout rover performs a reconnaissance of the site and starts measuring samples with its remote and contact instrument suite. When the laboratory rover has completed analyses at the previous site, it drives to the next site following the path already scouted. The scouted path could be marked physically on the Martian surface by using beacons or it could be identified on a map loaded on the laboratory rover. Even though the laboratory rover does not need to perform path planning activities, it still needs to check its location with respect to the path. It is assumed in this study that the localization task requires only ten percent of the localization and path planning effort normally required on un-explored terrain. As a consequence, the laboratory rover is able to travel from site to site at a faster rate than the scout rover. This, and the fact that both rovers perform scientific measurements in parallel, contribute to an increased availability and productivity of the scout-laboratory concept compared to a traditional integral rover (Section 2.3.3). In the next section, the multi-rover performance and cost are compared to that of the baseline single rover concept in the conduct of the MSL science mission.

3.8.2 Concept Evaluation

The baseline MSL, scout, and laboratory rovers are modeled using MSE; the default site-to-site traverse is 500 meters and the number of samples analyzed per site is ten. According to MSE calculations, the minimum-size MSL rover has a 0.45 meter wheel diameter and analyzes 129 samples in 700 sols. Its lifecycle cost is estimated at $1,160M.

Various scout and laboratory designs were evaluated with wheel diameters ranging from 0.25 meters to 0.45 meters, and mission durations ranging from 100 sols to 700 sols. The minimum-size laboratory rover has a 0.40 meter wheel; its traverse capability is 567 meters per sol and its measurement time is, on average, two and a half sols per sample. Although, the minimum-size scout rover has a 0.35 meter wheel, a 0.40 meter wheel rover is chosen because it matches the design of the laboratory vehicle and creates platforming opportunities

(rover platforms are discussed in Chapter 5). A 0.40 meter wheel scout rover has a traverse capability of 353 meters per sol and its measurement time is on average one sol per sample.

For site-to-site distances under two kilometers, the laboratory rover is the operational bottleneck. It is therefore the laboratory rover performance which determines the performance of the scout-laboratory rover team. Based on the default itinerary, it takes the scout-laboratory team 480 sols to analyze 129 samples; the scout-laboratory mission saved 220 sols compared to the single rover mission. The lifecycle cost of the scout rover, added to that of the laboratory rover, is $1,930M. This figure includes duplication of every system cost (two launches, two cruise systems, two EDL systems, the scout and laboratory rovers) because the two rovers combined are too heavy to be landed in the same EDL system. Operations costs are calculated for only one rover since both rovers are operated simultaneously and in the same region of Mars. Because the scout and laboratory vehicles are very similar, savings can be expected during their formulation and development. It is estimated that the cost of the second MER rover was 50% of what the first rover would have cost if it had been a single rover mission [Squyres, 2005]. Still, savings of 25% over the formulation and development of the scout-laboratory team are not sufficient for the concept to be competitive with the single rover option. More than 40% savings would be needed for the concept to be cost-effective. Moreover, mission success considerations also favor the single rover option because it only requires one successful launch and one successful landing instead of two.

This exercise demonstrated that, with the help MSE, advance mission study engineers are able to assess the benefits and costs of a mission concept in just a few hours. MSE is therefore of great value to mission concept developers and proposal managers who need to support their conceptual studies with performance and cost figures.

3.9 Rover Design Document

3.9.1 Objectives

The rover design document is new a collection of high level design relationships for Mars robotic rovers. For deep space missions, there has been little published work of design rules-of-thumb [Lamassoure, 2005], such as can be found for Earth orbiters. *Space Mission Analysis*

and Design (SMAD) [Larson, 1992] is a comprehensive resource for rules of thumb, empirical formulas, and algorithms for the design of low-Earth orbit, unmanned satellites. Some design guidelines provided in SMAD are broad enough that they can be applicable to deep space missions as well. For example, in MSE the design of the solar power subsystem is based on a design process developed in SMAD. Human Space Mission Analysis and Design (HSMAD) [Larson, 1999] dedicates a few pages to the design of crewed lunar rovers; in particular, it provides a design algorithm to rapidly obtain order-of-magnitude estimates of mass and power requirements for a pressurized rover. The intent of the rover design document is to provide similar resources for the particular case of Mars robotic rover systems.

The design document provides design rules of thumb and also references to articles relevant to the field of Mars rover design. The document is a collection of parametric relationships that help design and evaluate rover properties and performance (e.g. speed), both at the system and subsystem level, based on broadly defined scientific mission objectives. This collection of relationships has been compiled through the development years of MSE.

This document is intended for students who desire to understand the high level scaling laws of rover systems and science payload designers who need to measure the impact of their payload on a rover vehicle. This document can also serve as the starting point for the development of more elaborated rover system design tools, such as MSE.

3.9.2 System Level Relationships

The subsequent relationships size the rover system properties and performance based on rover scientific payload and wheel diameter.

Mass fractions

Wilson et al. [Wilson, 2005] provide a database of eight Team X rover designs (Figure 3-9), which are used to derive mass fraction relationships.

Payload mass fraction

Based on Team X designs, Sojourner and MER, the payload mass fraction $\alpha_{science}$ of a rover is between 8% and 16% of the total rover mass and it is on average 12%. Therefore, for a

given scientific payload mass $M_{science}$, including instruments and acquisition tools, the expected total rover mass M_{rover} is provided by the following relationship.

$$M_{rover} = \frac{1}{\alpha_{science}} M_{science}$$

$$8\% \leq \alpha_{science} \leq 16\%$$

(3-12)

Cost

Operations Cost

According to the NASA budget request for 2005 [NASA, 2005] and to [MER, 2004] the average operations cost rate of a rover is approximately $1.25M per month.

Formulation and development cost

The formulation and development cost, without power system development, of a rover as a function of mass is provided by Equation (3-9). As a reference, Kwan et al. [Kwan, 2005] discuss the cost modeling techniques employed at JPL. They also provide the costs of JPL's deep space missions launched between 1965 and 2005.

3.9.3 Subsystem Level Design

Detailed procedures for the design of rover subsystem have been developed in the author's previous work [Lamamy, 2004]. The key subsystem sizing relationships are summarized below.

Power subsystem

Solar power system

The procedure presented in SMAD for sizing solar panels is applicable to the design of rover solar panels with only one major modification. The solar panel design of a Mars surface vehicle must account for degradations due to deposition of Martian dust on the panels; over time, dust deposition contributes to the degradation of power output. The first 300 sols of Spirit operations show that dust deposition losses reach a maximum of 30% over time.

Figure 3-13 shows experimental data collected during Spirit operations as well as an exponential function, represented by a solid line, which matches experimental data.
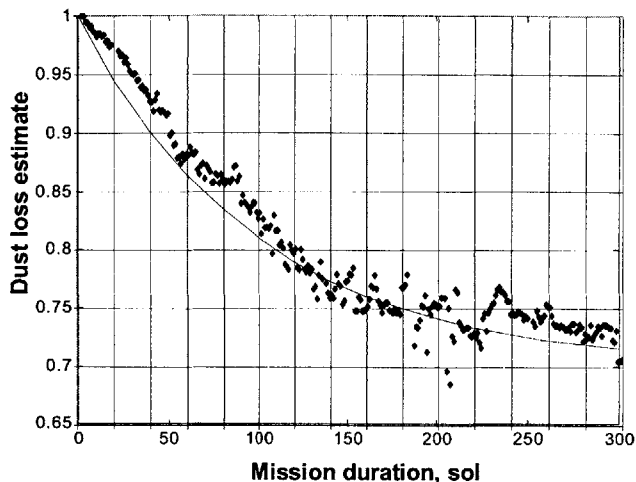
Figure 3-13 Power loss due to dust deposition on Spirit's solar panels

The equation for the exponential function which is the loss due to dust deposition L_{dust} as a function of mission duration T is given below.

$$L_{dust} = 0.7 + 0.3 \times e^{-T/100}$$ (3-13)

In this equation, the mission duration T is expressed in sols.

Radioisotope power system

Balint [Balint, 2005] provides detailed information regarding the current RPS designs. Table 3-7 summarizes the chief properties of Multi-Mission Radioisotope Thermoelectric Generators (MMRTG) and Stirling Radioisotope Generators (SRG).

Table 3-7 Characteristics of various radioisotope power systems

	MMRTG	Upgraded MMRTG	SRG
Power per unit, We	125	160	116
Mass per unit, kg	44	40	34
Quantity of Pu^{238}, kg	4		1

The quantity of Pu[238] used by a RPS system impacts its cost significantly since the cost of one gram of Pu[238] is estimated at $2000 [Balint, 2005].

Mobility

Aspect ratio

For a rocker-bogie suspension, the wheelbase and track are approximately the same length. Using the wheel diameter as a unit length, the wheelbase and track of a rover are between four and five times the wheel diameter.

Rock clearance

A rover equipped with a rocker-bogie suspension is able to drive over a rock whose size is less than one to one and a half times the wheel diameter. A rock distribution model developed by Golombek et al. [Golombek, 1997, 2002, 2005] calculates the abundance of rocks that are larger than a given size. Using this model, it is possible to determine the density of rocks that are larger than the surmountable rock size for a given wheel diameter.

Mechanical Speed

As mentioned in the previous MSE mobility section, traditional Mars rovers have been designed with conservative mechanical speeds. Figure 3-6 shows the speed of Mars rovers and research testbed rovers as a function of wheel diameter D_{wheel}. The linear approximation of Mars rover speeds V_{mech} is given in the equation below.

$$V_{mech} = 0.1 \times D_{wheel} \qquad (3\text{-}14)$$

Autonomous Speed

The autonomous speed of a rover is defined over a plan-move cycle. Using the notations introduced in Equations (3-8) and (3-10), the equation for the autonomous speed of a rover is given in Equation (3-15).

$$V_{auto} = \frac{D_{cycle}}{\dfrac{D_{cycle}}{V_{mech}} + T_{acq} + T_{proc}} \qquad (3\text{-}15)$$

The image acquisition and processing durations are provided by Goldberg et al. for the case of MER [Goldberg, 2002].

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$$T_{acq} = 9 \sec$$
$$T_{proc} = 18 \sec$$

(3-16)

Visual odometry is not taken into account in the processing duration of Equation (3-16). Visual odometry takes between two and three minutes on MER and can be performed every ten meters in slip check mode during long traverses.

Subsystem cost

In the early conceptual design phase, subsystem cost models often use cost estimating relationships. JPL's Planetary Mission Cost Model (PMCM) uses such relationships to calculate subsystem costs of a variety of spacecraft. Table 3-8 lists the parameters used in PMCM for subsystem cost estimating relationships [Kwan 2005 and Morse 2006]. SMAD also provides cost estimating relationships for most spacecraft subsystems. The subsystem cost breakdown of Team X designs provided by Wilson et al. [Wilson, 2005] can be used to benchmark the cost estimating relationships in the case of rover systems.

Table 3-8 Cost parameters used in the cost estimating relationship of PMCM

Subsystems	Cost parameters
Attitude control system	mass, heritage of design
Command and data handling	processor speed, number of instruments
Power	power source type, solar array area, number of RPS, battery size
Propulsion	propulsion type, specific impulse, mass
Structure	mass, number of types of mechanisms, number of mechanisms
Communications	power, antenna diameter, bands, mass
Mechanical build-up	rover dry mass
Software	number of advanced instruments

3.10 Conclusions

The description of MSE proved that MSE is a mature rover system design tool useful for pre-Phase A analyses. The benchmarking of MSE with other tools showed that MSE offers

unique modeling capabilities, especially its ability to rapidly explore a large trade space of rover designs. The validation exercise demonstrated the MSE engineering and exploration models have sufficient fidelity for pre-Phase A analyses. The scout-laboratory case example showed that MSE can effectively be used to rapidly assess the performance and costs of a given rover mission concept.

New MSE capabilities are currently being developed. The mobility subsystem has recently been expanded to capture suspensions other than the traditional rocker-bogie, including tracks, four wheel suspension, legged mobility, and hybrid mobility [McCloskey, 2007]. In addition, a drill model has been created to understand the impact of equipping MER and MSL class rover systems with drills, both on the engineering design and on scientific capabilities. MSE will be used to analyze the trade-off between sample accessibility and sample analysis capability. For a given payload allocation, the mass allocated to drills, to reach scientifically worthy underground layers, is in competition with that allocated to scientific instruments, to analyze the samples collected.

Chapter 4

Value of Autonomy for Surface

Exploration

The description of a new method to assess the value of autonomy infusion in Mars rover operations is provided in this chapter; the method is applied to two functions of surface exploration: *site-to-site traverse* and *sample approach* (*Autonomy*, Chapter 3). Sample approach is the subject of current autonomy development on the Mars Exploration Rovers (MER) for future use on the Mars Science Laboratory (MSL) [Udomkesmalee, 2005].

4.1 Previous Research

In previous work, the author proposed an approach to calculate the maximum investment for autonomy infusion in a given application [Lamamy, 2004]. The costing approach was not based on an evaluation of the effort involved in autonomy development; instead, it was based on an evaluation of the returns generated by improved autonomy. A system design model (MSE) was used to calculate the ratio of scientific return per dollar for state-of-the-art rover missions. The costing rationale was that improved autonomy is valuable if it increases this ratio by a given amount. Thus, a maximum autonomy infusion budget can be calculated based on a target return on investment ratio and on an estimate of returns generated by improved autonomy. The method proposed in this chapter is an enhancement of this first approach; it is more rigorous and has higher fidelity.

The JPL START (Strategic Assessment of Risk and Technology) research group has made significant contributions in the rationalization of strategic technology investments for future missions [Elfes, 2006]. Part of the group's efforts has focused on the creation of methodologies for guiding the development of future autonomy technologies. In one proposed methodology [Lincoln, 2003], a range of surface exploration functions was selected and the value of improving autonomy for each of these functions was assessed. The best autonomy application was then identified based on considerations of probability of success, performance, and costs (technology development difficulty). Although useful in its own right, this methodology is not easily transitioned to study autonomy infusion in other functions and on other missions. Performance was evaluated with respect to a utility function that was specific to the rover mission being studied; the creation of utility functions is often either subjective or based on intensive multi-attribute utility analyses. In addition, risk assessment relied on specific experimental and field data from the FIDO test rover operations, but such extensive operational data of analogous systems is not always available.

Another proposed methodology [Howard, 2003 and 2004] evaluated the relative strengths of autonomy technologies by quantifying their benefits in terms of mission scientific return. Like in the first approach proposed by Lamamy, Howard et al. derived the relevance of autonomy technologies from their impact on mission goals; in their analyses, maximizing scientific return was the primary objective of exploration missions. Thus, Howard et al. considered the benefits of autonomy with respect to three attributes of scientific return: *quantity*, *quality*, and *range*. Influence model diagrams were used to quantify the impact of autonomy on each attribute. The scenario parameters of their influence model are the same as those used in MSE: number of samples analyzed per site, site-to-site distance, and mission duration. However, compared to MSE, influence diagrams provide qualitative, rather than quantitative, assessments of autonomy benefits. Howard et al. use the *number of sols saved* in surface operations as a measure of autonomy impact on a mission. The method described in the next section goes one step further; reductions in operations are linked to cost savings which provide a first estimate of the value of autonomy technology.

4.2 Proposed Method

This work builds on previous methodologies to improve the quantitative assessment of the value of autonomy in future exploration missions. The resulting method is referred to, in this study, as Autonomy Valuation Method (AVM).

4.2.1 Function value and technology value

Like in the methodology presented by Howard et al., the value of autonomy infusion in a function is linked to an increase in scientific return. However, AVM distinguishes two factors necessary to the value of autonomy at the mission level ($V_{auto}^{mission}$): value of the function in the mission context ($V_{function}^{mission}$) and value of autonomy infusion in the function context ($V_{auto}^{function}$). Autonomy at the mission level is valuable if the function in the mission context *and* autonomy in the function context are valuable; in other words, $V_{auto}^{mission}$ behaves as the product of $V_{function}^{mission}$ and $V_{auto}^{function}$.

$$V_{auto}^{mission} = V_{function}^{mission} \times V_{auto}^{function} \tag{4-1}$$

The first factor measures the potential of the improved function to increase scientific return. The second factor is a ranking of autonomy with respect to other technological solutions capable of improving the function.

4.2.2 Pricing of scientific return

The application of AVM in this thesis is limited to autonomy technologies which increase the *quantity* of scientific return. It is difficult to place a monetary value on an increase in scientific return (e.g. one extra sample analyzed). A proposition made in this thesis is that the value of scientific return can be measured in terms of operations cost.

In this method, the costing principle is that the maximum worth of a technology, which improves return, is the worth of other solutions which improve return equally. In exploration missions, a simple solution to increase scientific production is to extend operations. Because mission operations have a known cost, they serve as a very useful benchmark to evaluate the maximum worth of other solutions that increase scientific production. Consider, for example, an improved autonomy technology that would enable a

rover to collect five extra samples within its baseline mission duration; with state-of-the-art technologies, the collection of five samples requires one month. Therefore, improved autonomy generates the same return as one month of operations; assuming an operations spending rate of $1.25M a month (*Cost*, Chapter 3), the improved autonomy technology is worth at most $1.25M. In other words, the maximum investment allocation for the development of this autonomy technology should be $1.25M. The significance of this result is not the exact value of the investment but its order of magnitude. This autonomy technology is valuable if the calculated maximum investment is significantly higher than the expected development cost, estimated based on experience.

The same pricing approach is used to assess the worth of autonomy technologies with respect to mechanical solutions; the site-to-site traverse example described subsequently is an illustration of this approach. To a certain extent, this pricing approach is analogous to replicating portfolio methods used in finance.

4.2.3 System design model

The application of AVM requires a system design model capable of calculating the impact of technology on system design and operations. The sophistication of the models depends on the type of technology and functions studied. In the sample approach example, a simple surface exploration model is sufficient to obtain a first estimation of autonomy benefits; however, MSE, which is a more sophisticated rover modeling tool, supports the analysis with sensitivity calculations.

4.2.4 Method description

Several assumptions are made regarding the use of this method. Users have identified a priori a surface exploration function which could be improved from a state-of-the-art to an advanced level with infusion of autonomy. They use this method to decide whether it is worth developing new autonomy technology to improve this function. Lastly, the users have a reasonable idea of the order of magnitude of the expected autonomy development cost. AVM is organized in four steps; financial analogies are provided next to the title of each step.

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1. **Assess function value – Assess market value**

The purpose of this step is to quantify the potential savings generated at the mission level by the improved function. Only functions with sufficient savings are considered for further analysis. If a satisfactory evaluation cannot be completed in this step, the process is repeated in the last step (step 4).

2. **Identify competing technologies – Identify competitors**

The purpose of this step is to identify technologies that could improve the function to its advanced level. These technologies serve as benchmarks in the next step.

3. **Compare value of autonomy with respect to competing technologies – Set target cost for autonomy product**

The system design model is used to compare the performance of autonomy and competing technologies and to calculate costs of developing competing technologies. The cost of competing technologies of equal performance is the maximum recommended budget for autonomy infusion.

4. **Verify relevance of autonomy technology in mission context – Compare market rate of return with that of other markets**

The evaluation process of the first step is repeated in light of the information gathered regarding autonomy performance and cost. The relevance of autonomy infusion for the given function is assessed in the mission context.

4.2.5 Limitations of the Method

In the current method implementation, risk factors are not explicitly taken into account when comparing technologies; risk remains a qualitative, user judgment. In addition, the benefits of a technology are evaluated in the context of a given mission; the potential for technology feed-forward to future missions is not captured.

4.2.6 Software Cost in MSE

The MSE development and launch cost model is an cost estimating relationship based on rover mass (*Cost*, Chapter 3). As a consequence, this cost model fails to capture cost variations coming from modifications to the baseline software architecture. This is the reason why the method does not directly compare the cost of autonomy development with that of competing technologies, but instead derives an autonomy budget recommendation

from the cost of competing technologies. The difficult problem of costing software development during early conceptual phases is substituted by the easier one of costing known competing technologies.

4.3 Sample Approach and Site-to-Site Traverse

Sample approach and *site-to-site traverse* are two surface exploration functions described in the *Autonomy* section of Chapter 3. Sample approach involves driving short distances within a site, ten meters or less, and positioning the rover and its instruments correctly with respect to science targets (e.g. a rock). Site-to-site traversing is the activity of driving between sites selected by the science team; site-to-site distances range from tens of meters to kilometers.

4.3.1 Autonomy infusion for increased availability

The purpose of infusing autonomy in sample approach and site-to-site traverse is to reduce the amount of time needed to perform these activities. Hence, autonomy infusion improves scientific productivity by means of increased rover *availability*; the two other aspects of scientific return, quality and range, are not directly affected by sample approach and site-to-site autonomy. The availability (A) of a rover is defined in the *Concept Generation* section of Chapter 2 as the fraction of time a rover spends performing scientific activities (*imaging* and *measuring*) over the whole mission duration (Equation (4-2)).

$$A = \frac{T_{imaging} + T_{measuring}}{T_{traveling} + T_{imaging} + T_{targeting} + T_{approaching} + T_{analyzing} + T_{comm}} \quad (4\text{-}2)$$

where

$$T_{traveling} = T_{moving} + T_{sensing} + T_{mapping} + T_{planning} + T_{locating} \quad (4\text{-}3)$$
$$T_{analyzing} = T_{acquiring} + T_{handling} + T_{measuring}$$

The notation $T_{process}$ refers to the execution time of the *process* activity. The *imaging* and *measuring* processes are the two value-related processes of rover operations. Improved sample approach and site-to-site traverse increase availability by reducing $T_{approaching}$ and $T_{traversing}$, respectively.

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4.3.2 Processing efficiency in site-to-site navigation

The notion of *processing efficiency* (*Autonomy*, Chapter 3) is a measure of how fast a rover is able process navigation calculations involved in site-to-site traverse. Processing efficiency η_{proc} has two factors which are on-board processing power N_{MIPS} and algorithm execution time T_{alg}. The MER design is used as a reference for processing power and algorithm execution time (Equation (3-3)).

$$\eta_{proc} = \frac{N_{MIPS}}{N_{MIPS}^{MER}} \frac{T_{alg}}{T_{alg}^{MER}} \tag{4-4}$$

Algorithm efficiency (T_{alg}/ T_{alg}^{MER}) is a relative measure of the efficiency of the navigation software and is, in this sense, a measure of site-to-site navigation autonomy (*Autonomy*, Chapter 3). Processing efficiency η_{proc} affects the time needed to process navigation images T_{proc}, and consequently, the overall planning activity duration T_{plan} (Equation (3-8)).

$$T_{proc} = \eta_{proc} T_{proc}^{MER}$$
$$T_{plan} = T_{acq}^{MER} + T_{proc} \tag{4-5}$$

4.4 Value of Sample Approach Autonomy

In this section, AVM is applied to the sample approach function in the context of MSL and ExoMars missions.

4.4.1 Current research

In MSE, the state-of-the-art level of sample approach autonomy is modeled after MER operations as of 2005 (*Autonomy*, Chapter 3). With this level of autonomy, a rover uses at least three sols to approach and place an instrument on a pre-defined scientific target [Huntsberger, 2005]. The three sol duration is primarily driven by the need for two communication cycles with Earth. Autonomy developers at NASA and ESA have been working on executing sample approach in a single sol; in this study, the single-sol sample approach capability defines the advanced level of sample approach autonomy. The Jet

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Propulsion Laboratory is developing a Single Command Approach and Instrument Placement (SCAIP) framework with the goal of demonstrating single-sol sample approach on MER [Huntsberger, 2005]. The Computer Science Laboratory of the University of Wales is working on the development of the same capability for implementation on ExoMars [Barnes, 2006].

In both cases, the argument for pursuing the advanced capability has been that it would maximize scientific return and enable a more efficient use of surface operation time [Huntsberger 2005 and Barnes 2006]. The authors, however, do not provide any quantitative analysis to support their claims and it is not a priori obvious that potential savings in mission operations and increased scientific return would offset the cost of developing advanced sample approach autonomy.

4.4.2 Method Applied to Sample Approach

AVM is applied step-by-step to the case of the sample approach activity.

1. Value of sample approach

The value of improved sample approach depends on the operation scenario, and more specifically, on the expected number of samples analyzed during the mission. Improved sample approach saves two sols of operations for every sample approach activity; assuming a baseline operations spending rate of $1.25M per month (*Cost*, Chapter 3), the improved function saves approximately $86K per successful approach.

The following paragraphs describe the application of the valuation method to MSL- and ExoMars-type missions. The results show that while advanced sample approach is certainly relevant for MSL-type missions, it is less critical for ExoMars-type missions.

2. Competing technologies

The sample approach task involves mostly on-board navigation and localization capabilities that no mechanical solutions can easily improve. The alternative to improving sample approach is to lengthen operations.

3. Autonomy value with respect to operations and relevance in the mission context

Because there is no mechanical alternative for improving sample approach, the third and fourth step of the method are combined.

MSL-type missions

In this analysis, a baseline MSL rover is defined with a 0.5 meter wheel, RPS power, state-of-the-art traverse autonomy, and the baseline MSL science package (*Mars Surface Explorers*, Chapter 1). MSE is used to model designs with state-of-the-art and advanced sample approach autonomy and with mission durations ranging from a reference of 668 sols (one Martian year) to 1028 sols, in increments of 30 sols. The *site-to-site distance* parameter is set equal to one kilometer and the *number of samples analyzed per site* equal to ten.

The scientific return and cost of the various rovers are represented in Figure 4-1. The mission cost (x-axis) does not include advanced autonomy development cost. The designs represented by dots use state-of-the-art sample approach autonomy, and those represented by squares used the advanced level. The MSL reference points with state-of-the-art and advanced autonomy are labeled *MSL soa* and *MSL adv*, respectively.
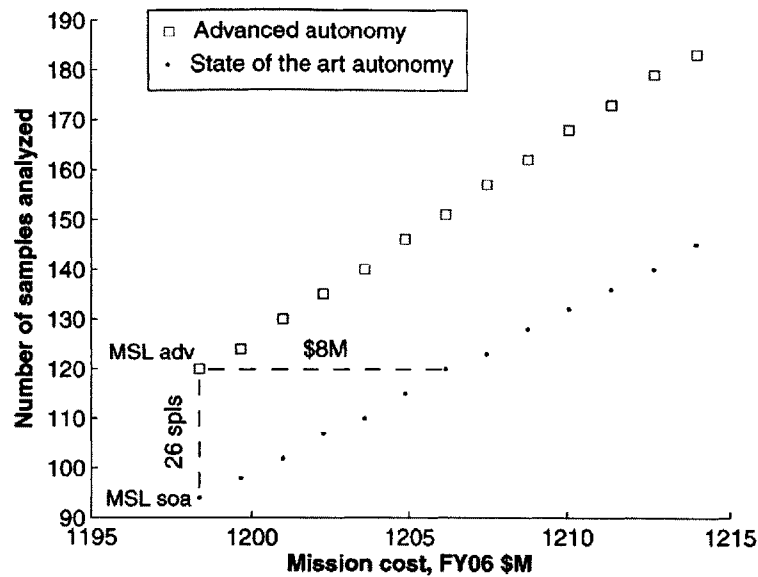
Figure 4-1 Benefits of sample approach autonomy for a MSL-type mission

Because autonomy-related costs are not captured in mission cost of Figure 4-1, the cost of advanced autonomy rovers is the same as that of the state-of-the-art rovers of equal mission duration. For example the two reference MSL missions (*MSL soa* and *MSL adv*) have the same mission cost in the figure.

In Figure 4-1, mission cost and scientific return increase linearly with mission duration. For this particular surface exploration scenario, the sample return rate is approximately four samples per month. The rate of return of advanced rovers is slightly higher than that of state-of-the-art rovers. Figure 4-1 indicates that *MSL adv* analyzes 120 samples; that is 26 samples more than *MSL soa*. For a state-of-the-art rover to return 120 samples, its mission duration must be extended by approximately 180 sols; this extension would cost almost $8M in operations. Thus, for this particular mission, the budget for developing sample approach autonomy should be at most $8M.

The derivation of this budget is sensitive to a number of parameters including the expected daily cost of operations, site-to-site distance, and number of samples analyzed per site. However, the important result of this short analysis is not the budget figure itself but the fact that it is almost an order of magnitude larger than the likely budget required for the development of advanced sample approach autonomy. To put this budget in perspective,

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$8M would represent 10% of the total budget for the MSL Focused Technology Program whose task is to develop very challenging technologies including the MSL EDL, the long traverse mobility system, and the sample processing and distribution tool [Caffrey04].

In order to quantify the sensitivity of the recommended budget to surface scenario parameters, the budget calculation process has been repeated for site-to-site distances ranging from 100 meters to two kilometers and for numbers of samples per site ranging from one to twenty. Figure 4-2 shows contours of constant number of samples analyzed by the *MSL adv* rover for these parameter ranges. Figure 4-3 shows contours of maximum autonomy budget development. The previous surface itinerary case of Figure 4-1, defined by a site-to-site traverse of one kilometer and 10 samples per site, is labeled *MSL* in Figure 4-3. This particular scenario is shown to be between the contour lines of $7M and $8M in Figure 4-3.
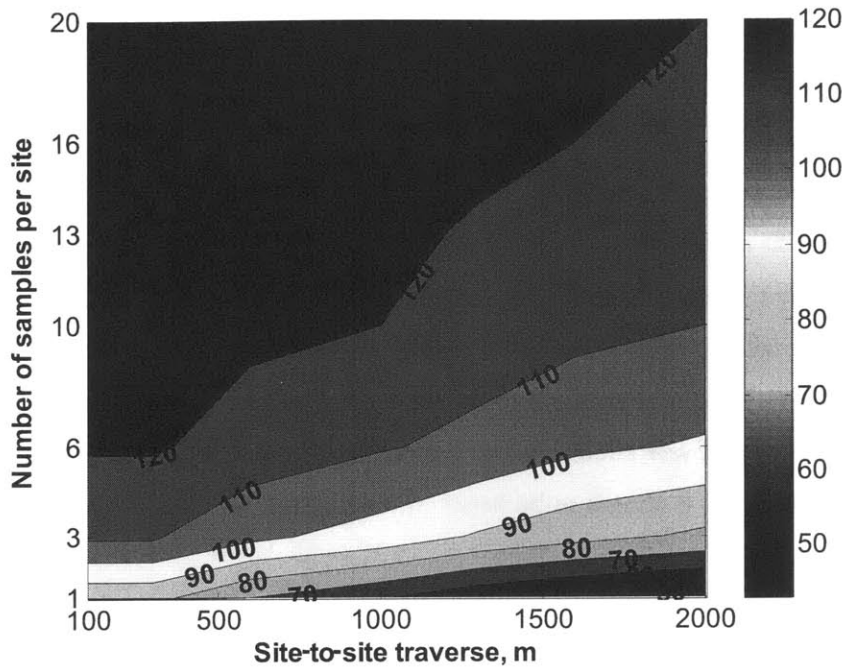
Figure 4-2 Contours of number of samples analyzed N_{spl} for MSL-type missions.
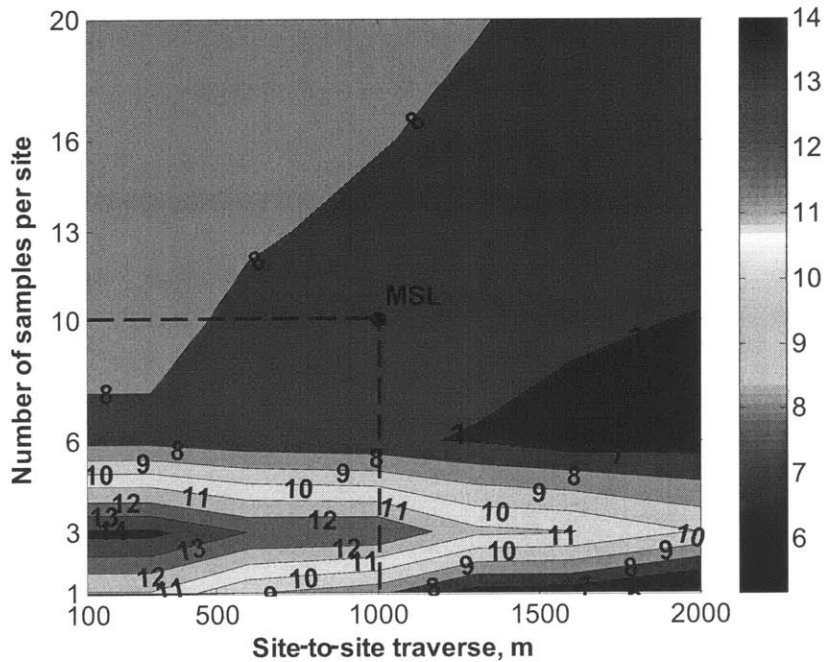
Figure 4-3 Contours of maximum autonomy development budget for MSL-type missions.
Budget contours are in FY06 $M.

As expected, the number of samples analyzed N_{spl} is highest when the site-to-site distance is short and the number of samples analyzed per site $N_{s/s}$ is high (higher left corner in Figure 4-2). However, it is surprising that the contour distribution of samples (Figure 4-2) does not match that of budget (Figure 4-3). The maximum autonomy budget is highest for short site-to-site distances and $N_{s/s}$ around three. This is due to the non-linearity of N_{spl} when $N_{s/s}$ increases. The time required to analyze samples at one site is the time to approach and handle a sample $T_{approaching} + T_{handling}$ (Equation (4-2)) times the number of samples per site $N_{s/s}$. This represents one factor of the denominator on the right hand side of Equation (4-6). The other factors are the duration of traverse to the next site $T_{traveling}$, of imaging the site $T_{imaging}$, of targeting of samples $T_{targeting}$, and of communication with Earth T_{comm}. The numerator $T_{mission}$ is the total mission duration. Therefore, the fraction represents the number of sites a rover can visit within the mission duration. This number of sites, multiplied by the number of samples per site $N_{s/s}$, is thus the number of samples analyzed during the mission.

$$N_{spl} = N_{s/s} \frac{T_{mission}}{T_{traveling} + T_{comm} + T_{imaging} + T_{targeting} + N_{s/s}\left(T_{approaching} + T_{analyzing}\right)} \qquad (4\text{-}6)$$

Using MSE, Figure 4-4 shows the number of samples analyzed as a function of the number of samples per site, for a set 100 meter site-to-site distance. The solid line with square symbols is the function for a rover with advanced autonomy ($T_{approaching}=1$ sol); the solid line with dot symbols is the function for a rover with state-of-the-art autonomy ($T_{approaching}=3$ sols); the dotted line is the difference. The two solid curves reach a ceiling value for $N_{s/s}$ greater than six. However, for $N_{s/s}$ between one and six, the advanced autonomy curve shows a higher rate of sample increase than the state-of-the-art curve. For this reason, the difference of number of sample analyzed, between advanced and state-of-the-art rovers, is not a monotonic function of $N_{s/s}$; the difference (dotted curve) peaks for $N_{s/s} = 3$. Now, since the value of advanced autonomy is proportional to the gain in number of samples, advanced autonomy is most valuable in science scenarios with three samples per site.

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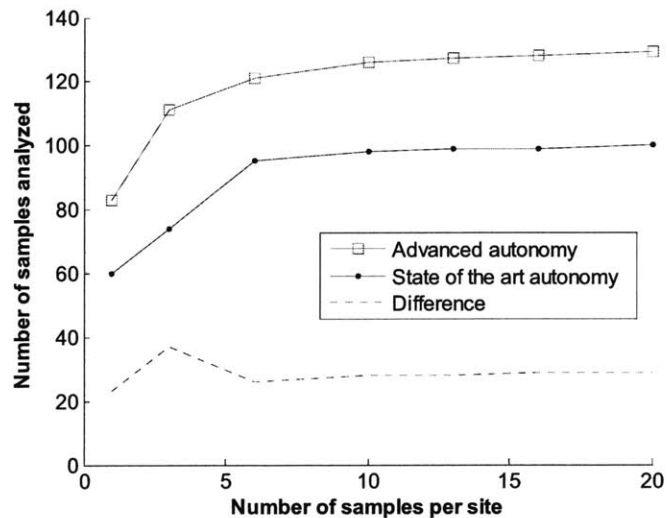
Figure 4-4 Number of samples analyzed as a function of number of samples per site for a 100 meter site-to-site traverse

According to Figure 4-3, the maximum budgets for advanced autonomy development range from $6M to $14M, and for most scenarios between $7M and $8M. Hence, the conclusions derived previously from Figure 4-1 still hold. In the case of MSL-type missions, advanced sample approach autonomy is a valuable asset worth developing.

ExoMars-type missions

ExoMars-type rovers are modeled with a 0.25 meter diameter wheel, solar power, state-of-the-art traverse autonomy, the eight kilogram ExoMars payload, and a baseline mission duration of 180 sols (*Mars Surface Explorers*, Chapter 1). Figure 4-5 shows the contour of maximum autonomy development budgets for the ExoMars mission.
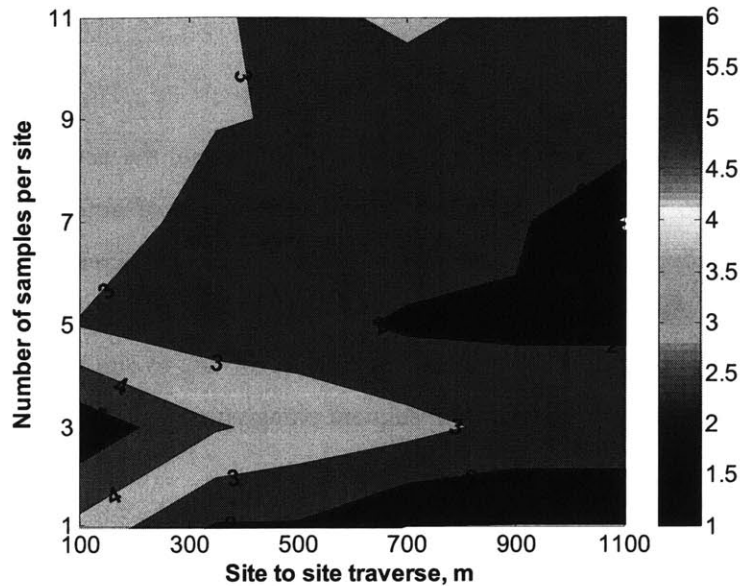
Figure 4-5 Contours of maximum autonomy development budget for ExoMars-type missions. Budget contours are in FY06 $M

While the contour shape of Figure 4-5 is similar to that of Figure 4-3, ExoMars maximum autonomy budgets are between $1M and $6M, instead of $6M and $14M in the case of MSL. As expected, advanced autonomy is less valuable for short duration missions, such as ExoMars, because they involve a smaller number of sample approach activities. For most scenarios, maximum allowable budgets are between $2M and $3M.

In the case of ExoMars, the margin between the expected cost of autonomy development and its mean maximum budget (between $2M and $3M) is a lot less. In this situation, one solution is to take advantage of the flexible nature of software and postpone the development of sample approach autonomy until after landing and beginning of rover operations. MER software was developed with this approach in mind; only software necessary for the nominal mission was implemented in the original software [Biesiadecki & Maimone, 2005]. This option strategy has several benefits: resources are spent on the development of advanced autonomy only after a successful start of operations is confirmed; the autonomy can be tailored to the specific environment of the rover; and the likelihood of mission extensions provides opportunities for software development.

4.5 Value of Processing Efficiency for Faster Site-to-Site Traverse

The function considered in this section is site-to-site traverse, the activity of driving from one scientific site to another one. In this case, the objective of autonomy infusion is to reduce the time needed for site-to-site traverse, which leads to an increase in the rover's daily traverse capability. As mentioned in the section which introduced processing efficiency, algorithm efficiency is used, in this thesis, as measure of site-to-site navigation autonomy. The AVM four steps are applied in the subsequent paragraphs.

1. Value of improved daily traverse

The use of autonomous drives (*Autonomy*, Chapter 3) has significantly improved MER's site-to-site traverse capability. The combination of blind and autonomous drives has enabled MER to double the daily odometry achievable with blind drives only [Biesiadecki, 2005b]. As of August 15, 2005, after 555 sols of operations, Opportunity had covered almost six kilometers [Biesiadecki & Maimone, 2005]. Over such a distance, the use of autonomous drives reduces operations by 45 sols, which corresponds approximately to $2M. Increasing daily traverse capability through the development of autonomous drives was therefore relevant to the MER mission. The next paragraphs discuss the benefits of improving daily traverse for MSL by developing even more advanced autonomy.

2. Competing technologies

An autonomous traverse is composed of a succession of two-step cycles. During the first step, the rover plans its path over a given distance; during the second step, the rover drives this distance by following the computed path. Therefore, rover traverse is improved either by reducing the duration of path planning calculations or by increasing rover mechanical speed.

Sojourner, MER, and MSL have been designed with nearly the same mechanical speeds (Figure 3-6) but with increasing processing speeds. This fact indicates that NASA has so far relied on increased processing efficiency to improve daily traverse.

3. Valuing improved processing efficiency with respect to increased mechanical speed

Impact of processing efficiency and mechanical speed on rover design

Increasing processing efficiency and increasing mechanical speed have very different impacts on rover design and cost. On the one hand, in MSE, the impact of increased processing efficiency on rover hardware is negligible; for example, the RAD6000 and RAD750 computers have similar mass and power requirements [BAE Systems, 2006 and 2006b]. On the other hand, increasing mechanical speed impacts the design of the wheel motors and of the power system and, consequently, of the whole rover structure. The system mass growth has heavy consequences on the mission development and launch cost (*Cost*, Chapter 3).

Daily traverse calculations in time-constrained operations

Daily traverse capability D_{sol} is the metric used to compare the benefits of increased processing efficiency and increased mechanical speed. Daily traverse has two components. First, the distance covered during the blind drive D_{blind} and, second, the distance covered during the autonomous drive. The latter is equal to the distance of each plan-move cycle D_{cycle} times the number of cycles N_{cycle} the rover is able to perform during a sol.

$$D_{sol} = D_{blind} + N_{cycle}D_{cycle} \tag{4-7}$$

The feasible number of plan-move cycles depends on the energy and time available after the blind drive is complete. MER and MSL rovers are often operated in energy- and time-constrained modes [Erickson, 2002 and Schilling, 1996]. In the case of energy-constrained operations, it is difficult to derive a formal equation for N_{cycle} because the energy calculations involve energy profiles from all subsystems. In the subsequent paragraphs, the case of time-constrained operations is first examined because it leads to a formal expression of N_{cycle}. Then, energy- and time-constrained operations are analyzed using MSE.

In the case of time-constrained operations, a rover is able to drive only for a given amount of time T_{drive}. The number of cycles the rover is able to execute is derived from the amount of time left after completion of the blind drive D_{blind}. The equation for N_{cycle} is provided below.

$$N_{cycle} = \frac{T_{drive} - \dfrac{D_{blind}}{V_{mech}}}{T_{moving} + T_{planning}} \qquad (4\text{-}8)$$

where $T_{planning}$ and T_{moving} are the durations for path planning and moving activities, respectively.

$$T_{planning} = T_{acq}^{MER} + \eta_{proc} T_{proc}^{MER}$$

$$T_{moving} = \frac{D_{cycle}}{V_{mech}} \qquad (4\text{-}9)$$

Combining Equations (4-7) and (3-8) yields an expression for daily traverse as a function of T_{moving}, $T_{planning}$, and T_{drive}.

$$D_{sol} = \frac{D_{blind} T_{planning} + D_{cycle} T_{drive}}{T_{moving} + T_{planning}} \qquad (4\text{-}10)$$

Figure 4-6 and Figure 4-7 are graphical representations of Equation (4-10) for a MER-type mission. Daily odometry is plotted as a function of processing efficiency η_{proc} (Figure 4-6) and mechanical speed V_{mech} (Figure 4-7). In each figure, a red square represents baseline MER capability as modeled by Equation (4-10); the daily odometry of a MER-type rover is close to 200 meters. This result is consistent with the operations of Opportunity; on good terrain conditions, Opportunity often achieved daily traverses of over 150 meters and, as of sol 410, the longest daily traverse of Opportunity has been 220 meters [Biesiadecki, 2005].

The figures also show that daily odometry reaches a plateau when processing efficiency and mechanical speed are increased independently. For high processing speeds, T_{acq} and T_{move} become bottlenecks in the autonomous drive process (Equations (4-9) and (4-10)). The same phenomenon happens when mechanical speed increases; T_{plan} rapidly becomes the bottleneck.

Figure 4-6 and Figure 4-7 indicate that processing efficiency can improve daily odometry more than mechanical speed can. However, at best, daily odometry reaches a maximum of 340 meters per sol. This improvement only represents a reduction of 12 sols of operations over Opportunity's 6000 meter traverse. This result indicates that even though higher processing efficiency is more valuable than higher mechanical speed, its value is not

significant at the mission level. In the next paragraphs, this analysis is repeated for the case of energy- and time-constrained operations.
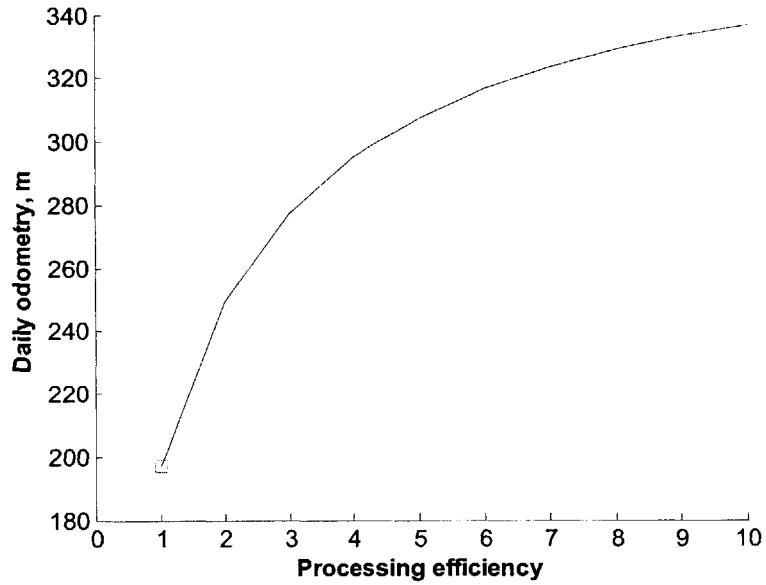
Figure 4-6 Daily odometry as a function of processing efficiency
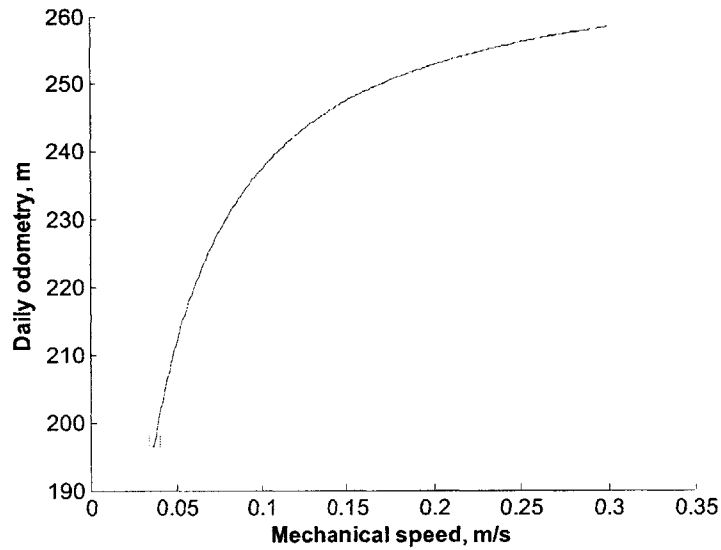
Figure 4-7 Daily odometry as a function of mechanical speed

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Daily traverse calculations in energy- and time-constrained operations

In MSE, the number of cycles is calculated iteratively between the power and autonomy modules so that operations satisfy time *and* energy constraints. Based on this calculation, the daily odometry is computed in MSE with Equations (4-7) and (3-8).

The MSL mission is used as context for comparing the benefits and costs of processing efficiency and mechanical speed. Various MSL designs are created with processing efficiencies ranging from one to five times that of a RAD6000 and with mechanical speeds ranging from one to five times the baseline MSL speed. The daily odometry capability and cost of each design is represented in Figure 4-8 by a square. Solid lines connect designs with constant processing efficiency; dash lines connect those with constant mechanical speed. The contour lines of processing efficiencies equal to 1, 2.5, and 5 are represented with thicker solid lines; the first two are labeled *RAD6000* and *RAD750*, respectively, because they correspond to the processing efficiencies of rovers equipped with these processors and state-of-the-art algorithm efficiency. The baseline MSL design, which uses a RAD750 processor and has the same algorithm efficiency as MSR, is labeled *MSL*.

Two observations about Figure 4-8 confirm previous statements about the effect of processing efficiency and mechanical speed on rover design and odometry capability. First, the slopes of mechanical speed contour lines (dash lines) are larger than those of processing efficiency contour lines. This means that improving processing efficiency is the more cost-effective solution for increasing daily traverse. Second, daily odometry exhibits decreasing rates of returns when each variable is increased independently — similar observations were made about Figure 4-6 and Figure 4-7. The factor of increase in daily odometry when doubling V_{MSL} is more than half that when quadrupling V_{MSL}; similarly, the factor of increase in daily odometry when doubling processing efficiency is more than half that when quadrupling processing efficiency (Figure 4-8).

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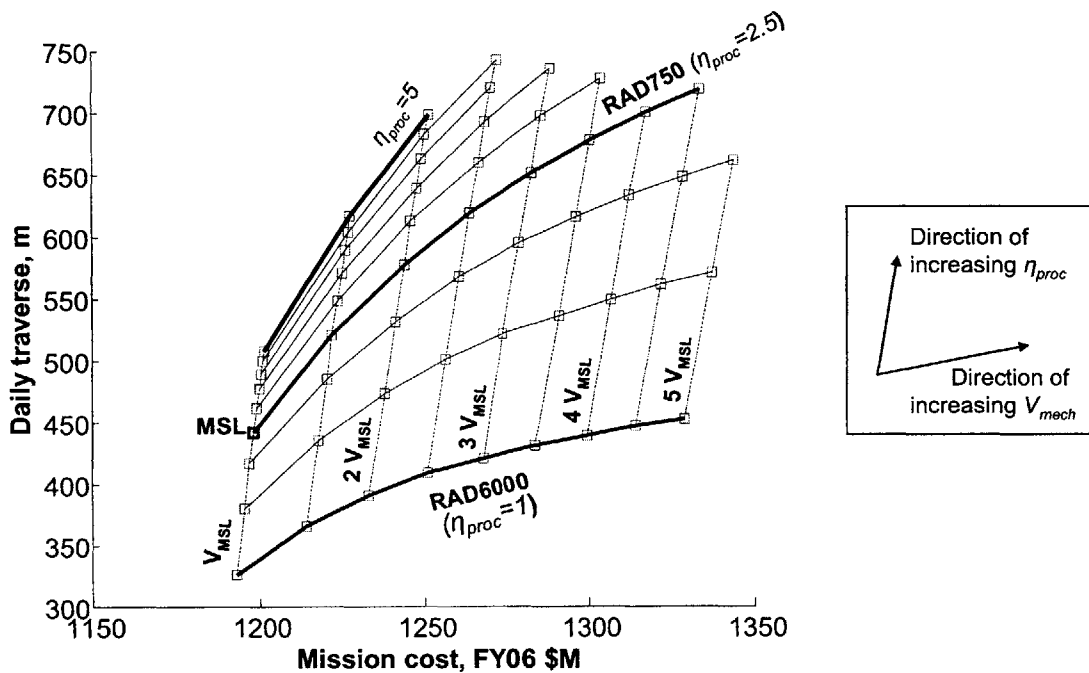
Figure 4-8 Daily traverse as a function of mission cost for a MSL-type rover with increasing processing efficiency and mechanical speed.

Contours of constant processing efficiency (solid lines) and contours of constant mechanical speed (dash lines) are shown.

Figure 4-9 is a zoom of Figure 4-8 around the MSL design point. The only processing contour line shown in Figure 4-9 is that for $\eta_{proc}= 2.5$, labeled *RAD750*. Below this line, the shaded area represents the part of the design space that is dominated by designs with $\eta_{proc}= 2.5$; for each design in this region there exists a design with $\eta_{proc}= 2.5$ which is less expensive and has a better daily traverse capability.

Points above the contour line represent designs with $\eta_{proc}> 2.5$; higher processing efficiencies are achieved by improving the algorithm efficiency, meaning by improving autonomy. For example, the design point labeled MSL^{η} has twice the processing efficiency of the baseline MSL design ($\eta_{proc}=5$) and a gain of more than 50 meters in daily odometry. As shown in Figure 4-1, the mission cost in Figure 4-9 does not include the cost of improving autonomy beyond MSL baseline capability. Designs with the baseline processing efficiency ($\eta_{proc}= 2.5$) are used as references to derive a maximum budget for autonomy improvement.

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The design point labeled MSL^I has an odometry capability comparable to MSL^J. MSL^I is a design with $\eta_{proc}= 2.5$ but with a mechanical speed increased a little less than 50%, compared to the MSL baseline speed. In other words, MSL^I is a mechanical solution which achieves the daily traverse capability of MSL^J with current autonomy but increased mechanical speed. The cost impact of increasing mechanical speed is captured in MSE and is clearly visible in Figure 4-9. The cost difference between MSL^J , the autonomy solution, and MSL^I , the mechanical solution, is $17M. Hence, as long as the cost of developing autonomy to increase η_{proc} from 2.5 to 5 is less than $17M, improving processing efficiency is the better solution to increase daily odometry above 500 meters. Based on the arguments already mentioned in the sample approach section, $17M is likely larger than the cost of infusing autonomy for this particular application and, therefore, makes the development of this technology attractive.

The above budget calculation process is repeated for other MSL^J points with processing efficiencies between 2.5 and 5. Figure 4-10 summarizes the results; it shows the maximum budget corresponding to processing efficiency ranging from 2.5 to 5. This chart can be used by autonomy developers to assess whether the expected cost of improving autonomy algorithms to a given value is cost-effective compared to the mechanical solution. If the cost of developing a given level of processing efficiency is less than the corresponding maximum budget, i.e. under the curve in Figure 4-10, the processing efficiency solution is cost-effective compared to the mechanical solution. Given the magnitude of the budgets (y-axis), it is likely that developing autonomy is always a more cost-effective solution. However, the example above showed that doubling processing efficiency only increased daily odometry by slightly more than 50 meters. It is unsure whether a 50 meter increase in daily odometry is valuable at the mission level.

4. Relevance of improved processing efficiency in the mission context

MSL is being designed for a targeted total traverse capability of 20 kilometers [MSL, 2006]. With its baseline daily odometry (as modeled by MSE), it would take approximately 44 driving sols to complete this traverse. Doubling the rover processing efficiency would only save five driving sols (11% reduction). Although improved processing efficiency is a cost-effective technological solution, the analysis performed suggests that it is not worth investing in this technology development for the sole purpose of improving daily traverse.

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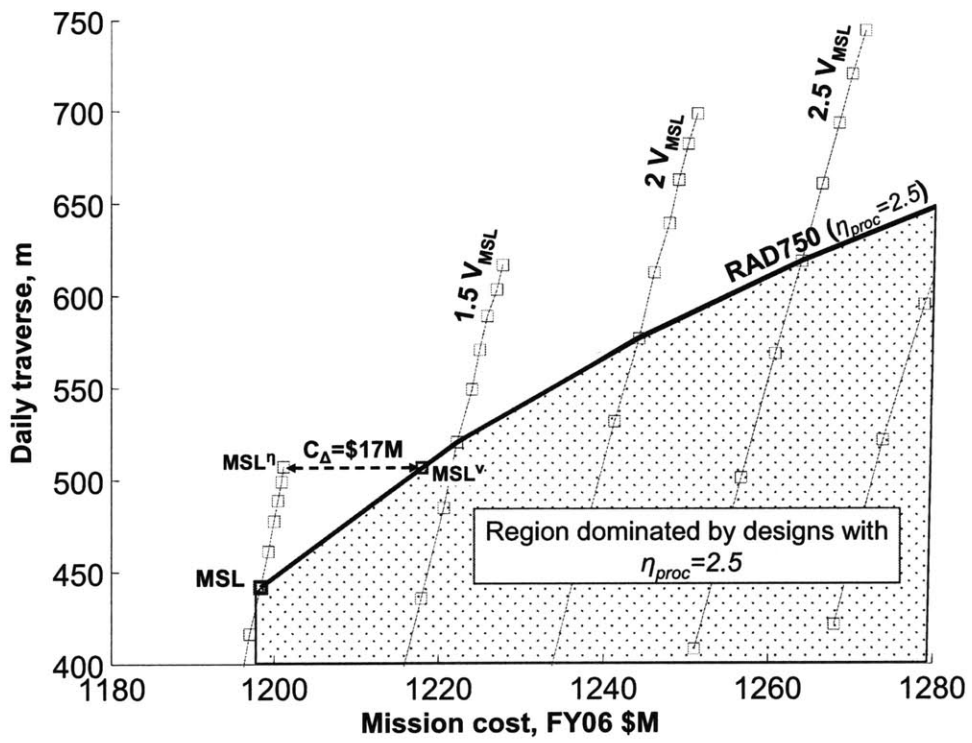
Figure 4-9 Value of processing efficiency
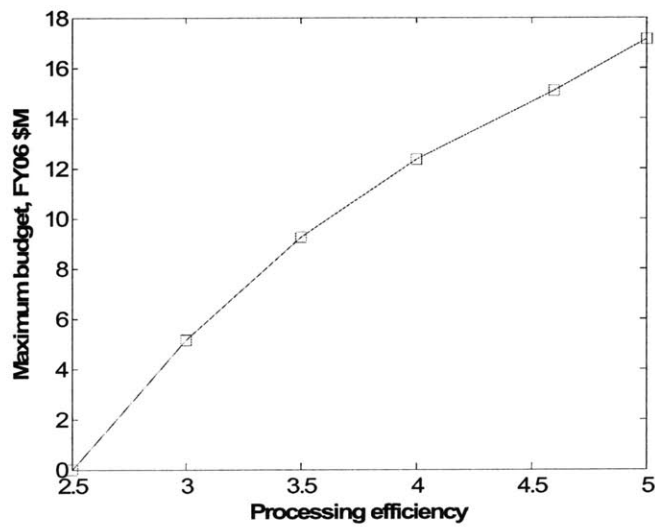
Figure 4-10 Maximum budget for improving processing efficiency as a function of
processing efficiency

4.5.1 Conclusions

A method for assessing the relevance of autonomy in surface exploration was presented. The method relies on the principle that the monetary worth of autonomy can be evaluated by benchmarking its performance against that of competing solutions with known costs. The method improves upon previous methods by enabling a dollar-based quantitative assessment of autonomy development value. The proposed method has been applied to sample approach autonomy and site-to-site traverse autonomy; the results show that the former is more relevant to future missions than the latter. This analytical result supports NASA's decision to develop sample approach autonomy for MSL. These applications demonstrate that the association of the method with a system design model provides useful quantitative guidance in determining the value of autonomy infusion in future missions.

Chapter 5

Platform Strategies for Mars Rover

Exploration

The aim of the analysis presented in this chapter is to assess the benefits of implementing a platform strategy for rover missions of the Mars Exploration Program (MEP). This methodology, however, is not specific to rover missions and can be applied to other fields of robotic space exploration. As stated in the *Platform strategy* section of Chapter 2, platform strategies can potentially reduce the cost of a space campaign (i.e. sequence of missions). On the one hand, at the campaign level, the re-use of platform components on several generations of spacecraft creates savings. On the other hand, at the mission level, a spacecraft designed with platform components is not optimal for its specific mission objectives. The proposed methodology was developed to enable quantitative analyses of the affordability trade-off of platform strategies applied to space exploration.

This methodology is adapted from existing commercial platform methods to the particular case of space exploration platforms. The methodology is used to determine the optimal number of platforms to maximize performance and minimize cost of a family of spacecraft missions. A significant contribution of this methodology is the development of an innovative optimization technique which enables the complete search of large platform option spaces. The subsequent sections provide a description of the methodology as well as an example of its application to MEP rover missions.

5.1 Glossary

The following definitions have been adapted from Simpson et al. [Simpson, 2001]; the expression *N-family* is specific to this study.

- *Product family*: a group of related products that share common features, components, and subsystems, and satisfy a variety of market segments. A product family comprises a set of variables, features or components that remain constant from product to product (platform components), and others that vary from product to product (variant components).

- *Product platform*: the set of parameters, features, and/or components that remain constant from product to product, within a given product family.

- *Platform design variables*: design parameters that remain constant from product to product within a given product family which constitute the product platform.

- *Variant design variables*: design variables that vary from product to product within a given product family.

- *Product variant*: product family members derived from the product platform through instantiation of one or more variant design variables.

- *N-family*: a product family whose products are variants of a given set of N product platforms.

5.2 Motivation

Contrary to the other methods discussed in this thesis, which optimize a single product (a particular rover design), a platform strategy optimizes a family of products. A platform strategy is "an effective and deliberate program of component reuse which takes advantage of economies of scale across the product family, while minimizing the negative impact of reuse on individual product variant distinctiveness and performance" [de Weck, 2004]. The advantages and disadvantages of platform strategies are discussed in the *Platform strategy* section of Chapter 2. Figure 2-22 shows which stakeholder figures of merit favor platform strategies as opposed to customized product development. As mentioned in the introduction, the affordability trade-off requires a quantitative analysis to determine whether

the non-optimality of platform-based products is offset by the savings generated across the product family through re-use.

In the particular case of the Mars program, several characteristics of the rover exploration architecture suggest that it could benefit from platform strategies [de Weck, 2004]:

- The Mars rover exploration architecture has some common basic sets of attributes. Section 2.1 shows that rover missions of the MEP exhibit a high level of commonality at the functional, physical, technical, and operational levels.

- The Mars rover exploration architecture has highly interconnected systems (e.g. surface vehicles and orbiters) with a need for future growth and a constant update of technologies (Figure 5-1).
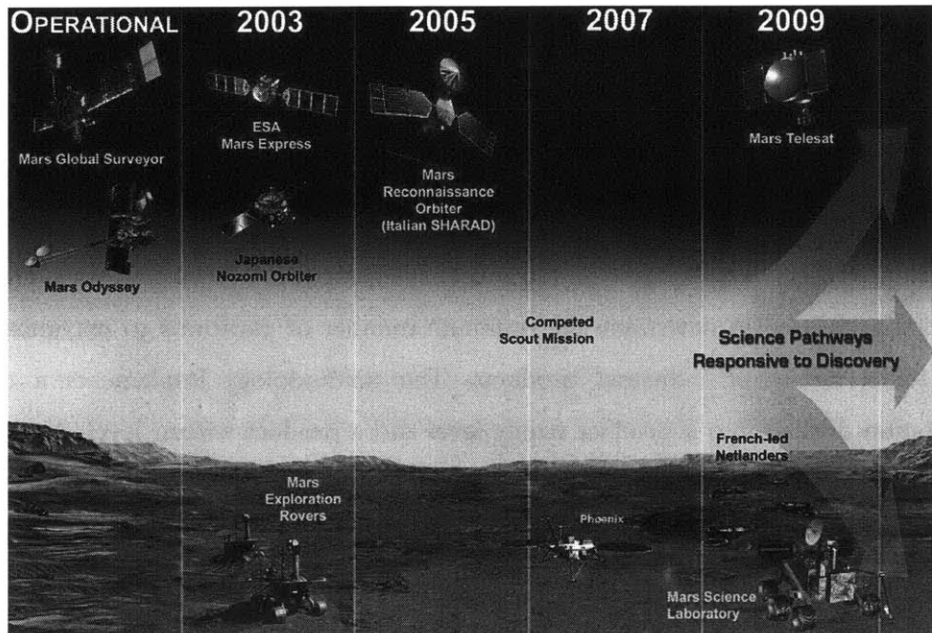
Figure 5-1 Illustration of the Mars Exploration Program timeline [Hubbard04]

- The Mars rover exploration architecture has stable core functionality but has variability in secondary functions. For example, the primary functions *traveling*, *collecting* and *communicating* (Section 2.3.1) are common to all scientific rover missions. However, the more detailed functions of the scientific payload depend on mission-specific objectives.

Similar considerations have motivated the implementation of platform strategies in the field of space exploration. For example, in March 2001, ESA issued a call for ideas for a low cost mission derived from the platform developed for Mars Express and launched in 2003 [Gimenez, 2002]; Mars Express itself re-used elements of the Rosetta mission. The Venus Express concept, approved in November 2002 and developed in record time, was successfully launched in November 2005. The re-use of the propulsion module was a major piece of the platform strategy whereas most of the re-design work went into adapting the thermal subsystem to the Venusian environment [Hunter, 2004]. NASA is also considering reusing parts of MER and MSL designs for a new Mars rover mission in 2016 [MAPG, 2006].

Whereas platform strategies for commercial products have been widely studied, little research has been done on the optimization of platform strategies for space exploration products. The approach proposed by Gonzalez-Zugasti et al. [Gonzalez, 2000] is limited to spacecraft platform families that use only one platform. Furthermore, the approach relies heavily on expert participation and is, therefore, not adequate for the analysis of large option spaces. The methodology proposed in this thesis for space exploration platforms is adapted from that proposed by de Weck et al. [de Weck, 2004] for commercial platforms. De Weck's methodology is used to determine the optimum number of platforms to maximize overall profit for a family of industrial products. The methodology implements a two-level optimization divided into a product family level and a product variant level. At the family level, decision makers choose and optimize product family variables, such as the selection of market segments, number of platforms, platform design variables. Given a set of family variables, each product variant is then optimized with respect to its specific market segment within the constraint of the platform the variant is based on. Product variants are optimized to match the performance of market leaders, which are the products with the largest sales volumes in each market (based on historical data). The optimization process iterates between the family and variant levels until the product family with the best overall profit is found.

5.3 Platforms in the Context of Space Exploration

There exists a parallel between the industrial architectures analyzed by de Weck et al. and space exploration architectures. Still, some fundamental differences make the methodology proposed by de Weck not readily applicable to the study of space exploration platform strategies. Industrial products are optimized for targeted market segments; an example of market segment in the car industry is that of sports utility vehicles. A given market segment addresses specific stakeholder needs; for example, the sport cars market is targeted for drivers who value speed and esthetics. Similarly in the space exploration field, the definition of mission objectives addresses specific aspects of the needs of MEP stakeholders. Therefore, in this study a space exploration mission is considered the analog of a market segment; the two expressions are used interchangeably. Table 5-1 lists analogies between industrial and space exploration architectures. Space exploration roadmaps developed by space agencies serve to identify future potential mission segments. In the case of NASA Mars rover exploration, these missions include MSL, AFL, mid-rover, MSL-clone, and MSR [MAPG, 2006b].

Table 5-1 Analogies between industrial and space exploration architectures

Industry terminology	Space exploration terminology
Product family	Space campaign
Market segment	Mission segment
Product	Spacecraft

A major difference between space exploration and industry is that, unlike the latter, the former is not a competitive and profitable environment. NASA is currently the only provider of planetary space exploration products to the US government; other national space agencies have the same role for their respective governments. Consequently in the field of space exploration, there are no direct equivalents to commercial notions of sales volume and profit. The optimization procedure proposed by de Weck et al. relies on an access to sales volume and profit data of existing products. Because no such data is available for future space missions, the proposed methodology uses instead a system design model, such as MSE, capable of evaluating the cost and performance of a wide array of space products. The

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need for a system design model is a feature that is common to this methodology and to that proposed by Gonzalez et al.. the reliance on a system design model makes the flow of the optimization process significantly different from that in de Weck's methodology.

Another difference between commercial and space exploration platform strategies is related to the phase during which savings occur. In commercial applications, platform strategies generate major savings during the production phase. Production costs decrease with the number of platform units produced because of learning curve effects. The cost C^K of K platform units is less than K times the cost of the first unit, also called Theoretical First Unit (TFU) cost. The cost C^K of a family of K identical platforms is:

$$C^K = TFU \times K^B \leq TFU \times K \tag{5-1}$$

where

$$B = 1 - \frac{\ln\left(\dfrac{100\%}{S}\right)}{\ln(2)} \tag{5-2}$$

The learning curve slope S is typically 95% for families of less than 10 units ($K \leq 10$) [Larson, 1992].

Unlike most platform-derived commercial products, space exploration products are produced in small number and at a low rate. For example, the rate of production of a Mars rover is, on average, one every six years. Hence, savings during the production phase (Phase C/D, Section 1.1) are limited. Instead, major savings happen during the project formulation phase, which spans from pre-Phase A to Phase B. The one-time platform design cost is amortized across multiple products. For example, the Phoenix scout mission concept is based on the refurbishment of an existing lander for the Mars Surveryor Program, but with new scientific instruments and a modified power and communications subsystems [Smith 2004]. The reuse strategy implemented on Phoenix enabled the project to start directly in Phase B, the last of the three project formulation phases. Mars Express and Venus Express, ESA's platform-based orbiter family, have shown similar reductions in project formulation phases.

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Figure 5-2 shows a comparison of Phase B and Phase C/D durations for a variety of ESA projects [McCoy, 2005]. Mars Express reused elements of Rosetta, and Venus Express relied heavily on element reuse from Rosetta and especially Mars Express; the Cluster II mission was a re-build of Cluster I whose launcher failed; all remaining missions are one-of-kind. Venus Express clearly stands out as the mission with the shortest Phase B among ESA scientific missions conducted to date. McCoy et al. pointed out that the evolution of the schedules of Rosetta, Mars Express, and Venus Express exhibits a large decrease in formulation time and little decrease in development time. The re-build of Cluster II, however, shows significant reductions in both formulation and development phases.
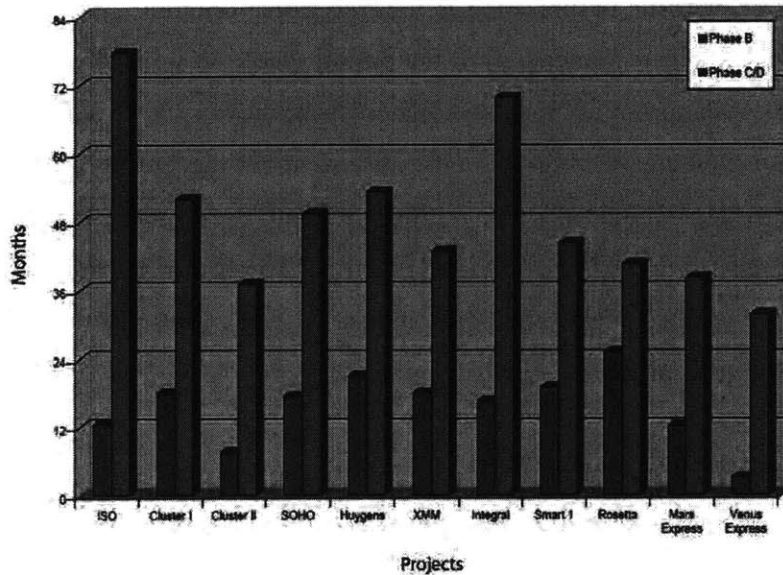
Figure 5-2 Comparison of Phase B (left column) and Phase C/D (right column) durations for a variety of ESA projects [McCoy, 2005]

This observation supports the claim that the benefits of a platform strategy are more apparent in the formulation phase than in the development phase, unless the new product is an exact replicate of a first unit and is developed shortly after the first unit. Step 8 of the methodology provides more discussion about the costing of space platform families.

5.4 Basis of the Methodology

This section describes the mathematical foundation of the optimization procedure described in Section 5.5. The methodology addresses two optimization cases. In the first case (A), platform families are optimized for cost with a constraint on minimum performance. In the second case (B), platform strategies are optimized for both cost and performance. A single optimization technique has been developed to address both optimization problems.

For many platform optimization problems the option space, the space of all possible platform families, is too vast to be searched exhaustively. Heuristic optimization techniques, such as genetic algorithm and simulated annealing, could be used to uncover optimal product families by only evaluating a fraction of the space. There is no guarantee, however, that the result of heuristic optimization is the true global optimum. This study proposes a technique for the implicit enumeration of the option space. An implicit enumeration enables the systematic evaluation of all possible solutions without explicitly evaluating all solutions. The proposed technique, based on two observations about the nature of the product family option space, reduces significantly the number of candidate product families such that an exhaustive search of the option space is practical. The size reduction is not based on heuristics but on mathematical considerations; an exhaustive search of the reduced option space does, therefore, uncover the global optimum.

5.4.1 Initial problem statement

The methodology is described step by step in the Section 5.5. Steps 1 to 3 define M market segments with specific performance functions. Step 4 defines a set of design variables and Step 7 identifies the variables characterizing platform components and those characterizing variant components. Based on the design variables of Step 4, Step 6 creates a trade space of product variants for each market. The purpose of the optimization process is to find product families that optimize problems A and B while using only a given number N of platforms. The process is repeated for $N = \{1, \ldots, M\}$ in order to determine the optimal number N.

The platform design variables identified in Step 7 determine a total number $(N_{\mathcal{P}})$ of product platforms. In this analysis, the space of platform products is noted $\mathcal{P}$ and the space

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of market segments is noted $\mathfrak{M}$. Therefore, in mathematical terms, $N_{\mathcal{P}}$ is the cardinality (card), or number elements, of the set $\mathcal{P}$. M is the cardinality of the set $\mathfrak{M}$.

$$N_{\mathcal{P}} = \text{card}\left(\mathcal{P}\right)$$
$$M = \text{card}\left(\mathfrak{M}\right)$$

(5-3)

A *N-family* is defined as a family whose products are variants of a given set of N product platforms.

Optimization objective functions

Problem A: cost minimization

The mathematical expression of the optimization problem A is to find the set J of N elements of $\mathcal{P}$ so that a N-family derived from J minimizes product family cost. The general expression of the cost (C_F) of a product family with N platforms is given below.

$$C_F = \sum_{j=1}^{N} C_j$$

(5-4)

$$C_j = C_j^{nr} + K_j C_j^r + \left(K_j\right)^B TFU_j + \sum_{i=1}^{K_j} C_{ij}^v$$

(5-5)

In this equation, C_j represents the added cost of all family variants of a given platform j; the number of such variants is K_j. The cost C_j is the sum of non-recurring costs (C_j^{nr}), recurring costs (C_j^r), learning-curve-related costs (TFU_j), and variant costs (C_{ij}^v). A more detailed expression of product family cost is provided in Step 8. The savings in non-recurring costs and economies of scale occur when all the variants of a given platform are considered together. For this reason, the product family cost C_F cannot be decomposed into the sum of independent product variant costs. In other words, the family cost is not a separable function [deNeufville, 1990, p.144] because the cost of a product variant depends on the selection of other product variants of the family.

Problem B: performance and cost optimization

The mathematical expression of the optimization problem B is to find the set J of N elements of $\mathcal{P}$ so that a N-family derived from J optimizes the goal vector $\Gamma_{\mathcal{B}}$:

$$\Gamma_{\mathcal{B}} = \left\{ \begin{array}{l} \text{maximize product family performance} \\ \text{minimize product family cost} \end{array} \right\} \tag{5-6}$$

The two-objective optimization problem expressed in Equation (5-6) is transformed into a single-objective optimization problem by introducing a value function [deNeufville, 1990, p.360]. The value function V is a mathematical expression used to quantify how well a product family optimizes $\Gamma_{\mathcal{B}}$. The function is constructed as the weighted sum of the family's normalized performance $\overline{S}_F$ and normalized cost $\overline{C}_F$ (the normalization process is detailed in Step 8).

$$V = \omega \overline{S}_F + (1 - \omega) \frac{1}{\overline{C}_F} \tag{5-7}$$

The weight ω captures the relative importance of the performance and cost objectives; for a given weight, there exist one product family which maximizes the value function. The notation P_{ijk} is used to refer to the product defined as the kth variant of the jth platform in the ith segment. The normalized performance of P_{ijk} is noted $\overline{S}_{ijk}$ and its normalized cost is noted $\overline{C}_{ijk}$; a bar above the variables signifies a normalization. With these notations, the value function of a family is:

$$V = \omega \sum_i \overline{S}_{ijk} + (1 - \omega) \frac{1}{\sum_i \overline{C}_{ijk}} \tag{5-8}$$

The performance and cost of a family are assumed to be equal to the sum of the performances and costs of its elements − rigorous expressions of family performance and cost are provided in Step 8. In Equation (5-8), the performance and cost of each product are normalized within each market. In Equation (5-8), the value function of the family cannot be decomposed into individual functions associated with each product (Equation (5-9)); in other words, the value function V is not separable.

$$V \neq \sum_{i,j,k} \left(\omega_1 \overline{S}_{ijk} + (1 - \omega_1) \frac{1}{\overline{C}_{ijk}} \right) \tag{5-9}$$

The non-separability of the optimization objective functions is the mathematical expression of the fact that the benefits of platform strategies are visible only at the family level.

Dimension of the option space

Given all the product variants in every market segment, the set of all possible product platform families can be searched exhaustively and the best one identified. However, this approach is not satisfactory because the number of possible families increases dramatically with the number of markets and platforms considered.

The space and number of product variants of the jth platform in the ith market are noted P_{ij} and N_{ij}, respectively.

$$N_{ij} = \text{card}\left(P_{ij}\right) \tag{5-10}$$

The number of products in the ith market is then

$$N_i = \sum_{j=1}^{N_{ij}} N_{ij} \tag{5-11}$$

The number Ψ of possible product families is the number of possible combinations of products in each market segment.

$$\Psi = \prod_{i=1}^{M}\left(N_i\right)$$

$$\Psi = \prod_{i=1}^{M}\left(\sum_{j=1}^{N_{ij}} N_{ij}\right) \sim \left(\overline{N}_{ij} N_{ij}\right)^{M} \tag{5-12}$$

The equation above shows that the magnitude of Ψ is very sensitive to the exponent M, which is the number of market segments. Six campaign scenarios are analyzed in the result section at the end of this chapter. The number of possible families in the Campaign 5 scenario, which has four missions (M=4), is approximately $30*10^9$. The number of possible families in the Campaign 6 scenario, which has five missions (M=5), is approximately $30*10^{12}$. The proposed optimization technique for exploring the option space of platform families is based on two observations described in the two subsequent sections.

5.4.2 First observation: Pareto reduction

The first observation is that optimal product families must be composed of product variants that are Pareto optimal compared to all other variants of the same platform in the same market. A Pareto optimal variant of the jth platform in the ith market maximizes performance and minimizes cost compared to other variants of the same platform in the same market. The space of Pareto optimal variants of the jth platform in the ith market is noted Π_{ij}. A proof by contradiction demonstrates the initial statement.

If the statement is wrong, there exists a family F_1 optimizing Γ which has at least one product P_{ijk} that is not a Pareto optimal variant of the platform j in the market i. By definition, there exists a Pareto optimal variant P_{ijd} of the same platform in the same market which dominates P_{ijk}:

$$\exists P_{1jd} \text{ such that } \{S_{1jd} \geq S_{1jk} \text{ and } C_{1jd} < C_{1jk}\} \text{ or } \{S_{1jd} > S_{1jk} \text{ and } C_{1jd} \leq C_{1jk}\} \qquad (5\text{-}13)$$

A family F_2 is defined as the family F_1 but with P_{ijd} substituted for P_{ijk}. Based on the above relationship, F_2 dominates F_1 which contradicts the fact that F_1 optimizes Γ. Therefore, the statement is true: all products of an optimal family are optimal variants of a platform in the corresponding market. A two-layer optimization can be implemented. First, the Pareto optimal variants of each platform in each market are identified. Second, the optimal product family using these optimal variants is identified.

In this analysis, in order to identify the optimal variants of a set, all variants of the set are evaluated. A description of the procedure is given in Step 10. Therefore, determining the Pareto optimal variants of each platform in each market requires the evaluation of all variants of all platforms in all markets.

$$\Phi_1 = \sum_{i=1}^{M} \sum_{j=1}^{N_g} N_{ij} \qquad (5\text{-}14)$$

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The space of Pareto optimal variants of the jth platform in the ith marker is noted Π_{ij}. The number of optimal variants in Π_{ij} is noted N_{ij}^{Π}.

$$N_{ij}^{\Pi} = \text{card}\left(\Pi_{ij}\right) \qquad (5\text{-}15)$$

With these notations, the number of family options left to evaluate after the Pareto reductions is given by the equation below. The equation is similar to Equation (5-12), but N_{ij}^{Π} is substituted for N_{ij}.

$$\Psi_1 = \prod_{i=1}^{M}\left(\sum_{j=1}^{N_{ij}} N_{ij}^{\Pi}\right) \qquad (5\text{-}16)$$

In the case of Campaign 5, the number of evaluations required to identify Pareto optimal variants is 1,600. The number of possible product families after the reduction is 51,000.

5.4.3 Second observation: Partition reduction

The second observation is that the problem of assigning N platforms to the space of market segments ($\mathfrak{M}$) is equivalent to partitioning of $\mathfrak{M}$ into N subsets and assigning one platform to each subset. In the case N=2, consider two sets M_1 and M_2 forming a partition of $\mathfrak{M}$ (i.e. $M_1 \cap M_2 = \varnothing$ and $M_1 \cup M_2 = \mathfrak{M}$). In mathematical terms, the underlying statement is that if two 1-families F_1 and F_2 optimize the subsets M_1 and M_2, respectively, then the 2-family $F=\{ F_1, F_2 \}$ is the optimal 2-family for the partition $\{M_1, M_2\}$.

If F_1 and F_2 use distinct platforms, the cost of F is the sum of the costs of F_1 and F_2 because the association of the two families does not generate further economies of scale. In other words, there are economies of scale at the level of F_1 and F_2 but not at the level of F. In this situation, the performance *and* cost functions are separable over the sets M_1 and M_2. Therefore, the family F is the optimal 2-family for the partition $\{M_1, M_2\}$.

If F_1 and F_2 use the same platform, the family F is in fact a 1-family. The cost of F is less than or equal to the sum of the costs of F_1 and F_2 because the association of F_1 and F_2 creates more economies of scale. For this reason, F dominates all 2-families of the partition $\{M_1, M_2\}$ − F may not, however, be the optimal 1-family solution for $\mathfrak{M}=M_1 \cup M_2$ (case N=1).

Therefore, it is possible to optimize N subsets forming a partition of $\mathfrak{M}$ independently and the aggregated family F is optimal compared to all N-families of the same partition. The new formulation is a lot simpler because instead of optimizing families of N platforms, it optimizes families of one platform. The new formulation leads to the following optimization process:

1. Identify 1-families that optimize each subset of $\mathfrak{M}$

   a. For each subset of $\mathfrak{M}$ and for each platform, identify variants which optimize performance and cost over all markets of the subset. There are 2^M-1 non-empty subsets (SS) of $\mathfrak{M}$.

   b. Select the 1-family which optimizes performance and cost compared to other 1-families using other platforms.

The number Φ_2 of product family evaluations involved in this step is:

$$\Phi_2 = \sum_{s=1}^{2^{M-1}} \sum_{j=1}^{N_g} \prod_{i=1}^{\text{card}(SS_s)} N_{ij}^{\Pi}$$ (5-17)

For a given $\mathfrak{M}$ and $\mathcal{P}$, this first step needs to be performed only once.

2. Identify N-families that optimize each partition of $\mathfrak{M}$ with N subsets, for N={1,..., M}

   a. For a given partition of $\mathfrak{M}$ with N subsets, the best N-family is made of the 1-families optimizing each subset.

   b. For all values of N, compare N-families associated with all partitions of $\mathfrak{M}$ and select the one that optimizes performance and cost over all of the markets of $\mathfrak{M}$.

Given N, the number of partitions of the set $\mathfrak{M}$ of M elements into N subsets is a Stirling number of the second kind noted $\begin{Bmatrix} M \\ N \end{Bmatrix}$. The Stirling numbers of the second kind are given by the formula below.

$$\begin{Bmatrix} M \\ N \end{Bmatrix} = \frac{1}{N!} \sum_{a=1}^{N} (-1)^{N-a} C_a^N a^n$$ (5-18)

The number Φ_3 of product family evaluations involved in this step is:

$$\Phi_3 = \sum_{N=1}^{M} \left\{ \begin{matrix} M \\ N \end{matrix} \right\}$$

(5-19)

The number of product families that are evaluated in this process is equal to the sum of three terms:

$$\Phi = \Phi_1 + \Phi_2 + \Phi_3$$

$$\Phi \sim \overline{N}_{ij} N_{\mathcal{G}} M + 2^M N_{\mathcal{G}} \left(N_{\max}^{\Pi} \right)^{(M/2)} + \sum_{N=1}^{M} \left\{ \begin{matrix} M \\ N \end{matrix} \right\}$$

(5-20)

The term Φ_1 is given in Equation (5-14); it is the number of evaluations needed to identify the Pareto optimal variants of each platform in each market. In the case of Campaign 5, the number of evaluations involved in the partition reduction is 7,500. Hence, with the proposed optimization technique, the total number of evaluations needed to identify the optimal product family is less than 60,000. The size of the option space is reduced by six orders of magnitude.

5.4.4 Assumptions

This methodology makes several simplifying assumptions which are listed below.

- The context of this analysis is assumed to be one in which a space agency would deliberately and *a priori* use a platform strategy for its space exploration products. In reality, NASA is currently assessing the potential of an *a posteriori* platform strategy which would reuse MSL hardware for the AFL mission.

- A product family has at most one product in each mission segment.

- Variant components are mission-specific parts; their production does not benefit from the effect of learning curve savings or economies of scale.

- Product variants of a given platform share identical supporting elements, which, in the case of a rover mission, include the cruise system and EDL system (launch vehicle not included).

- The design overhead involved in designing a component as a platform component is not taken into account.

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More assumptions are made specifically for the application of the methodology to MEP missions:

- The study of MSR, in this thesis, addresses the rover portion of the mission; it does not address the Mars Ascent Vehicle (MAV) or other spacecraft involved in the return of the sample to Earth.

- The influence of planetary protection on the design of platform components is not captured.

5.5   Proposed Methodology

This section contains a description of the methodology and of its application to MEP rover missions. Figure 5-3 is a map of the methodology which starts with the first step *Identify market segments* in the upper left corner. The major steps of the methodology are listed on the left and are executed sequentially from top to bottom; intermediate products of each step are listed in the middle and tools supporting the execution of steps are listed on right.

The goal of the application MEP rover missions is to determine the optimal number of platforms for accomplishing all foreseeable Mars rover missions if an *a priori* platform strategy were adapted. The rover components selected to form the platform include the mobility, WEB, and power subsystems. There are three reasons that motivate this choice. First, mobility, WEB, and power systems are defining characteristics of a vehicle design. According to the principle, stated in the *Platform strategy* section of Chapter 2, "Customize where it is hot, platform where it is not", the mobility, WEB and power subsystems are good platform component candidates because, compared to the arm and mast, they are less sensitive to scientific requirements (e.g. instrumentation design). Second, MSE is well suited for the analysis of mobility, WEB, and power subsystems. Third, reuse strategies of propulsion, structure, and power components have already successfully been applied to orbiter product families (e.g. Mars Express and Venus Express). The analysis performed in this chapter aims at determining the number and combinations of rover platforms necessary to accommodate a wide array of scientific payloads.
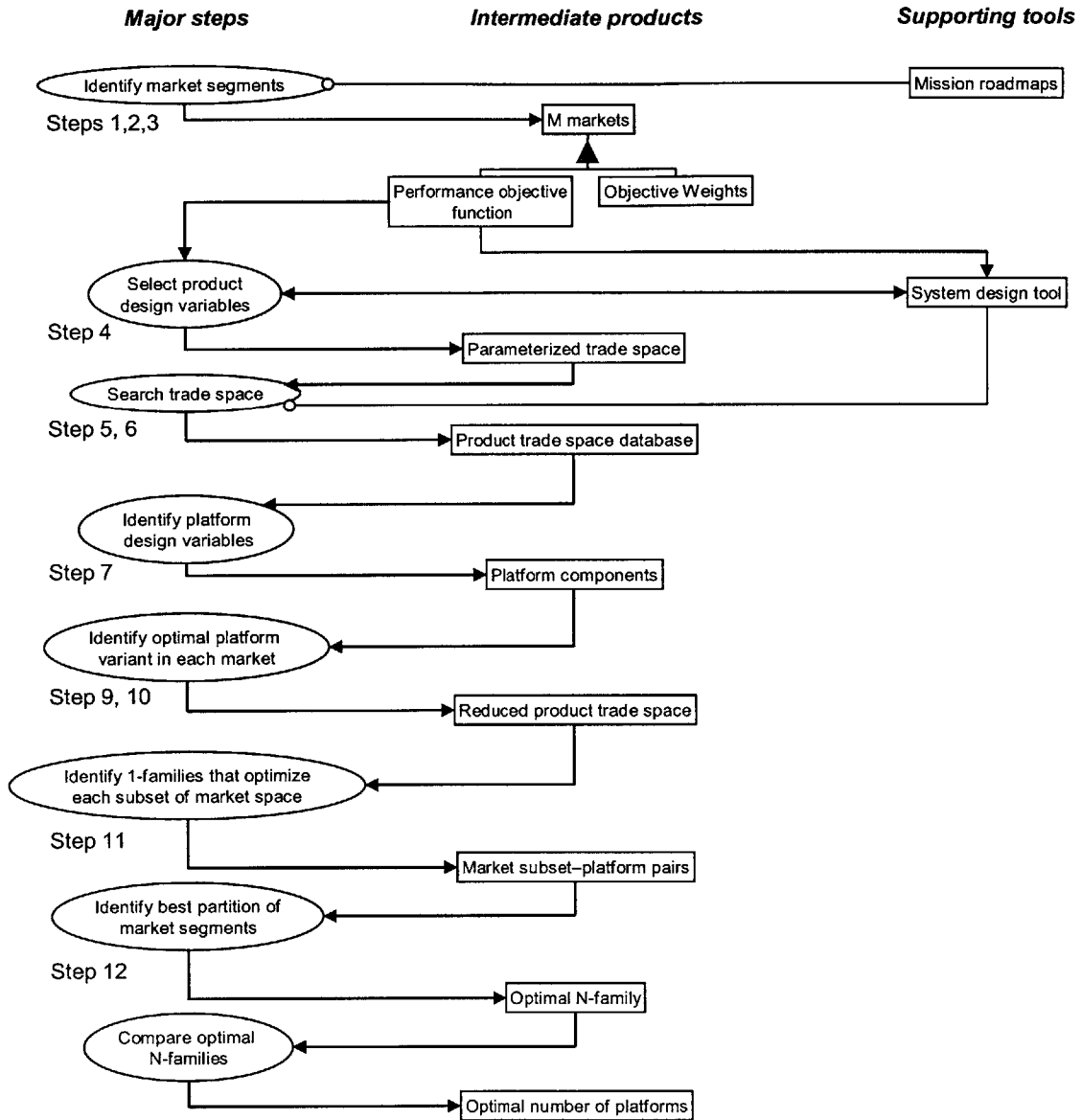
Figure 5-3 Map of the methodology for the optimization of platform strategies

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Step 1: Identify mission segments

As previously stated, the equivalent to a market segment in the field of space exploration is a mission segment. Missions are identified from mission roadmaps defined by space agencies; each mission is characterized by scientific objectives (e.g. proposed scientific payload) and a launch date.

Mars rover example

Future NASA missions include MSL in 2009; several candidate missions for the 2016 opportunity, including AFL, mid-rover, and MSL-clone [MAPG, 2006b]; and a MSR mission scheduled no earlier than 2020. Concepts studied by JPL's concurrent engineering team (Team X) are used to define instrument payloads for each mission [Wilson, 2005]. Two AFL concepts are considered; the MER-C and MSL-MHP concepts are used for the mid-rover and MSL-clone missions, respectively. MER is also added to the list and brings the number of mission segments to seven. In the subsequent results section, the methodology is applied to several combinations of these missions.

Step 2: Identify mission-specific performance objective functions and constraints

This step is similar to the third step of de Weck's methodology. Objective functions are mathematical expressions of mission objectives. Market segments may share common objectives and have specific ones as well.

Mars rover example

For example, the mission objective of a traditional rover mission is to maximize scientific return by analyzing as many samples as possible. Because each mission is optimized independently, the *number of samples analyzed* is an appropriate metric of scientific return. For MSR-type missions, however, the objective of surface operations is to collect only a few samples and secure them in a Mars Ascent Vehicle (MAV); some MSR scenarios allocate as little as 30 sols for collecting samples because the samples must quickly be transferred to Mars orbit [Matousek, 1998]. For this reason, the performance objective of the MSR mission is to minimize the mission duration needed to return at least five samples. Table 5-2 lists all selected rover missions with their objectives and constraints.

Table 5-2 Rover mission segments

Index	Mission	Performance objective	Launch opportunity	Landing latitude (deg)
1	MER (2 rovers)	Maximize number of samples	2003	+/- 15
2	MSR	Minimize mission duration	2020+	+/- 15
3	MER-C (2 rovers)	Maximize number of samples	2016/2018	+/- 15
4	MSL MHP	Maximize number of samples	2016/2018	+/- 60
5	MSL	Maximize number of samples	2009	+/- 60
6	AFL baseline	Maximize number of samples	2016/2018	+/- 60
7	AFL augmented	Maximize number of samples	2016/2018	+/- 60

The missions are ranked in order of increasing scientific payload mass (Figure 5-4).
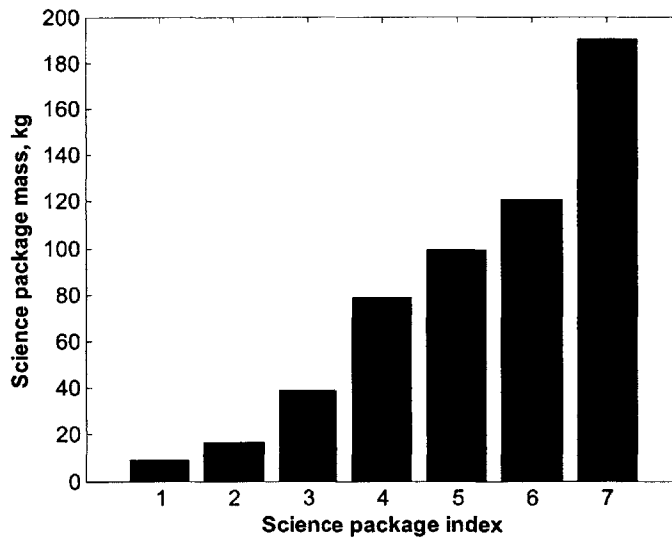
Figure 5-4 Mass distribution of scientific payloads for each mission

Step 3: Establish weight factors for each performance objective function

In this step, two levels of weight factors are introduced. First, each segment's performance objectives are weighted with respect to each other to reflect stakeholder preferences. The weights are gathered in a matrix Ω_j whose rows correspond to mission objectives and columns to missions.

$$\Omega_1 = \begin{pmatrix} w_{11} & \cdots & w_{1M} \\ \cdots & \cdots & \cdots \\ w_{Q1} & \cdots & w_{QM} \end{pmatrix} \tag{5-21}$$

with

$$\sum_{q=1}^{Q} w_{qi} = 1$$

The normalized performance $\overline{S}_{ijk}$ of a product P_{ijk} in the ith mission segment is the weighted sum of the normalized performance of the product for each objective of the mission segment.

$$\overline{S}_{ijk} = \sum_{q=1}^{Q_i} w_{qi} \overline{S}_{ijk}^{q} \tag{5-22}$$

The performance for each objective is normalized by the best performance in the given segment:

$$\overline{S}_{ijk}^{q} = \frac{S_{ijk}^{q}}{\max\limits_{j,k}\left(S_{ijk}^{q}\right)} \tag{5-23}$$

Second, the overall performance objective is weighted with respect to the cost objective. The general expression of the resulting value function of a product family is:

$$V = \frac{\omega}{M} \sum_{i=1}^{M} \left(\overline{S}_{ijk}\right) + \left(1 - \omega\right)\frac{1}{\overline{C}_F} \tag{5-24}$$

The first term of the sum is the family's weighted performance; C_F is the family's cost. The value function is constructed so that its range of values is between zero and one. Another layer of weights could be added to distinguish stakeholder preferences among market segments. In Equation (5-24), all missions are assumed to be equally valuable to stakeholders; all weights are equal to $^1/_M$.

Mars rover example

All missions have a single objective performance function; therefore, Ω_i is a row vector whose entries are all ones. For all missions but MSR, S_{ijk} is the number of samples analyzed by the rover P_{ijk}. In the case of MSR, S_{ijk} is the inverse of the surface duration needed for the rover P_{ijk} to collect five samples.

Step 4: Establish design variable set for each segment

The purpose of the fourth step is to define product design variables from which platform and variant design variables are selected in Step 7 – contrary to the second step of de Weck's methodology, no distinction is made at this time between the two types of variables. The selection of design variables should characterize all candidate platform components, capture relevant product design trade-offs, and facilitate the subsequent implementation of a system design model (Section 3.4). The outcome of this step is a set X of M design vectors x_i.

$$X = \{x_1, ..., x_M\}$$

(5-25)

Mars rover example

The MSE design vector, x_{MSE}, is an example of a design variable set that characterizes rover products of Mars exploration missions. The MSE design variables are used for all missions but the variable levels are mission-specific. For example, shorter mission durations are considered for MSR than for the remaining missions (Table 5-3).

Table 5-3 Trade space parameterization

Design variables	Levels	
wheel diameter, m	from 0.20 to 0.60, step: 0.05	
duration, sol	from 30 to 180, step:30	MSR mission segment
	from 100 to 700, step 50	all other missions
power source	solar and RPS	
computational power, RAD6000 equivalent	1 and 2.5	
Comm link	X band + UHF and UHF only	
sample approach autonomy	state of the art and advanced	

Step 5: Create a system design model

A system design model is needed to search the space of products within each market segment (mission). The system design model must accept the previously defined design variables as inputs and produce product performance figures as outputs. The product performance figures (e.g. number of samples analyzed and mission duration) are defined according to the performance objective functions of each market; the performance figures are not normalized in this step. MSE is the system design model used in this study to explore the space of rover products.

Step 6: Search the product trade space of each market

In this step, the system design model is used to explore the trade space of products. A full-factorial search method is employed (Section 3.3). The outcome of this step is M sets of product trade spaces.

Mars rover example

MSE was used to generate product trade spaces for all selected Mars missions based on the trade space parameterization of Table 5-3. Figure 5-5 shows the performance and cost of products grouped by market segments (missions): MER, MER-C, MSL-MHP, MSL, and AFL. Larger missions tend to have smaller numbers of samples analyzed because they run more measurements on each sample. Product performance should not be compared across missions since the *number of samples analyzed* metric is only appropriate to rank products with similar scientific payloads.
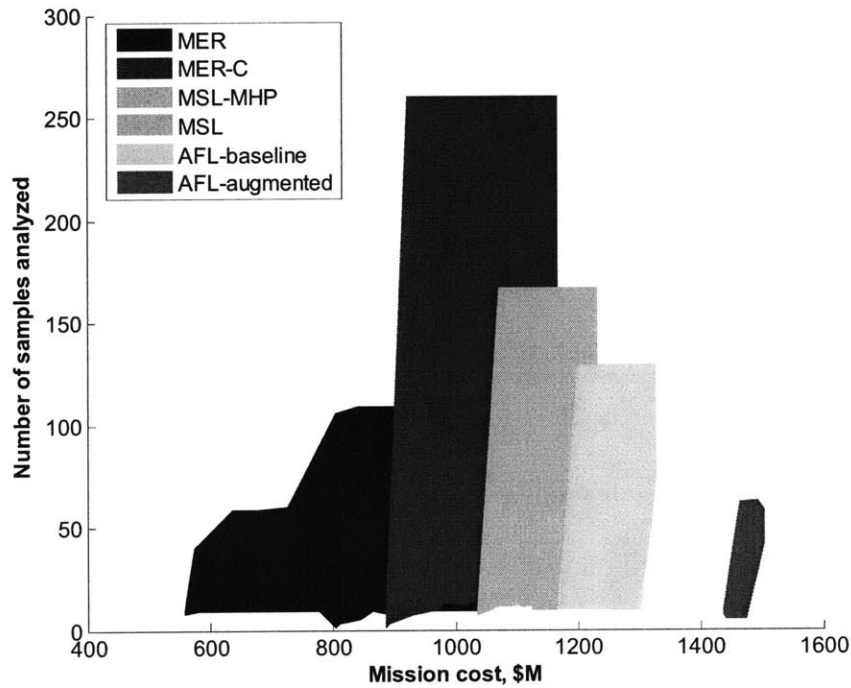
Figure 5-5 MER mission product trade space

The x-axis span of each mission trade space is an indication of the range of rover vehicles which can achieve the mission. As expected, there are more rover designs able to carry the

MER payload than the AFL payload. Table 5-4 lists the number of products that comprise each mission segment trade space.

Table 5-4 Number of products in each mission segment

Mission	Number of products
MER	900
Mars fetch II	486
MER-C	624
MSL MHP	520
MSL	416
AFL baseline	416
AFL augmented	184

The total number of products in the trade space is the sum of the number of products in each mission segment; this number is 3546. The total number of possible product families is the product of the number of products in each mission segment; this number is approximately $4.5*10^{18}$.

Step 7: Distinguish product platform components and product variant components

In the approach proposed by Gonzalez, platform components are identified by experts via an iterative examination of requirements, flexibility of subsystems, availability of resources, and schedule constraints [Gonzalez, 2000]. In this methodology, the component platform selection process can also be supported by analyses of the product trade spaces previously created; for example, candidate platform components exhibit little sensitivity with respect to mission objectives (e.g. scientific payload).

The outcome of this step is the identification of platform design variables and corresponding platform components. The remaining design variables are variant design variables. If no satisfactory set of platform design variables can be identified, the original set of design variables should be modified (step 5). The number (N_P) of platforms modeled in the product family trade space is equal to the product of the number of levels L_x of each platform design variable x_{pk}.

$$N_P = \prod_k L_{x_{pk}}$$

(5-26)

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Mars rover example

Arguments were provided at the beginning of this analysis that support the decision to select the mobility, WEB, and power source as platform components. The corresponding platform design variables are wheel size and power source type. The wheel diameter is the scaling parameter of the mobility system and, together with the power source type, drives the structural properties of the WEB. The remaining rover components are variant components; they include payload, arm, mast, thermal components, batteries, and avionics.

In this study, all Mars rover mission trade spaces include nine wheel diameters (levels) ranging from 0.2 meters to 0.6 meters and two levels of the power system (either solar or RPS) (Table 5-3). There are therefore 18 possible combinations of wheels and power systems. Of these, three do not have feasible solutions. The examination of the product database shows that rovers with a 0.20 meter wheel and RPS-powered rovers with a 0.25 meter wheel are infeasible because they cannot accommodate the payload and all subsystems. The total number of platforms is therefore $N_p=15$; the platforms are listed in Table 5-5.

Table 5-5 List of feasible Mars rover platforms

name	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}
wheel, m	0.25	0.30	0.30	0.35	0.35	0.40	0.40	0.45	0.45	0.50	0.50	0.55	0.55	0.60	0.60
power source	sol	sol	RPS	sol	RPS	sol	RPS	sol	RPS	sol	RPS	sol	RPS	sol	RPS

Figure 5-6 shows the scientific return and cost of MER products; the products are grouped according to the platform they belong to. The examination of the figure leads to several comments about the MER trade space. First, the elongated vertical shape of platform loci suggests that the impact on product cost (and mass) of variant design variables is small compared to that of platform design variables. The width along the x-axis of each loci, which shows the sensitivity to variant design variables, is smaller than the separation between loci, which shows the sensitivity to platform design variables. This supports the previous statement about the wheel diameter and the power system being key drivers of rover system properties. Second, the switch from a solar power source to a RPS power source creates a large increase in both product performance and cost. Third, increasing the wheel diameter

above 0.35m does not improve performance – this result may change for rockier terrain types.
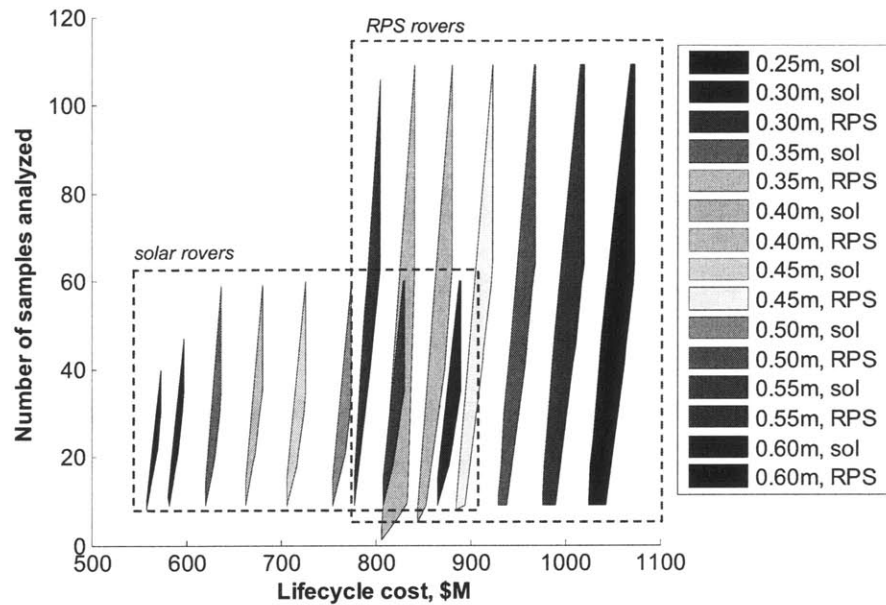
Figure 5-6 MER mission product trade space with product grouped by platform

Step 8: Estimate the cost of product platform components

The purpose of this step is to calculate the cost of product families by taking into account savings generated by platform strategies. The lifecycle cost of a product is broken down into several elements as shown in Figure 5-7. Platform strategies generate savings at the formulation level and platform component development level. Lifecycle and operations costs are calculated using the system design model; the difference of the two is formulation and development cost C^{AD} which covers costs from pre-Phase A to Phase D. Formulation cost and development cost are calculated as percentages of C^{AD}.
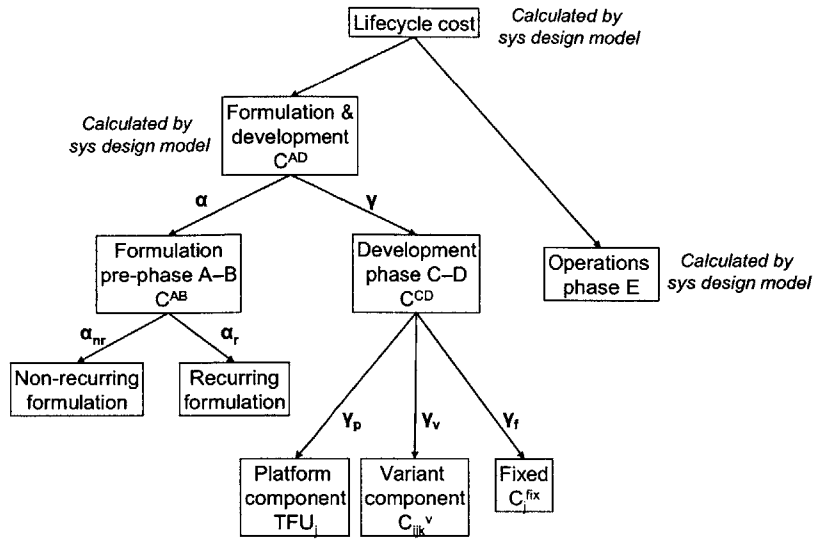
Figure 5-7 Decomposition of product lifecycle cost

As stated at the introduction to this analysis, only a fraction of the original formulation effort is repeated, for each mission, for platform-derived products following the first unit (Figure 5-7). Development cost is further decomposed into the platform component cost (*TFU*), variant component cost (C_{ijk}^v), and fixed recurring costs (C_j^{fix}). Learning curve effects apply to the development of platform components; the development cost of K units of a platform component is given by Equation (5-1). Based on this decomposition, the formulation and development cost of a family of K products derived from the same platform is given in Equation (5-27).

$$C_{j,K}^{AD} = \alpha\left(\alpha_{nr}C_j^{AB} + \alpha_r K C_j^{AB}\right) + \gamma\left(K^B TFU_j + \sum_{i=1}^{K} C_{ijk}^v + KC_j^{fix}\right) \qquad (5\text{-}27)$$

The various fractions α and γ are determined based on historical data from similar missions. The updated product family lifecycle cost is the sum of development cost given in Equation (5-27) and of the operations cost calculated by the system design model.

$$C_{j,K}^{AE} = C_{j,K}^{AD} + C_j^E \qquad (5\text{-}28)$$

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Mars rover example

Table 5-6 lists formulation and development costs as percentages of C^{AD} for several Mars missions.

Table 5-6 Formulation and development costs for Mars orbiting and surface missions ([NASA, 2005], [NASA, 2008])

	Total (FY06 $M)	Formulation	Development
Mars Odyssey Orbiter	373	12%	88%
Mars Reconnaissance Orbiter (MRO)	511	11%	89%
Mars Exploration Rovers (MER)	750	9%	91%
Mars Science Laboratory (MSL)	942	36%	64%

MSL's formulation cost ratio diverges significantly from that of Mars Odyssey, MRO, and MER. MER has a low formulation cost ratio because it had a single formulation phase but two rover products were developed. This analysis considers formulation cost ratios ranging from 10% to 20% with a default value of 15%.

Experience with Venus Express suggests that the share of recurring formulation costs is between a quarter and a third of theoretical first unit's formulation costs (Figure 5-2).

$$\frac{1}{4} \leq \alpha_r \leq \frac{1}{3}$$
$$\alpha_{nr} = 1 - \alpha_r$$

(5-29)

This analysis assumes that an average production rate of one rover every six years is not sufficient to justify benefits from production learning curve; the learning curve slope is set at S=100% which means B=1 in Equation (5-27). The subsequent paragraphs decompose development cost into TFU, variant cost, and fixed cost.

The 2008 budget request of MSL provides a decomposition of development cost (Table 5-7) which is used in this analysis to derive γ_p, γ_v, γ_f. The cost breakdown of the MSL mission provided by the NASA budget request does not match exactly the cost breakdown used in this analysis. In Table 5-7, rover development cost is combined with that of spacecraft and carrier. This study assumes the spacecraft and carrier are platform components of the rover architecture; in other words, they benefit from the same learning curve as do rover platform

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components. Because, in this analysis, rover platform components drive the system mass and dimensions, two rover variants of the same platform could use identical spacecraft and carriers. With this assumption, *TFU* includes development costs of the rover platform components, spacecraft, and carrier.

Table 5-7 MSL development cost breakdown

Element	Development Cost Estimate (FY07 $M)	Ratio of total development cost
Spacecraft, rover, & carrier	424.8	40%
Payload	64.9	6%
Systems I&T	46.5	4%
Launch vehicle/services	182.6	17%
Ground systems	45.5	4%
Science/technology	11.4	1%
Other	292.8	28%

The cost $C^{s/c}$ of the spacecraft, carrier, and rover provided in Table 5-7 includes *TFU* and rover variant component costs. The remaining variant component costs are included in payload cost. This analysis assumes *TFU* constitutes 60% of $C^{s/c}$.

$$TFU = \delta C^{s/c}$$
$$\delta = 60\%$$
(5-30)

According to Table 5-7, $C^{s/c}$ is 40% of the total product development cost; therefore *TFU* is 24% of the total development cost.

$$TFU = \gamma_p C^{CD}, \gamma_p = 24\%$$
(5-31)

The share of variant component cost includes the remaining 40% of $C^{s/c}$ and payload cost.

$$C^{v}_{ijk} = \gamma_v C^{CD}, \gamma_v = 22\%$$
(5-32)

In Table 5-7, costs not related to the spacecraft, rover, carrier, and payload are considered fixed recurring costs.

$$C^{fix} = \gamma_f C^{CD}, \gamma_f = 54\%$$
(5-33)

Because this analysis assumes there is no learning curve benefit in the production of rover missions, all the savings generated by the platform strategy happen during the formulation phase. With α=15% (Table 5-6) and α_{nr}=75% (Equation (5-29)), a platform strategy saves approximately 11.25% of the total formulation and development cost of each new platform-

derived product. The question answered in the subsequent paragraphs is whether these savings are sufficient to offset the costs due to the non-optimality of platform families.

Step 9: Cost minimization

In this step, the minimum cost N-family is identified. The Pareto and partition reductions (Sections 5.4.2 and 5.4.3) are applied to the trade space of product variants. In this case, the optimal product variant of a platform in a market is simply the minimum cost variant. In other words, the Pareto front of optimal variants is reduced to one variant per platform per market. There at most N_p*M variants in the reduced trade space and $(N_p)^M$ possible product families.

The partition reduction is applied to this reduced trade space. The task is to assign the best platform to every combination of mission markets (i.e. every subset of $\mathfrak{M}$). The set $\mathfrak{M}$ of mission segments has M elements; there are therefore 2^M-1 non-empty subsets of $\mathfrak{M}$. Given a subset SS and a platform j, 1-families are constructed by combining the minimum cost variant of j for each market of SS. The best combination is that which the cost function of Equation (5-27). Because within a 1-family all cost are constants, except for variant costs, minimizing the cost function of Equation (5-27) is the same as minimizing the cost function of Equation (5-34).

$$C_{j,K}^{v} = \sum_{i=1}^{K} C_{ijk}^{v} \tag{5-34}$$

where

$$K = card(SS) \tag{5-35}$$

The optimal platform for the subset SS is the one with the minimum cost function. The outcome of this step is 2^M-1 optimal platforms associated with each subset of $\mathfrak{M}$.

The previous subsets of mission segments are used to construct partitions of the space $\mathfrak{M}$. The number of partitions of the set $\mathfrak{M}$ of M elements into N subsets is a Stirling number of the second kind noted $\begin{Bmatrix} M \\ N \end{Bmatrix}$ (Equation (5-18)). The total number Φ_j of partitions of $\mathfrak{M}$ is given by Equation (5-19); the number of partitions of a set of M elements is also called the Mth Bell number. Bell numbers increase rapidly with the size of the set; while for M ranging

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from 7 to 10, the corresponding Bell numbers are 877, 4140, 21147, 115975. The enumeration of all partitions of a set larger than 10 is a computationally expensive, but purely mathematical, problem. The enumeration can be solved independently and its results saved in a database accessed by platform optimization algorithms.

As proved in Section 5.4.3, for a given partition of $\mathfrak{M}$ with N subsets, the minimum-cost N-family is made of the minimum-cost 1-families over each subset. The N-family with the overall minimum cost is the optimal product family of $\mathfrak{M}$ with at most N platforms. The process is repeated and the optimal N-family is identified for each value of N ranging from 1 to M. Among the M product families, the one with the minimum cost is the optimal one and the number of platforms it uses is the optimal number of platforms.

The knowledge of the minimum cost product families for each subset of $\mathfrak{M}$ is used to normalize cost functions in the optimization problem B (cost and performance) described in Step 10 through 12.

Step 10: Performance and cost optimization – Identify optimal variants of each platform in each market

In this step, the Pareto reduction is performed, for the optimization problem B, on the original trade space produced by Step 6. Pareto optimal variants of each platform in each market are identified from the product database. By definition, to be Pareto optimal, a variant must satisfy two conditions. First, its performance must be higher than that of other variants with lower costs. Second, its cost must be lower than that of other variants with higher performances. Reciprocally, for every dominated variant, i.e. non-Pareto optimal variant, there exists at least on other variant which has both a higher performance and a lower cost. The next paragraph describes an algorithm to identify Pareto optimal variants of a platform within a market.

First, all variants of a given platform are sorted in an array based on lifecycle cost; the first element V_1 of the array is the variant with the lowest cost. By definition, V_1 is a Pareto optimal variant; it is the first element in the array of Pareto optimal variants Π. Then, the next variant V_2, of higher cost, is considered. The variant V_2 is optimal if its performance is better than that of all elements of Π, i.e. V_1. If V_2 is Pareto optimal it is added to the list of elements of Π. The process is repeated for all the remaining variants in order of increasing

cost. The variant V_k is optimal if its performance is better than that of all elements of Π. In the remaining paragraphs, the list of Pareto optimal variants of the jth platform in the ith market is noted Π_{ij}.

The number Φ_{Pareto} of product evaluations performed in this step is given in Equation (5-36) where N_{ij} is the number of variants of the jth platform in the ith segment (Equation (5-10)).

$$\Phi_{Pareto} = \sum_{i=1}^{M} \sum_{j=1}^{N_P} N_{ij} \qquad (5\text{-}36)$$

Mars rover example

Based on Table 5-4, the number of product evaluations performed in this step is $\Phi_{Pareto}=3546$. The total number of optimal product variants in each mission segment is listed in Table 5-8.

Table 5-8 Number of optimal products in each mission segment

Mission	Number of optimal products
MER	189
Mars fetch II	20
MER-C	108
MSL MHP	79
MSL	60
AFL baseline	64
AFL augmented	26

The total number of products left in the trade space is 546. The total number of possible product families is approximately $3*10^{12}$. The Pareto reduction reduced the number of candidate families in the whole trade space of seven missions by six orders of magnitude.

Step 11: Identify 1-families that optimize each subset of $\mathfrak{M}$

This is the first stage of the partition reduction process (Section 5.4.3) applied to the optimization problem B. The process is very similar to that described in Step 9 for the cost minimization. The task is to assign the best platform to every combination of mission

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markets (i.e. every subset of $\mathfrak{M}$). The set $\mathfrak{M}$ of mission segments has M elements; there are therefore $2^M\text{-}1$ non-empty subsets of $\mathfrak{M}$.

Given a subset SS and a platform j, 1-families are constructed by combining optimal variants of j for each market of SS. The best combination is that which maximizes the value function of Equation (5-37), which is derived from Equation (5-24) and Equation (5-28).

$$V_j^{SS} = \frac{\omega}{K}\sum_{i \in SS}\overline{S}_{ijk} + (1-\omega)\frac{1}{\overline{C}_{j,K}^{AE}} \tag{5-37}$$

where

$$\overline{C}_{j,K}^{AE} = \frac{C_{j,K}^{AE}}{C_{SS}^{\min}} \tag{5-38}$$

$$K = card(SS)$$

Equation (5-38) shows that the cost of a 1-family for the subset SS is normalized by the cost of the minimum-cost 1-family, for the same subset, identified in Step 9. Then, the optimal platform for SS is the one with the largest value function. The outcome of this step is $2^M\text{-}1$ optimal platforms associated with one subset of $\mathfrak{M}$. This step is can be computationally expensive; the number Φ_2 of family evaluations involved is given by Equation (5-17). If needed, heuristic optimization techniques could be used to speed the search of the optimal 1-family associated with a given subset.

Step 12: Identify the optimal partition of N subsets of $\mathfrak{M}$

This is the second stage of the partition reduction process. The previous subsets of mission segments are used to construct partitions of the space $\mathfrak{M}$ as in Step 9. As proved in Section 5.4.3, for a given partition of $\mathfrak{M}$ with N subsets, the optimal N-family is made of the 1-families optimizing each subset. The value function of a N-family associated with each N-partition of $\mathfrak{M}$ is given in Equation **Error! Reference source not found.**.

$$V^{\mathfrak{M}} = \frac{\omega}{M}\sum_{n=1}^{N}\left(\sum_{i \in SS_n}\overline{S}_{ijk}\right) + (1-\omega)\frac{1}{\sum_{i=1}^{N}\overline{C}_{j,K_n}^{AE}} \tag{5-39}$$

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where

$$K_n = card(SS_n)$$ (5-40)

The N-family with the highest value function is the optimal product family of $\mathfrak{M}$ with at most N platforms. The process is repeated and the optimal N-family is identified for each value of N ranging from 1 to M. Among the M product families, the one with the highest value function is the optimal one. The number of platforms it uses is the optimal number of platforms. The results of this methodology, as applied to the Mars rover example are detailed in the next section.

5.6 Mars Rover Example Results

In this section, cost minimization and performance-cost optimization methods are applied to six campaign scenarios which combine missions introduced in Table 5-2. A campaign is defined as a series of missions (a set of markets) which constitute an exploration program. The six campaigns considered in this example are listed in Table 5-9.

Table 5-9 Mars exploration campaign examples

	Campaign 1	Campaign 2	Campaign 3	Campaign 4	Campaign 5	Campaign 6
MER						✓
MSR	✓	✓	✓	✓	✓	✓
Mid Rover		✓			✓	✓
MSL	✓	✓	✓	✓	✓	✓
MSL MHP				✓		
AFL-b	✓				✓	✓
AFL-a			✓			

Campaigns labeled 1 through 4 have three missions which involve MSL, MSR and one of the 2016/2018 candidate missions: Mid-rover, MSL-MHP, baseline AFL (AFL-b), and augmented AFL (AFL-a). Campaign 5 has four missions and augments Campaign 2 with AFL-b. The sixth campaign has five missions and augments Campaign 5 with MER.

5.6.1 Cost Minimization of Campaign 5

The results of the cost minimization method applied to Campaign 5 (Table 5-9) are illustrated in Figure 5-8. The figure is organized in four sections described below. The results assume a 15% formulation cost ratio and a 100% learning curve slope.
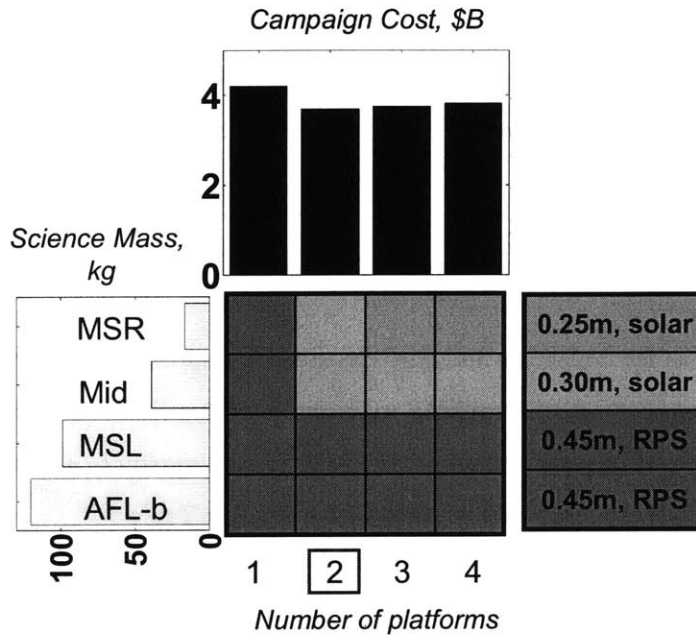
Figure 5-8 Results of the cost minimization methods applied to Campaign 5

In the left section, a horizontal bar chart shows the mass of the scientific payload on each of the four missions in Campaign 5. The plot shows that the scientific payloads cover a wide range in mass, from almost 10 kilograms to more than 100 kilograms. Two groups of payload can be distinguished. The first group, the light payload group, includes the MSR and Mid-rover missions. The second group, the heavy payload group, includes the MSL and AFL-b missions.

In the lower-middle section of the figure, a four-by-four matrix shows the composition of the minimum-cost product families for the number of platforms ranging from one to four. Each row of the matrix corresponds to a mission (from top to bottom): MSR, Mid-rover, MSL, and AFL-b. Each column of the matrix corresponds to a given number of platforms (N). The matrix assigns a mission to its optimal platform in each of the four cases. By

definition for the case N=1 (first column), all missions are assigned to the same platform. This is illustrated by the fact that all the cells of the first column have the same background shade. This background shade corresponds to that of a cell in the left section of the figure. In the case N=1, the result of the cost-minimization process is that all missions use a 0.45 meter wheel, RPS-powered rover. In the case N=2 (second column), two platforms are used; the corresponding column has two groups of cells with different background shade. The top group, corresponding to the MSR and Mid-rover rows, has a lighter background shade which corresponds to that of the 0.30 meter wheel, solar-powered rover in the left section of the figure. The bottom group, corresponding to the MSL and AFL rows, use the same 0.45 meter wheel, RPS-powered rover as in the case N=1. In the cases N=3, the optimal product family uses three platforms. The figure shows that the optimal product family is composed of a 0.25 meter wheel, solar-powered rover for the MSR mission, a 0.30 meter wheel, solar-powered rover for the Mid-rover mission, and two 0.45 meter wheel, RPS-powered rovers for the MSL and AFL missions. The same family is also optimal for the case N=4. Because the MSL and AFL missions share very similar requirements, the MSL-optimal and AFL-optimal rovers use the same platform.

In the top section of the figure, a vertical bar chart shows the cost of each minimum-cost product family for N ranging from one to four. The overall minimum-cost product family is that which uses two platforms, one for the light payload group and one for the heavy payload group. The most expensive one is that which uses one platform. Because the mission requirements of the MSR and AFL-b missions are very different, the one-platform solution is penalized; operating a 0.45 meter wheel, RPS-powered rover to perform the MSR mission is not efficient. The savings generated by the optimal platform strategy (N=2) compared to a customized strategy (N=4) are approximately 3.5% of the total family cost for N=4.

5.6.2 Cost Minimization for the Six Campaigns

Results for 15% formulation cost ratio and 100% learning curve slope

The results of the cost minimization method applied to the six campaigns are summarized in Table 5-10. The table is organized in two parts. The top half of the table has the same format as Table 5-9; it lists the optimal platform strategies for each campaign and each value

of N. The lower half shows the cost of the minimum-cost product family, for each campaign and each value of N, as well as the savings generated by platform strategies.

Table 5-10 Minimum-cost product families for the six campaigns

Shaded backgrounds are used to group similar platforms.

P$_1$: 0.25m, solar; P$_2$: 0.30m, solar; P$_7$: 0.40m, RPS; P$_9$: 0.45m, RPS; P$_{15}$: 0.60m, RPS

# platforms	Campaign 1			Campaign 2			Campaign 3			Campaign 4			Campaign 5				Campaign 6				
	N=1	N=2	N=3	N=1	N=2	N=3	N=1	N=2	N=3	N=1	N=2	N=3	N=1	N=2	N=3	N=4	N=1	N=2	N=3	N=4	N=5
MER																	P$_9$	P$_2$	P$_1$	P$_1$	P$_1$
MSR	P$_9$	P$_1$	P$_1$	P$_9$	P$_2$	P$_1$	P$_{15}$	P$_1$	P$_1$	P$_9$	P$_1$	P$_1$	P$_9$	P$_2$	P$_1$	P$_1$	P$_9$	P$_2$	P$_1$	P$_1$	P$_1$
Mid Rover				P$_9$	P$_2$	P$_2$							P$_9$	P$_2$	P$_2$	P$_2$	P$_9$	P$_2$	P$_2$	P$_2$	P$_2$
MSL	P$_9$	P$_9$	P$_9$	P$_9$	P$_9$	P$_9$	P$_{15}$	P$_{15}$	P$_9$	P$_9$	P$_9$	P$_9$	P$_9$	P$_9$	P$_9$	P$_9$	P$_9$	P$_9$	P$_9$	P$_9$	P$_9$
MSL MHP										P$_9$	P$_9$	P$_7$									
AFL-b	P$_9$	P$_9$	P$_9$										P$_9$	P$_9$	P$_9$	P$_9$	P$_9$	P$_9$	P$_9$	P$_9$	P$_9$
AFL-a							P$_{15}$	P$_{15}$	P$_{15}$												

	Campaign 1	Campaign 2	Campaign 3	Campaign 4	Campaign 5	Campaign 6
Campaign cost, $B	(bar chart)	(bar chart)	(bar chart)	(bar chart)	(bar chart)	(bar chart)
Benefits, $M (a priori),	N/A	29	0	77	55	N/A
Benefits, $M (a posteriori)	N/A	29	0	77	130	N/A

In the top of half of the table, the left column lists all seven missions and the top row lists all six campaigns, as in Table 5-9. A number of columns are shown under each campaign; the number of columns is equal to M, the number of missions involved in the campaign. Each column represents a platform strategy, as in Figure 5-8 where each column of the central matrix represents a platform strategy. Each column is labeled N=i where i is the number of platforms used in the strategy. The entry at the intersection of a platform strategy column and a mission row is the optimal platform P$_j$ used for that particular mission (platform indices are listed in Table 5-5). Hence, the set of platforms listed in a particular column is the minimum-cost product family for the corresponding scenario. Platforms listed in columns labeled N=1 are all the same because these columns correspond to platform strategies where a single platform is used to conduct all missions in that campaign. The minimum-cost product families listed under Campaign 5 for N ranging from one to four are the same as those illustrated in Figure 5-8.

The cost of each minimum-cost product family is represented graphically in the lower half of Table 5-10. For each campaign, a bar plot shows the cost of each platform strategy for N=1 to M. The y-axis of each plot is the family cost in FY06 $B; the x-axis is the number of platforms (N) in the family. The optimal number of platforms N* is that for which the product family cost is minimum. For each campaign, N=N* is printed in bold font in the second row of the table. For most campaigns, the optimal number of platforms is two. However, in Campaign 3 the optimal number of platforms is three because the mission requirements of MSR, MSL, and AFL-a are not sufficiently compatible (Figure 5-4).

The benefits generated by platform strategies are provided below each plot. The benefits are the cost difference between the optimal platform strategy (N= N*) and the customized strategy (N=M). In some cases, the customized product family (N=M) still shares common platforms across several missions. This is true for campaigns 1, 5 and 6. Two calculations of benefits are distinguished depending on whether the design team is aware a priori that platform strategies are possible. Campaign 5 is used as an example to illustrate the two situations. In the first situation, even though designers are not implementing a platform strategy, they know *a priori* that MSL and AFL-b have compatible requirements and will, therefore, share components. The cost calculation of the customized product family (N=4) takes into account the savings generated by using the same platform P_9 for MSL and AFL-b. The benefits of the optimal platform strategy are, in this situation, $55M (listed in the *Benefits a priori* row of Table 5-10). In the second situation, designers do not know until the MSL and AFL-b missions are designed that they both use the same platform. The cost calculation of the customized product family does not take into account any platform savings, which means the customized solution appears more expensive compared to the optimal platform strategy solution. In this situation, the benefits are $130M (listed in the *Benefits a posteriori* row). Still, with both calculations, platform strategies exhibit limited benefits. The savings of optimal platform strategies represent only 1% to 4% of the customized solution costs.

Sensitivities to performance cost ratio and learning curve slope

Previous calculations used a learning curve slope of 100%; a learning curve slope of more than 95% is recommended for productions of 10 units or less [Larson, 1992]. Moreover, Table 5-6 showed that formulation cost ratios can range from 10% to 20%, depending on

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missions. Table 5-11 lists a posteriori platform benefits for these ranges of formulation cost ratio and learning curve slope.

Table 5-11 Benefits for formulation cost ratios (α) ranging from 10% to 15% and learning curve slope (S) ranging from 95% to 100%.

Benefits as percentages of total campaign budgets are included in parentheses.

S	α	Campaign 1	Campaign 2	Campaign 3	Campaign 4	Campaign 5	Campaign 6
100%	10%	67 (2.5%)	7 (2.5%)	0	43 (1.5%)	74 (2%)	106 (2%)
100%	15%	101 (3.5%)	29 (1%)	0	77 (3%)	129 (3.5%)	159 (3.5%)
100%	20%	135 (5%)	51 (2%)	21 (1%)	110 (4%)	185 (5%)	232 (5%)
95%	15%	152 (5%)	56 (2%)	29 (1%)	118 (4%)	197 (5%)	257 (5.5%)

Variations of α and S have a homogeneous effect on all campaigns. Table 5-11 shows that for likely values of α and S, a posteriori platform benefits can be expected to range from approximately 2% to 5% of total campaign budgets.

5.6.3 Campaign performance and cost optimization

The same campaigns are now optimized for performance and cost using values of the objective weigh ω (Equation (5-24)) ranging from zero to one. The case $\omega = 0$ corresponds to the cost minimization already analyzed in the previous section. Cost minimization results are used to normalize cost numbers in the performance and cost optimization method. The optimal product platform families for each value of ω are listed in Table 5-12.

Table 5-12 Pareto product families

ω	0	0.1 to 0.2	0.4 to 0.9	1
Campaign 1	P_1, P_9	P_1, P_9	P_3, P_9	P_9
Campaign 2	P_2, P_9	P_2, P_9	P_5, P_9	P_9
Campaign 3	P_1, P_9, P_{15}	P_1, P_9, P_{15}	P_3, P_9, P_{15}	P_{15}
Campaign 4	P_1, P_9	P_1, P_9	P_3, P_9	P_9
Campaign 5	P_2, P_9	P_2, P_9	P_5, P_9	P_9
Campaign 6	P_1, P_2, P_9	P_2, P_9	P_5, P_9	P_9

The table shows that, except for Campaign 6, the optimal number of platforms does not change for values of ω ranging from 0 to 0.9 (emphasis towards the performance goal). As expected, when only performance is optimized ($\omega = 1$), the optimal strategy uses the largest platform, from that campaign Pareto optimal set, for all missions. Furthermore, only the

MSR and Mid-rover missions have platforms that vary with ω. For MSR, the platform P_1 (0.25 meter wheel, solar power) is upgraded to P_3 (0.30 meter wheel and RPS power). For Mid-rover, the platform P_2 (0.30 meter wheel, solar power) is upgraded to P_5 (0.35 meter wheel, RPS). Once upgraded to RPS power the platforms, do not change because increasing the wheel diameter of a RPS-powered rover does not significantly increases its performance, as illustrated in Figure 5-5.

5.7 Conclusions

This section described two efficient methods for analyzing platform strategies in the context of space exploration products. The implicit enumeration technique used in both methods enables the search of platform option spaces with as many as ten market segments. For problems involving more market segments, the implicit enumeration does not sufficiently reduce the size of the option space. However, since space exploration roadmaps rarely forecast more than ten missions into the future, this problem does not limit the usefulness of the methods. Some limitations of these methods include the fact that they do not capture the stochastic nature of mission roadmaps (political redirection). These methods, supplemented with a real options analysis, could value platform strategies in the face of uncertainties regarding the occurrence of future missions and their requirements.

For the six campaigns considered, platform strategies generated limited savings (at most 5% of the customized campaign cost) compared to the customized strategy. These savings are judged not sufficient to offset policy and cultural factors that act for a customization of space products. These factors are discussed in the introduction of this chapter and the *Platform strategy* section of Chapter 2. In order to be successful, a platform strategy would need to impose a fundamental paradigm shift from science-driven products, optimized for scientific performance under cost constraints, to platform-derived products, optimized for cost under scientific performance constraints.

Chapter 6

Conclusions and Recommendations

This chapter presents a thesis summary, the thesis contributions and recommendations for future work.

6.1 Thesis summary

This thesis develops a set of methods and tools for the formulation, evaluation, and optimization of rover mission concepts. It addresses the need for a) a rationale and structure to organize Mars surface exploration concepts, b) a rover system design model with rapid trade space exploration capability and c) an analysis of the technical and physical implementation aspects of rover design. Accordingly, the thesis was organized in three stages. The first stage (formulation) is dedicated to the qualitative exploration of surface exploration concepts. A functional decomposition process is proposed to structure the design space of exploration concepts. The resulting concept and figure of merit trees provide designers with an overview of the design space and an understanding of the sensitivity of each concept implementation with stakeholder figures of merit. The second stage (evaluation) focuses on the quantitative exploration of rover designs. The description of the Mars Surface Exploration (MSE) tool demonstrated the tool's ability to perform rapid exploration of rover design trade spaces with pre-Phase A fidelity. The third stage (optimization) addresses the quantitative optimization of complex aspects of rover architectures. Two methods were proposed to value autonomy technologies and to develop and optimize space exploraiton platform strategies. The methods relied on the figure of merit tree and system architecting principles, identified in the formulation stage, and on

MSE's analytical capabilities. The optimization stage proved that the combined products of the three stages form a useful pre-Phase A decision-making tool. The subsequent paragraphs go other the results of each stage in more detail.

The formulation stage delivers three products. The first product is the characterization of NASA's current design approach to rover flight projects. This task is achieved by a reverse engineering process which compares the functional, physical, technical, and operational aspects of Sojourner, MER, and MSL. This allows the distinction between rover class attributes, attributes common to all NASA rovers, and rover design choices, attributes specific to some rovers. The rover class attributes characterize NASA's approach to the design of rover systems.

The two other products are the concept and figure of merit trees. They are the results of the parallel decomposition of the abstract definitions of Mars exploration function and form. In the functional decomposition process, the stakeholders of Mars exploration and their figures of merit are identified. The three core functions of surface exploration, *traveling, collecting* and *communicating Mars data*, are derived. The successive allocations of these functions to agents of the MEP (surface probe, supporting systems, and ground control), then to vehicles of the probe, and finally to subsystems of each vehicle, generate a large number of surface mission concepts. Analogies between computer network architectures and surface exploration architectures prove very useful in rationalizing the allocation of functions among vehicles. In particular, the Generalized Information Network Analysis (GINA) framework provides a suitable set of metrics to evaluate surface vehicle networks. GINA's metrics are supplemented with a new metric, bandwidth, which characterizes the range of measurements a surface network is able to perform. The qualitative exploration of the trade space of surface exploration concepts is organized in two trees. The concept tree gathers a wide array of physical and technical implementations of surface exploration concepts. The figure of merit tree makes explicit all the decision steps which connect the generic definition of a Mars exploration mission to particular instantiations of a rover missions. The examination of this tree showed that affordability and resource efficiency are the driving figures of merit of NASA rover missions. The figures of merit and system architecting principles are the indicators which guide designers in the selection of valuable surface concepts. The process is

illustrated with the formulation of a multi-rover lunar mission concept which incorporates modular and platform capabilities.

The products of the evaluation stage are the Mars Surface Exploration (MSE) rover modeling tool and the Rover Mission Analysis and Design (RoMAD) document. MSE, and at a lesser degree RoMAD, are analytical models which enable the quantitative assessment of the performance of a given rover concept with respect to scientific productivity, range, and cost metrics. Improvements in the capability and fidelity of MSE models are presented. In particular, the new cost model, based on a regression analysis of Team X studies, shows that rover missions exhibit economies of scale. The system-level comparison of MSE simulations with those of Team X, on a number of mission scenarios, indicate that the tool is mature and ready to perform comparative analyses of rover concepts. As a demonstration of the tool's rapid modeling capabilities, a thorough assessment of a scout-laboratory mission concept is performed in less than two hours; the quantitative results indicate that the benefits in scientific productivity are not worth the costs of developing two rovers.

The RoMAD design document is an offspring of the development of MSE. It represents a collection of design rules of thumb and resources that have been collected during the creation of MSE. RoMAD supplements existing satellite and surface vehicle design books in the particular field of Mars robotic rovers. RoMAD provides system-level relationships, such as a payload mass fraction to estimate rover mass knowing the scientific instrumentation mass, cost relationships and subsystem relationships for sizing the power, structure and mobility subsystems.

In the optimization stage, two methods for optimizing autonomy technology investment and platform strategies are developed. The method for assessing autonomy technology investment relies on the principle that the monetary worth of autonomy can be evaluated by benchmarking its performance against that of competing solutions with known costs. The method improves upon previous methods by enabling a dollar-based quantitative assessment of autonomy development value. The proposed method has been applied to sample approach autonomy and site-to-site traverse autonomy; the results show that the former is more relevant to future missions than the latter. These applications demonstrate that the association of the method with a system design model provides useful quantitative guidance in determining the value of autonomy infusion in future missions.

The method for optimizing platform strategies in the context of deep space missions is based on an extensive body of research applied to commercial platforms. The study of space platforms has received little attention even though platform strategies have successfully been applied in space exploration; ESA's 2005 Venus Express mission is the most recent example. The method introduces an innovative optimization technique which enables a systematic evaluation of all possible platform product families without explicitly evaluating all of them. This technique makes feasible the exploration of large trade spaces of platform options.

The method is used to assess the potential of using platform strategies for the next decade of Mars rover exploration. The results of the analysis, for the six mission campaign scenarios considered, show that platform strategies generate at best savings in the order of five percent of the total campaign budget. These savings are judged not sufficient to offset policy and cultural factors which favor product customization. In order to be successful, a platform strategy would need to impose a fundamental paradigm shift from science driven products, optimized for scientific performance under cost constraints, to platform derived products, optimized for cost under scientific performance constraints. This case study illustrates how both qualitative inputs, based on consideration of figures of merit from the formulation stage, and quantitative inputs, derived from MSE analytical capabilities, enable a grounded decision-making process which captures all relevant factors in sufficient details.

6.2 Contributions

As stated in the introduction (Chapter 1), the goal of this research is to provide advance study engineers with theoretical and quantitative means to better explore the broad spectrum of architectural options and produce sound mission concepts. The contributions made to this goal are listed in Table 6-1.

Table 6-1 Summary of thesis contributions

Contributions	Value	Beneficiaries
Map of surface mission concept paths	- maps planetary surface exploration alternatives; - correlates stakeholder needs to concept selection.	Mission Systems Concepts grp
Mars Surface Exploration rover design tool	- evaluates performance and cost of traditional rover concepts; - enables rapid exploration of large trade spaces; - is validated with JPL pre-Phase A modeling environment; - is equipped integrated tools to conduct trade space analyses	- Mars advanced study grp - Science steering grp
Rover design document	- provides meta-relationships for rapid assessment of a rover concept's system properties	- Proposal managers - Educators
Autonomy valuation method	- enables dollar-based assessement of relevance of new autonomy technology in future missions	Mars Technology Program
Platform strategy analysis method	- develops and optimizes platform strategies for deep space exploration programs	Mars Technology Program

6.3 Recommendations and Future Work

This thesis has developed several theoretical and analytical products for conducting the trade space exploration of rover mission concepts in the early conceptual phase. For each product, capabilities can be further refined and the scope expanded.

- Surface mission concept paths
  - o Refinement: there is value in a representation which could capture all dimensions of the concept space at once. It is currently difficult to represent technical implementation options and platform strategy options, which happen over time, in a single diagram.
  - o Scope: although effort was made to create a generic map of surface mission concepts, more emphasis was put in the development of rover concepts. Further analysis of other vehicle concepts would complement the map.

- Mars Surface Exploration rover modeling tool (Figure 6-1)
  - o Refinement: the avionics subsystem includes the solid state amplifiers, transponders, and computers. The subsystem is currently scaled by using a parametric relationship based on the number of instruments and acquisition

tools on board the rover. To improve the fidelity of the model, the three components should be modeled with independent mass estimating relationships. Furthermore, the model of ground processing for operations needs to be refined in order to better capture the interactions of the science team with the rover during the sample targeting, handling and measuring activities.
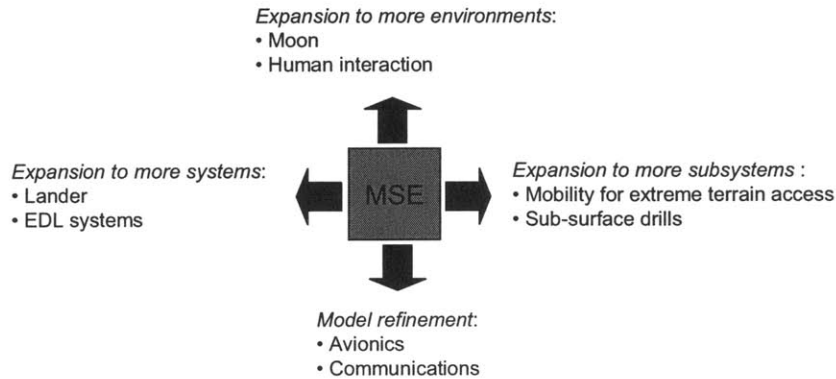
Figure 6-1 Illustration of directions for future work in the development of MSE

o   Scope: the scope of the tool can be expanded in several directions. Current work has focused on expanding the mobility and acquisition tools subsystems. The scope of the mobility subsystem has recently been expanded to capture suspensions other than the traditional rocker-bogie, including tracks, four wheel suspension, legged mobility, and hybrid mobility [McCloskey, 2007]. In addition, new MSE models are currently being developed to understand the impact of equipping MER and MSL class rover systems with drills, both on the engineering design and on scientific capabilities. MSE will be used to analyze the trade-off between sample accessibility and sample analysis capability. For a given payload allocation, the mass allocated to drills, to reach scientifically worthy underground layers, is in competition with that allocated to scientific instruments, to analyze the samples collected.

•   Case studies

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o Refinement: the autonomy technology assessment method can be adapted to autonomy functionalities whose main effect is not to increase scientific productivity but reduce operations. For example, a rover able to navigate autonomously from one site to another would alleviate the need for daily interactions with the operations team and, thereby, significantly reduce operations costs.

o Scope: the new mobility and drill modeling capabilities of MSE will make the tool particularly relevant to study mission concept alternatives for the Astrobiology Field Laboratory (AFL) mission. MSE will be able to compare the performance and cost of MSL-based concepts with other innovative concepts involving drills and legged mobility for extreme terrain access. Such analyses would provide the AFL science steering group with valuable information regarding the expected capabilities of each design.

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