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ABSTRACT

A spectrum of concepts for planetary rovers and rover missions, developed at the Jet Propulsion Laboratory and by supporting contractors during the 1989 fiscal year, is covered. Rovers studied range from tiny "micro" rovers to large and highly automated vehicles capable of travelling hundreds of kilometers and performing complex tasks. Rover concepts are addressed both for the Moon and Mars, including a Lunar/Mars common rover capable of supporting either program with relatively small modifications. Mission requirements considered include both Science and Human Exploration. Studies include a range of autonomy in rovers, from interactive "teleoperated" systems to those requiring an onboard System Executive making very high-level decisions. Both high- and low-technology rover options are addressed. Subsystems are described for a representative selection of these rovers, including: Mobility, Sample Acquisition, Science, Vehicle Control, Thermal Control, Power, Local Navigation, Computation and Communications. System descriptions of rover concepts include diagrams, technology levels, system characteristics, and performance measurement in terms of distance covered, samples collected, and area surveyed for specific representative missions. Rover development schedules and costs are addressed for Lunar and Mars exploration initiatives.

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EXECUTIVE SUMMARY

In FY88 and 89 a spectrum of concepts was developed for automated rovers to operate on the surface of the moon and Mars. The concepts range from "micro-rovers" for collecting limited surface samples in support of a local sample return mission, to large and highly automated vehicles capable of traversing hundreds of kilometers and performing a variety of complex tasks. Table 1E summarizes the rover concepts.

TABLE 1E - ROVER CONCEPT MATRIX

SIZE	POWER	OPS MODE	CONFIG	TECH LEV	RANGE (~3 YRS) MOON	MARS
Micro (1-3kg)	Solar/ MiniRTG† (~10 W)	Automated	Six-Legged "Ant"	Medium	<1 km	<1 km
Small (100-300kg)	Solar/ RTG† (~100 W)	Low-level functions automated	4 - 6 Wheels	Low	100 km	~10 km
Large (500-1000kg)	Solar (~200W)	Low-level functions automated	6 wheels	Low	10^2 km	~10 km
Large (500-1000kg)	RTG† (~500W)	Onboard translation & execution of human plans	6 wheels	Medium	10^3 km	10^2 km
Large (500-1000kg)	RTG† (~500W)	Some onboard planning	6 wheels, Simple Walker	High	10^3 km	10^3 km
Very large (>1000kg)	Dynamic (~25 KW)	As required	Special (e.g. Excavator, cargo truck, human carrier)	Medium	~1 km	----

† RTG = radioisotope thermoelectric generator

The rovers are designed to satisfy two types of requirements: 1) acting as precursors and assistants to human missions to the moon and Mars, and 2) performing scientific exploration - in particular investigating mineralogy and geology and collecting samples for return to earth. A small (~300 kg), low autonomy rover on the moon would traverse a potential habitation area, measuring surface properties by its own interaction with the soil and investigating the subsurface for obstacles to human landing and construction. Larger, more automated rovers would perform the same functions for Mars. Even larger, specialized vehicles would support human activities in base construction, cargo handling, mining, etc.

The primary differences between the moon and Mars are in the round-trip communication time (~3 seconds to 10s of minutes, respectively), and the environment (airless vs. a thin atmosphere, 28 day vs 24 hour night/day cycles). The communication distance makes a high level of automation very desirable for Mars rovers, but not particularly necessary for the moon. In addition, moon rover missions are expected to fly in the mid-to-late 1990s and Mars missions in the early 2000s, giving more time to develop technology to support automated Mars rovers.

Development of rover concepts included definition of design concepts and technology levels for each function: payloads/instruments, system control, mobility, local navigation, sample acquisition and engineering measurements, vehicle control, computation/data management, communications, power and thermal control. Performance for each concept was assessed in terms of mass, power, data and communication requirements by the use of operational scenarios and time lines defined to support each specific mission concept.

Instruments for sampling missions are primarily for remote sensing of mineralogy and chemistry and include spectrometers operating from infrared to x-ray, electromagnetic sounders for subsurface investigations, and instruments to analyze volatile components of the soil and rocks. Sample collection manipulators and tools, and sample storage and preservation mechanisms are included as part of the payloads.

Site characterization payloads include many of the same instruments as the sampling missions, with the addition of more sophisticated subsurface investigation techniques (detailed electromagnetic sounding, surface probes, seismic networks).

An architecture for control of complex rovers was developed and used to allocate control functions in a hierarchical fashion. The architecture fuses robotic control and traditional spacecraft control. It includes command, telemetry and fault protection functions. A concept for an onboard system executive to manage relatively autonomous subsystems was developed, and a computer architecture to support this hierarchical structure was defined. In addition, requirements were identified for an order-of-magnitude improvement in the speed of the ground control systems to interactively command the rover.

A large number of mobility concepts were developed in FY88. The selection was narrowed to wheeled vehicles and simple walkers. In FY89 FMC Corporation and Martin Marietta Corporation, under contract to JPL, each defined a mobility concept in some detail, including the development and test of models. FMC's concept, the "Attached Scout", is a 6-wheeled vehicle with three bodies connected by actively controllable joints. This joint control allows the vehicle to recover from a variety of emergency situations, including collapse of terrain, and vehicle roll-over. MMC's concept is a simple walker, the "Walking Beam" which consists of two bodies with three or four legs each, connected by a rail. It moves by one body retracting its legs, sliding over the other body, and lowering its legs to support a similar movement by the second body. The bodies are connected by a turntable to allow turning. JPL investigated wheeled vehicles with 4 to 6 wheels, and developed new computer techniques for analyzing the obstacle-climbing capability of wheeled vehicles. The two favored concepts feature a single body with suspension systems using "bogie" levers to allow large wheel deflections while maintaining body stability.

Local navigation is the function which directs and guides the rover over the terrain to a goal destination while sensing and avoiding obstacles. Several approaches to local navigation, with varying levels of onboard autonomy were considered. For the moon, or for Mars missions with several years of operation time on the surface, a low-level of automation is acceptable. For these missions operators on earth command the rover to move about 10 meters at a time, based on images sent to earth from the rover. The addition of onboard automation for sensing, perception, path planning, and execution monitoring greatly increases the performance of the rover traverse, and is necessary for Mars missions with limited surface time. JPL, FMC and MMC each studied a concept for this "semi-autonomous" navigation, using stereo imaging, structured light, and laser ranging, respectively, as the primary sensing mode.

A range of levels of autonomy for sample acquisition was also considered. Sample acquisition for low-technology rovers would use simple, specialized manipulators and tools for limited tasks, i.e. scooping soil. More complex missions drilling into rocks and regolith will require a substantial amount of onboard robotic control and demand dexterity and compliance in manipulation. Sample acquisition concepts were based on NASA Office of Aeronautics and Space Technology (OAST) research in space telerobotics.

The vehicle control concepts used traditional spacecraft control sensors, including accelerometers, tilt-meters, star sensors and sun sensors. In addition, sophisticated control for the more autonomous rovers may require a low-speed motion sensor. Vehicle control functions include commanding the mobility motors, pointing camera platforms for navigation and science, and pointing the communication antenna. Pointing a high-gain antenna at earth from the Mars surface proved to be a driver on vehicle control, requiring a star tracker and precision gyros.

Computation concepts ranged from adapting current spacecraft computation designs for the low-technology rovers, to the development of advanced parallel computation and data storage systems. The simple, low-autonomy rovers will require about 1 or 2 million instructions per second (MIPS) of onboard processing and can use current tape recorders for data storage. The semi-autonomous rovers will require around 10 MIPS of general purpose processing, special purpose processing for image understanding and science data reduction, plus advanced data storage (such as optical).

Communication concepts studied ranged from low-frequency, omni-directional rover antennas for communication with a Mars areostationary communications orbiter, through X-band systems using traveling-wave tubes (TWTs) and steerable high-gain antennas, to Ka-

Band phased arrays. The latter two concepts are for communicating directly with the earth from the Mars surface.

Power options included systems with state of the art RTGs, batteries and power management for near-term moon missions. At the other end of the spectrum, Fairchild Space Company, sponsored by DOE, designed special, advanced RTGs to work on the surface of Mars. Since the Martian atmosphere degrades the performance of space RTGs using the current practice of venting to vacuum, Fairchild conceived using a sealed canister to keep out the atmosphere, while allowing venting of Helium built up from radio-active decay. The power subsystem masses tended to drive the total mass of the rover design, making technology advancements in RTGs and batteries very attractive for future Mars missions. Solar options for the moon and Mars were also studied, including a study by AeroVironment, Inc. for Lewis Research Center [Hibbs89]. The low level of insolation at Mars, exacerbated by dust storms, makes solar a marginal option and requires large battery mass for night and idle keep-alive power. On the moon, with the use of radioisotope heater units (RHUs) for heat, solar may be feasible (and indeed Lunokhod showed the feasibility of a solar rover on the moon).

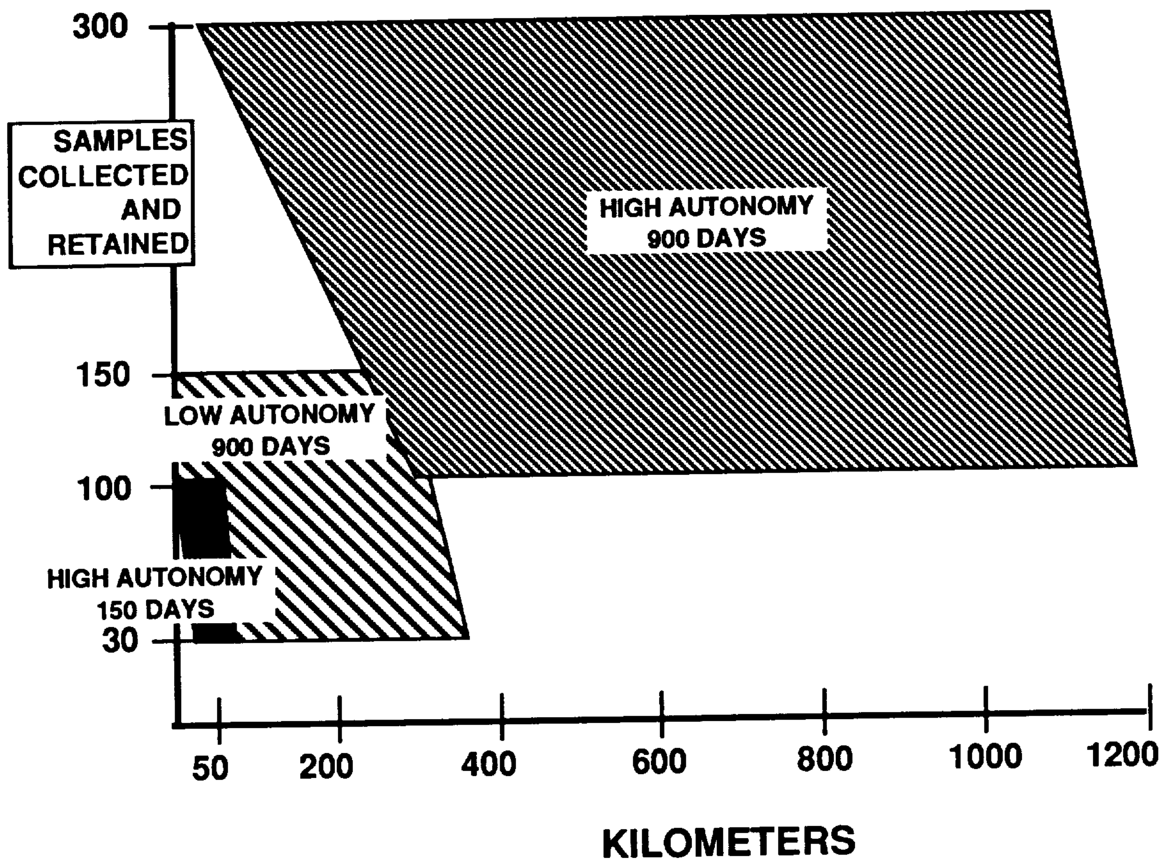
Thermal control is an issue on both planets because of the low temperatures at night, and on the moon because of the long day-night cycle with large temperature ranges. An analysis of the location of RTGs on the Mars rover showed that thermal control to maintain radiation is feasible. Thermal control issues of packaging an RTG-powered rover in an aeroshell for delivery to and landing on Mars were investigated with the Johnson Space Center.

The systems studied ranged in mass from a few kilograms to nearly a thousand, and required up to 500 watts of power generation and 700 watt-hours of energy storage. Large, RTG powered rovers for Mars operation can operate within a 900 kg mass budget, with technology advancements in power leading to lower masses.

Performance of the rovers was calculated primarily in terms of distance covered and number of samples collected. These variables also apply to human precursor missions for site characterization, since traverses covering a prospective 10 by 10 kilometer site, for example, may total several hundred kilometers. Figure E-1 compares the

SINGLE-ROVER PERFORMANCE RANGE OVER 900 DAYS FOR HIGH VS. LOW AUTONOMY

WIDE PERFORMANCE RANGE DUE TO: (1) VARIATION IN ASSUMPTIONS ON CONFIDENCE LEVELS (HIGH VS. LOW), (2) VARYING PENALTY FROM SURFACE SPECTRAL OBSCURATION (25-100% SAMPLE RETENTION), AND (3) VARYING STOPS FOR GROUND SCIENCE DECISIONS (0-7 HOURS/DAY).



E-1 - ROVER TRAVERSE AND SAMPLING PERFORMANCE SUMMARY

performance of sample-collecting rovers on Mars. On the moon there would be about a factor of 10 increase in the performance for a given level of automation. The figure varies several factors to arrive at the range of performance: level of automation (CARD vs semi-autonomous), time on the surface (from 215 to 900 days), operator confidence in the safety of the terrain and the capability of the rover, ability of the science instruments to remotely see attractive samples, and amount of time spent making decisions on earth. CARD stands for Computer-Aided Remote Driving. The large spread in the performance of the high-autonomy rover in 900 days is because of these other factors, and illustrates the need for thorough technology development and verification before flight.

The FY88 and 89 rover studies have shown that automated rovers can perform a variety of important functions on planetary surfaces, and that a range of concepts exists which is appropriate for the planet and time frame for rover exploration.

1.0 INTRODUCTION

Automated planetary rovers have been studied since the late 1960s (for the Moon) and the late 1970s (for Mars). The USSR successfully operated rovers on the Moon in 1970 and 1973 [Turnill74]. Using highly interactive control techniques the Lunokhods traveled 10 and 37 kilometers, respectively, during 11 and 4 month periods. Rovers were a favorite topic of University engineering design studies in the 1980s. Technology for rovers has been developed slowly but steadily since the late 1960s, primarily in the areas of mobility and navigation over rugged, unmarked terrain.

Most recently the Mars Rover Sample Return (MRSR) Development Flight Project studied a number of rover concepts in FY88 and 89. Additionally, at the end of FY89 a new activity to define a spectrum of possible rovers for preceding humans to the Moon and Mars began. This publication presents candidate requirements for rovers on the Moon and Mars, gives the status of the rover designs and performance, and describes some technical issues involved in meeting the mission requirements. Rovers may travel over the rough surfaces of the Moon and Mars, evaluating sites for future human habitation, searching for resources for use by humans, or collecting and storing samples for later return to Earth by a robotic Sample Return mission or by astronauts. The rovers can be directly controlled from the Earth or by astronauts at the planet or satellite, or can be highly automated - with automation meaning a large increase in the speed or amount of terrain covered, the sophistication of measurements, or in the variety of samples collected.

A spectrum of rover capabilities has been addressed over the past two years, ranging from small, simple rovers to be used as "long arms" for a sample return vehicle ("local" rovers), to highly automated rovers capable of covering hundreds of kilometers of planetary surface and collecting a wide variety of geological samples. The primary factors impacting the rover performance in terms of the quality of site characterization, or in the geological and geographical diversity of samples collected are:

- Effect of long communication-time delay
- Level of technology
- Time on the surface
- Variety and difficulty of activities to be performed
- Level of support from other mission elements

The 1988 study, led by JPL with support from FMC Corporation and Martin Marietta Astronautics Group, defined the trade space for designing rovers and narrowed the scope to a few concepts [Piv89], [FMC88], [MMC88]. The primary focus of the 1989 study was to develop more detailed concepts for large rovers capable of operating for long periods on planetary surfaces. The spectrum of these rovers can be characterized by three levels of technology: Simple, low-technology rovers; moderate rovers; and capable rovers. Micro-rovers to support local sample return, and small, low technology rovers for early Lunar operations were also addressed, in less detail. This document defines a set of possible requirements and constraints for Lunar and Mars rovers, outlines the spectrum of rover concepts developed to date, and defines the performance of the different concepts in meeting mission requirements.

2.0 ROVER REQUIREMENTS AND CONCEPTS

2.1 Possible Rover Mission Requirements

2.1.1 Science Requirements - Detailed requirements have been developed for scientific investigation of Mars by rovers collecting geologic samples for return to Earth [SWG89]. In order to characterize the Mars surface, rovers carrying a suite of remote sensing instruments should move over distances up to 1000 km, selecting a diverse set of rock, soil and subsurface samples, and packaging them for return to Earth. The samples may be brought to a sample return vehicle or cached for later return by automated or piloted vehicles. Rovers could also emplace packages of instruments to make long term weather and seismic measurements.

Samples may also be collected on the Moon and delivered to an astronaut base for analysis or return to Earth.

2.1.2 Human Exploration Requirements - As precursors to human exploration, rovers are required to determine the safety and utility of potential sites for human habitation on the Moon and Mars. This includes selecting a site, characterizing its surface and subsurface properties to determine (for example) that the soil will support landing of a piloted vehicle, and demonstrating safe and accurate landing (so that human landings are guaranteed to be in a tested-safe spot). The surface must support humans moving about on foot or in vehicles without falling into cavities or being buried by landslides.

Site selection requires that the rover investigate the suitability of the site for construction of a habitat, and for the presence of resources (especially water) that would be useful in the construction and operation of a human outpost.

Human exploration robotic precursors may also be required to demonstrate construction techniques and also demonstrate the ability to acquire and store resources. Robotic vehicles will also be involved in actual site preparation for human habitation, either as precursors to human landings, or as assistants to the crews of piloted missions. Site preparation is likely to include excavation (to bury habitats for radiation protection), assembly of structures, and resource mining.

One function of humans on planetary surfaces may be to do in-situ science investigations like those of Apollo. If so, precursors should characterize the landing site, and the nearby region, for scientific interest. Such characterization would be similar to the scientific investigations required of the Mars Rover Sample Return mission, but may or may not include sample collection.

2.1.3 <u>Rover Mission Characteristics and Constraints</u> - Missions to the Moon and Mars have different characteristics and place somewhat different constraints on rovers. Some of these characteristics are summarized in Table 1.

TABLE 1 - MOON AND MARS MISSION CHARACTERISTICS

PLANET	COMM DELAY	DAY/ NIGHT CYCLE	ATMOSPHERE	TEMP RANGE	GRAVITY	SURFACE
Moon	~3 sec	28 days	None	120-400°K	1/6 G	Dusty, Cratered, Well understood
Mars	5-40 min	24 hrs	7 Mbar, CO_2, Dust Storms	160-260°K	1/3 G	Dusty, Rough, Varied, Poorly understood

The long distance between the Earth and Mars means a long communication delay and makes a high level of rover automation much more important than on the Moon. In addition, sites on the Earth-facing side of the Moon are probably preferred for early human outposts. Communication from such sites between rovers and the Earth is relatively simple. However, a Mars rover must either have an orbital communication relay, or a complex, high frequency radio system with a steerable antenna, or both.

The day-night cycles affect operations strategies and power requirements (if solar energy is used), as well as the thermal control of the rover. The existence of an atmosphere on Mars affects the ability to use solar arrays for power (since dust cuts down the available solar energy). It also requires a different design for RTGs if nuclear power is used on Mars. Both planets have severe temperature extremes, which present a challenge for materials, lubricants and thermal control. The low gravity makes slow mobility easier but complicates control of vehicles traveling at higher speeds.

Finally, the Moon's surface is ancient and relatively well understood. It is composed of soil and rocks formed by ejecta from impact craters and is cratered at all scales. Mars, on the other hand, is well understood at only the two Viking lander sites, and even those sites exhibit characteristics which could complicate rover design and operations. For example, dust drifts of unknown bearing strength and depth are present at one site, while many "rocks" at another site appear to be amalgamated soil rather than solid minerals. Dust drifts and subsurface lava tubes on either the Moon or Mars may present unseen hazards to rovers, requiring a means of detecting or escaping from sudden, unforeseen drops during traverse. The unknown nature of Mars rocks makes the design of sample acquisition systems difficult.

2.1.4 <u>Schedule Requirements</u> - Current NASA planning is focussed on establishment of a Lunar outpost very early in the next century, leading to a Mars outpost mission in the second decade of the century. 2001 and 2015 are the dates currently being studied. This results in the need to fly a Lunar rover for site characterization in the mid-to-late 1990s, and possibly a second rover in about 2000 for resource assessment, technology demonstration, and/or site preparation. A Mars rover mission must precede the Mars human outpost sufficiently so that analysis of the conditions on Mars can impact the design of the piloted mission (about 8 years). This implies a date of 2001-2005 for the rover mission. The earlier dates for rovers will be necessary if a sample return is also required 8 years before the human mission, because return of a diverse (rover collected) set of samples would be highly desirable for surface characterization and site selection.

2.2 Spectrum of Rover Capabilities

A spectrum of rover concepts has been developed to satisfy these types of mission requirements. These are summarized in Table 2.

TABLE 2 - ROVER CONCEPT MATRIX

SIZE	POWER	OPS* MODE	CONFIG	TECH LEV	RANGE (~3 YRS) MOON	MARS
Micro (1-3kg)	Solar/ MiniRTG† (~10 W)	Automated	Six-Legged "Ant"	Medium	<1 km	<1 km
Small (100-300kg)	Solar/ RTG† (~100 W)	Low-level functions automated	4 - 6 Wheels	Low	100 km	~10 km
Large (500-1000kg)	Solar (~200W)	Low-level functions automated	6 wheels	Low	10^2 km	~10 km
Large (500-1000kg)	RTG† (~500W)	Onboard translation & execution of human plans	6 wheels	Medium	10^3 km	10^2 km
Large (500-1000kg)	RTG† (~500W)	Some onboard planning	6 wheels, Simple Walker	High	10^3 km	10^3 km
Very large (>1000kg)	Dynamic (~25 KW)	As required	Special (e.g. Excavator, cargo truck, human carrier)	Medium	~1 km	----

* OPS = Operations
† RTG = Radioisotope Thermoelectric Generator

The concepts range from small "local" rovers designed to collect samples a short distance from a sample return vehicle, through large, highly automated vehicles for long distance traverse and complex surface analysis, to very large machines for special purpose functions such as construction. These classes of rovers are summarized in this Section and described in more detail in Section 3.

Table 3 summarizes some of the functions that rovers would do to explore an area on a planet, to characterize potential human landing sites, and to assist in the construction of habitats for humans. The functions are listed by the size and capability of rovers required to perform them.

TABLE 3 - EXAMPLE MISSION FUNCTIONS VS ROVER TYPE

ROVER TYPE	EXPLORE	DETERMINE SITE SUITABILITY	CONSTRUCT
Local (Micro or small)	Local sample, Characterize small site	Image local site, Characterize top layer	None
Simple, Low technology (Small or large)	Characterize site (Remote sensing)	Radar for subsurface, Climb/Skid for friction, Imaging, Shallow digging	Construction technique demo (Small scale)
Moderate capability and technology (Large)	Collect diverse samples, Characterize area	Few meter regolith coring, Radar, etc for surface and subsurface	Construction Technique Demo, Simple Assembly, Shallow excavation
Capable, Advanced technology (Large)	Characterize region, Regional sampling, Few meter drilling	Few meter drilling	Automated light construction, Shallow excavation
Special Purpose (Very Large)	None	Deep drilling	Major excavation

2.2.1 <u>Small Rovers</u> - Small rovers may be very tiny (~1 kg) "micro-rovers" capable of single experiments or the collection of small samples over short distances. Ant-like micro-rovers using legged locomotion and an insect-type control system have been studied at MIT and JPL [Wilcox89]. A larger local rover (~100 kg), capable of retrieving a cache of samples left by an independent rover or of collecting samples within a kilometer of a sample return vehicle, was designed in FY88 [Piv89].

A small (~300 kg) rover was designed for Lunar operations in FY89. Such a rover could inspect the surface using visible and other spectra for remote sensing. The shallow (a few meters) subsurface could be investigated with electromagnetic sounding to detect cavities and boulders under the surface which might hamper habitat construction, or to look for bedrock on which to anchor structures. A simple pile-driver system was designed to penetrate the surface and provide "ground truth" for the electromagnetic sampling system. Solar or RTG power could be used, depending on whether night operations were needed.

2.2.2 Large Rovers - Large rovers (in the 500 to 1000 kg class) vary in their capabilities because of differences in the amount of onboard computation available (related to the level of autonomy of the vehicle) and the level of technology used. Three categories of large rovers of varying levels of autonomy were investigated in FY89, for Mars. The same types of rovers could be used on the Moon, although lower autonomy rovers can perform well on the Moon relative to Mars because the short communication times allow many functions to be effectively done on Earth (e.g. activity planning).

2.2.2.1 Level of autonomy - Autonomy for rovers is the measure of their ability to operate without direct, real time control by humans. Autonomy is implemented by automating rover functions to varying degrees. The level of automation in a Mars rover is reflected in the computational requirements on board the rover as a function of the desired level of autonomy, the information the system designers have on the environment that the rover will operate in, and the required level of reliability. A fully autonomous rover need not require excessive computation. Such a rover could be very autonomous simply by its inability to accept instructions from the ground, rather than its capability to make decisions on its own. A rover with very limited decision making would be sufficient if it did not have to be reliable. The "ant" micro-rover concept, for example, relies on having many, relatively expendable ants which are very autonomous, but not at all intelligent. Because a real planetary rover must be very reliable, an autonomous vehicle must be able to recognize unusual and unplanned-for conditions and to decide, on its own, a proper course of action. This requires a high level of onboard computation.

If the rover designers have a good knowledge of the environment and how the robot will perform in that environment then there will be few unexpected situations and the rover will be able to spend lots of time on each decision, or contact the Earth for help. In this case the onboard computational requirements can be modest.

If the system designers have little idea of what the environment will be like, then the rover will need to autonomously perceive and analyze a wide variety of ill-defined situations. Autonomy for this situation will be computationally much more costly. Because there will be many more unexpected situations, the rover will have to be able to resolve those situations quickly in order to be able to meet its other mission goals. This will preclude contacting Earth for most situations.

The rover's level of autonomy might be also looked at as the number and/or difficulty of interactions with humans required to perform some activity, such as a sample acquisition, a traverse of given length, or some science imaging. Fewer interactions are required with a more autonomous rover. Since a primary desire for sample-collecting rovers is for long traverses, this concept can be illustrated by comparing traverse methods and speeds among the simple, moderate and capable rovers.

Traversing 1 kilometer with the simple rover concept, for example, requires interactions with the human operators on the Earth (or on the planet or satellite) which are both numerous and difficult. (The Lunokhod operators in the early 1970s had considerable difficulty controlling the rover interactively.) Not only is a human commanding session required every 10-30 meters for a simple rover, but because the rover is less able to react safely to unexpected situations, extensive modelling of the rover's expected behavior would be required on Earth to try to make sure none of the planned commands could get the rover in trouble. (Note that since this modelling can't be 100% effective, mission risk is also increased.) This is similar to current methods of commanding robotic spacecraft.

The moderate rover, on the other hand, although it still requires a lot of interaction to do the same 1 kilometer traverse, has a higher level of autonomy in the form of additional onboard fault-handling. It can therefore be safely commanded with less ground modelling, which cuts down the difficulty (and hence the time) of the ground command bottleneck.

The capable rover, because of its use of a higher level of onboard automation, covers that same traverse with a single interaction with the operators. The difficulty of that single interaction is high (that is, a route of 1 kilometer must be generated and agreed to on Earth in about eight hours), and the rover must sit idly while the humans make decisions about the traverse. However the total time spent idle by the capable rover in covering the kilometer is much less than either of the other two.

2.2.2.2 Level of Technology - Simple rovers use technology as close as possible to the state of the art. They have a low level of onboard automation, equivalent to that of today's spacecraft, for executing ground-planned sequences of events and for protecting themselves from failures by switching redundant components to replace failed ones. Simple rovers use solar power (which limits capability to daytime operations and introduces risk in surviving nights), or state of the art RTGs. They carry a small number of instruments and are limited in their ability to perform tasks, such as sample collection. They have simple, omni-directional communication systems. At Mars this means that they communicate at low data rates or require support from communication orbiters. Simple rovers are relatively heavy, given their relatively poor performance, because advanced technologies (especially in power) generally reduce mass.

Moderate rovers use RTGs for higher performance and lower risk operations. They have a larger payload than simple rovers and can perform more tasks. They are somewhat more automated than simple rovers, and can respond to a bigger variety of failure modes. Therefore, they have more onboard computation, although only modest advancement in the state of the art is assumed.

Capable rovers are fully instrumented and are capable of sophisticated operations, such as collecting and analyzing a variety of types of rock samples. They utilize advanced technologies which reduce their mass and their operating risk, and increase their efficiency.

The human control support systems for the various rovers are also assumed to become more efficient and sophisticated in terms of speed of decision turn-around, ability to simulate rover performance in its environment, and ability to quickly analyze returned data.

2.2.3 Special Purpose Rovers - Special purpose rovers for direct support of human exploration missions have been conceptually defined by the Johnson Space Center [Roberts89]. Possible missions for these rovers include site preparation, cargo handling, construction, mining and human transport. Rovers resembling bulldozers, cranes and trucks may be sent as precursors to human landings, or used in conjunction with humans on the Moon or Mars. The rovers may be driven directly by humans, directed telerobotically by humans on the planet, or have similar levels of automation as large rovers and be operated from Earth. A brief study conducted by JPL and the Ames Research Center in FY88 [Phobos88] showed that Earth operation of robotic vehicles appears to be far more efficient than utilizing the extremely valuable time of astronauts, even for Mars missions. As with Apollo, humans will drive vehicles for long range operations. Unpressurized rovers, such as the Apollo Lunar rover can be used for trips of a few kilometers. Pressurized rovers will be required for long distance human travel.

2.3 Rover Concepts vs. Mission Requirements

The schedule constraints mentioned previously, combined with the mission requirements, indicate that the following types of rovers may be appropriate:

Mid 1990s - One or more simple, small or large rovers for Lunar outpost site characterization and regional resource assessment.

Late 1990s - One or more large, or moderate rovers for Lunar site preparation technology demonstration or to actually begin preparation of sites for human landings.

Near 2000 time frame - Special purpose rovers to assist humans in constructing and operating the Lunar outpost.

Middle of the first decade of the next century - Capable Mars rovers for site characterization and resource exploration. May include preparation for a sample return mission.

Late in that decade - Additional capable rovers for site characterization, technology demonstration, resource assessment, and preliminary site preparation.

In the second decade - Special purpose rovers to assist humans in constructing and operating the Mars outpost.

3.0 ROVER CONCEPT DEFINITIONS

3.1 Example Rover Mission Functions

Two types of missions were investigated for FY 89: site characterization and sample acquisition.

3.1.1 Site Characterization - The function of site characterization rovers is to measure the environmental conditions of potential human landing sites for factors affecting safety and habitability. The rovers will image the surface, use electromagnetic sounding to determine subsurface characteristics, and perform tasks to determine the soundness of the surface for landing and mobility. This last function will be fulfilled primarily by driving over the surface and observing soil behavior in response to physical contact by the rover wheels or feet. Electromagnetic sounding will be augmented with physical tests (digging, driving slim piles into the ground) to validate that the perceptions of the electromagnetic sensor are correct, that is, that a rock seen by the sensor is really a rock. Surface imaging will be augmented with other remote sensing spectra to determine mineral and chemical constituents of the surface. Many of these instruments will be the same as for science sampling missions. After site characterization the rovers may be sent off on long range traverses to characterize mineralogy in the area, i.e. look for potential resources.

3.1.2 Sample Acquisition and Return - The mission objectives for all three types of rovers were basically the same in FY88 and 89: to move over the Martian surface, collect rock and soil samples, and return them to a sample return vehicle (or to a cache for later retrieval by a sample return mission). The missions associated with these rover concepts were defined in FY88 and 89 by the MRSR Project [Rea89]. They all include some type of imaging orbiter, one or more rovers landed on Mars to collect samples, and sample return missions to retrieve or collect samples and bring them to Earth for analysis. The key mission variables include the capability of the rover, the amount of time the rover has on the surface before the samples must be delivered to the return vehicle, the availability of high resolution images (taken from orbit) of the area the rover must traverse (i.e. the foreknowledge of surface conditions), the availability of communications relay from the rover to Earth through orbiters, and the actual characteristics of the planet (whether there are many unseen hazards, whether interesting samples can be detected remotely by rover instrumentation, etc.).

3.2 Rover Functional Description

This section gives detailed descriptions of the rover concepts developed to date. First, candidate payloads are described. Then, some general information about rover functions is presented. Finally, functional implementations of each class of rovers are described in some detail. For large rovers a progression of capabilities, with associated performance and costs, is presented. Several new analysis and design tools were developed in FY89, especially in the area of System Control, Mobility, and Performance Evaluation. Some of these tools are described below, in conjunction with the concepts that they were used to develop.

3.2.1 Candidate Payloads - Two types of candidate payloads were developed for two possible major rover functions: site certification and sample acquisition.

3.2.1.1 Payloads for Sample Acquisition - Table 4 lists a suite of instruments [SWG89] recommended by the Mars Rover Sample Return Science Working Group for sample detection and analysis. The simple

TABLE 4 - INSTRUMENT CHARACTERISTICS

Instrument	Acro-nym	Mass (kg)	Power (W)	Dimensions (cm)	Data Volume (kbits/ analysis)	Cycle Time (min/ analysis)
Imag. cameras (stereo)	included as part of rover navigation system				16000	1
Point Spectrometer	PS	5	5	10x20x20	30	1
Imaging Spectrometer	IS	15	20	15x30x100	50	20
data analysis electronics		10	50	40x40x20		
Optical Microscope	OM	2	2	15x10x10	500	1
Alpha, Proton, X-ray Spectrometer	APXS	2	2	10x10x20	40	300
Neutron Spectrometer	NS	5	5	10x20x20	1	120
Electromagnetic sounder	EMS	3	1	30x25x10	50	20
data analysis electronics		10	50	40x40x20		
Differential Scanning Calorimeter	DSC	10	10	10000 cm^3	80	120
Evolved Gas Analyzer	EGA	12	25	25x25x20	800	120

and moderate rover concepts use a subset of these instruments. The capable rover is assumed to carry all of them except the point spectrometer. The sample acquisition and preservation mechanisms are also included in the payload.

3.2.1.2 Payloads for Site Certification - A site certification rover could include all the instruments of a sampling rover, in order to characterize the mineralogy and chemistry at a site. The electromagnetic sounder concept for purposes of determining whether obstacles to underground excavation exist is somewhat larger than the EMS for science. The concept includes two EMSs suspended on the sides of the rover 5 meters or so apart. They provide a "stereo" effect to aid in specifically locating and sizing obstacles up to a few meters below the surface. A system for probing the surface to establish ground truth for the EMS is also included in the payload.

3.2.2 Performance Assessment - The performance of the rovers was measured in FY88 and 89 primarily in terms of distance covered and number and quality of samples collected by the rover. The performance was also measured in terms of the power and time required to carry out traverse and sampling operations. Distance and number of samples were computed by developing operational scenarios and time lines which take into account the ability and need of the rover to interact with the ground. As discussed above in the section on levels of autonomy, more and longer ground interactions slow down the rover and lead to fewer samples being returned. Times for sensing the environment, taking and analyzing science data, computation, communication and Earth decision making were all accounted for.

The operational scenarios were used to define computational requirements, communication requirements, and power requirements. Models were used by JPL, FMC and MMC to define vehicle performance in a variety of terrains which might be encountered on Mars. The performance estimated for each class of rovers is defined in the following sections in terms of operational performance (e.g. distance traversed) and in terms of power and mass required.

3.3 Micro-Rovers

The micro-rover concept developed during a brief study in FY89 is based on a mobile robot developed at MIT under the direction of Rod Brooks [Brooks89]. The micro-rover resembles a mechanical ant, having 6 legs and feelers for contact sensing. The ant walks by automatically moving its legs, using a variety of gaits adapted to the terrain situation. Each leg swings forward. When it encounters an obstacle it swings back and is raised higher on the next forward motion, repeating until it surmounts the obstacle. An operational rover would include force sensing (currently being developed) in the legs and would use this information to make more sophisticated responses.

The micro-rover is envisioned to be powered by a 30 by 20 cm solar cell and a small, 2 watt-hour battery. At night it turns off. It would weigh about 1-2 kg and have a payload capacity somewhat greater than its mass. Its size is about 30 by 20 by 10 centimeters. It would use about 2 watts average during operation. Communication with the lander would be by a line of sight omni-radio transceiver with a whip antenna. A directional homing antenna would be used to send it out from the lander and guide it back.

The ant could include tiny cameras to provide an ant's-eye view of the terrain. If it climbed up a hill the view could become a small panorama. The cameras could also be used to see pebbles which the ant could be directed to pick up in vise-like jaws. Different ants could carry small instruments, e.g. a point spectrometer for up close looks at rocks and pebbles. Thirty ants could be carried for the same mass as one 100 kg local rover, and would provide redundancy to local sample collection.

3.4 Small Rovers

Small rovers have been designed as local rovers associated with Mars sample return missions, and as independent Lunar rovers for early human precursor missions.

3.4.1 Local Rovers - In local missions a small rover would be landed with a sample return vehicle [Piv89]. In a very short-range mission, the rover would traverse paths within about 100 meters from the ascent vehicle during its surface stay, and collect samples only in this local area. A local rover could also be used, in conjunction with the ability of the sample return vehicle to "pin-point land," to collect samples from a long-range rover, or to retrieve a cache of samples stored with a navigation aid by the more capable rover. In either of these cases, the long-range rover would identify and certify a safe landing site and emplace navigation aids for the landing of the sample return vehicle. The accuracy of a pin-point landing under these conditions is predicted to be about 100 meters.

A Mars local rover mission was needed for use in conjunction with a mission set adopted for study purposes in connection with the NASA 90-Day study [90-Day]. In this mission set, a local rover and sample return mission would occur in 2001, before any other Mars rover mission, and there would be no subsequent opportunity to return samples until the human exploration mission in 2015. This would make it necessary to land the local rover mission with less knowledge than if a rover mission had preceded it into the area, and to go much farther than the immediate 100 meters around the lander in order to be sure of getting true rock samples -- at least 1 km. Uncontaminated rock and dust samples are a minimum requirement. Our local rover concept for this mission is able to go out 5 km from the lander. Table 5 shows local rover mass allocation.

TABLE 5 - 5-KM 100 KG LOCAL ROVER MASS TABLE

POWER	56-W RTG, 6 WHR LI-TI BATTERIES	17.7 KG
STRUCTURE	CHASSIS, BODY	13.6
MOBILITY	MOTORS, HARMONIC GEARS, WHEELS	13.5
COMMUNICATIONS	ROVER - LANDER, 5 KBPS AT 5 KM	1.5
SAMPLING	3-DOF ARM, SCOOP, CAMERAS, DRILL	14.0
SCIENCE	POINT SPECTROMETER	3.0
	NEUTRON SPECTROMETER	3.0
	ELECTROMAGNETIC SOUNDING PARABOLA	5.0
THERMAL CONTROL	INSULATION, HEATERS, RHUs	5.0
VEHICLE CONTROL	ELECTRONICS, SENSORS, CAMERAS	16.4
COMPUTATION	GENERAL PURPOSE COMPUTER	7.0
		- - - -
TOTAL		99.7 KG

All local rovers are assumed to have a high degree of dependence on the lander. The 100-meter rover has more dependence than the 5-km version. For example, the 100-meter local rover could incorporate only energy storage, rather than having its own power source. This storage may be batteries or fuel cells. The lander is assumed to be powered by RTGs which are used to keep the ascent vehicle launch fuel warm as well as to power the lander and rover functions. The rover would be in constant communication with the lander and most computation for automated functions would be done on the lander. The lander provides communication with the Earth and contains the scientific instruments. The rover merely returns samples to the lander, and the lander instruments perform any characterization of the samples. The lander also processes, packages and preserves the samples and handles the subselection process.

The 5-km local rover could be similar except it must have its own RTG because it would generally be too far from the lander to return for battery charges. Communication rates would be much reduced when the rover was far from the lander. The rover would still be incapable of communicating with Earth on its own. In addition to acquiring samples, it would perform some other tasks judged necessary as precursors to human exploration (such as searching for water in the subsurface, and calibrating subsurface rubble and void sensing techniques) for later use in human habitation site surveying (although the local rover itself is not called upon to survey possible human habitation sites).

A single concept for a local rover was developed as part of the FY88 Rover study. This was modified slightly and expanded to several concepts in FY89.

3.4.1.1 Science - Local rovers are presumed to be constrained to 100 kg, with the result the science payload capability is very limited. The local rover may incorporate a point spectrometer to aid in sample selection and would relay spectral data through the lander to the Earth. All science analysis would be done by the lander.

In addition, the 5-km rover could carry an electromagnetic radiation emitter and a 1.8-meter diameter parabola, to test the electromagnetic sounding environment of Mars. The purpose would be to develop a system for sensing subsurface voids, rubble and water in later surveying missions. Because of the greatly reduced data rates (see 3.4.1.8), the EM sounding system could probably not be used at the full 5 km distance from the lander. With the small amount of remaining mass available for science, the rover could perhaps carry a neutron spectrometer as a redundant means of sensing subsurface water by reflected RTG neutrons.

3.4.1.2 System Control - System control is entirely from the Earth.

3.4.1.3 Mobility - A range of rover masses was addressed in FY89 to determine whether different mobility designs would be optimal for different sizes of rover. Six-wheeled vehicles have the advantage of being able to use four or five traction wheels to assist the wheel in surmounting an obstacle. Because of this they can climb over surfaces which have lower coefficients of friction. As the vehicles become lighter, e.g. less than 100 kg, the weight of the drive mechanisms and suspension begins to dominate the design, giving a mass advantage to four wheeled vehicles. However, the advantage in reliability and mobility performance of six wheels makes it desirable to retain them if at all possible.

JPL analyzed four configurations for small rovers in FY89, all with wheels. Four variables were considered for mobility options: mass available, number of wheels, suspension type, and steering mechanism. The step height capability of a rover is related to the number of wheels. Both six and four wheeled systems were evaluated. The suspension determines what types of obstacles the rover can handle, as well as the stability of the instrument platforms. The options studied were the four-wheeled "Clearance Car" (Figure 1), the "Delta Goat" (Figure 2), the "Pantograph" (Figure 3), and the "Rocker Bogie" (Figure 4).

The Clearance Car is merely the four-wheeled front body of the Delta Goat. The Delta Goat is a derivative of a vehicle with three bodies and six wheels which was designed in the 1960s for possible use as a Lunar rover. The Delta Goat has been revised to improve ground clearance and uses four wheels on a front body and two on a rear trailer. The Pantograph and Rocker Bogie are described in the Section on Moderate Rovers.

Three different kinds of steering were evaluated: scuff steering (where the wheels are driven differentially to drive one side forward more than the other to make a turn), wagon steering (where the whole front axle turns), and Ackerman steering (where the front wheels are turned, as on an ordinary automobile). Each design was evaluated with each type of steering, except that the Pantograph and Rocker Bogie cannot use wagon steering.

Small, light mobility systems were studied by JPL for use as local rovers or as simple, slow, long-range rovers given ample surface time to cover ground. For the simple rover the mobility designs were evaluated for their ability to move across obstacles while requiring low mass (as little as 50 kg for the mobility system and structure). The evaluation was partly mathematical and partly subjective, with a specific mobility index defined as the ability of a configuration to surmount a one-meter obstacle divided by the configuration's mass.

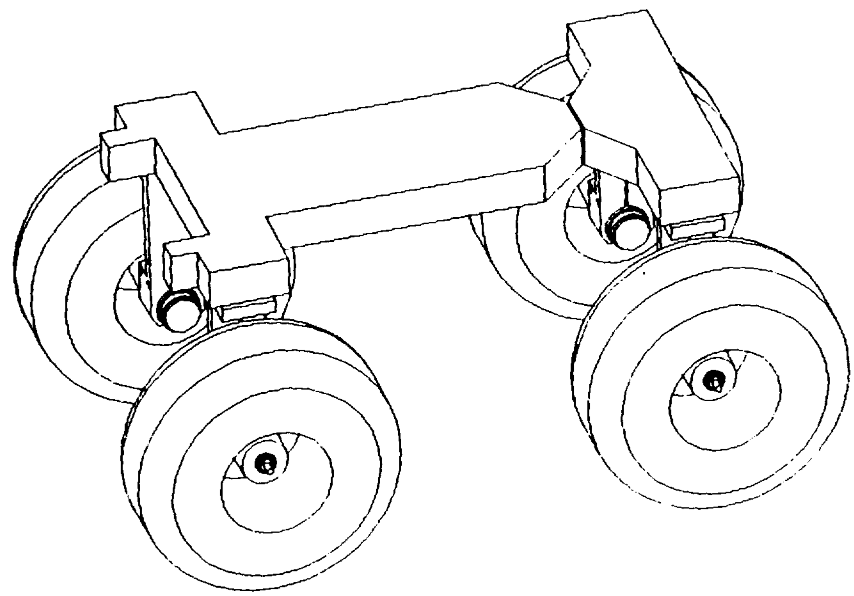


Figure 1 - Clearance Car

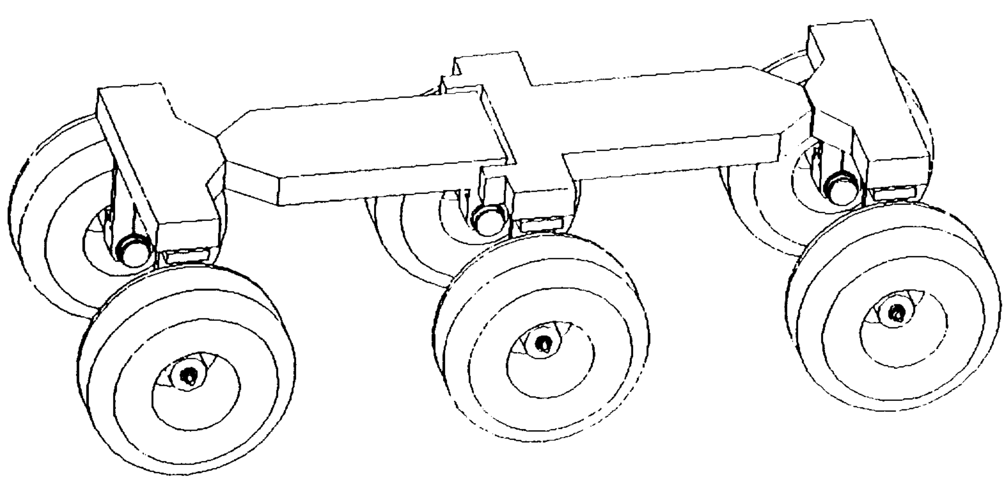


Figure 2 - Delta Goat

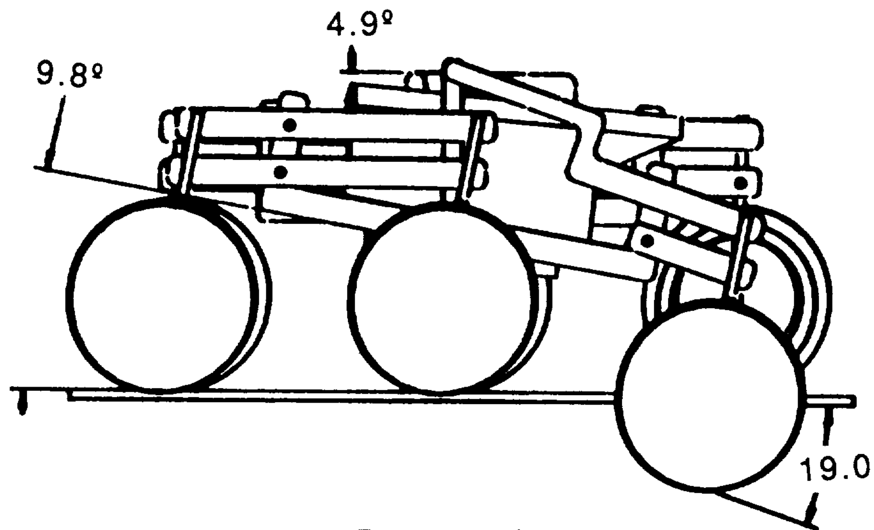


Figure 3 - Pantograph

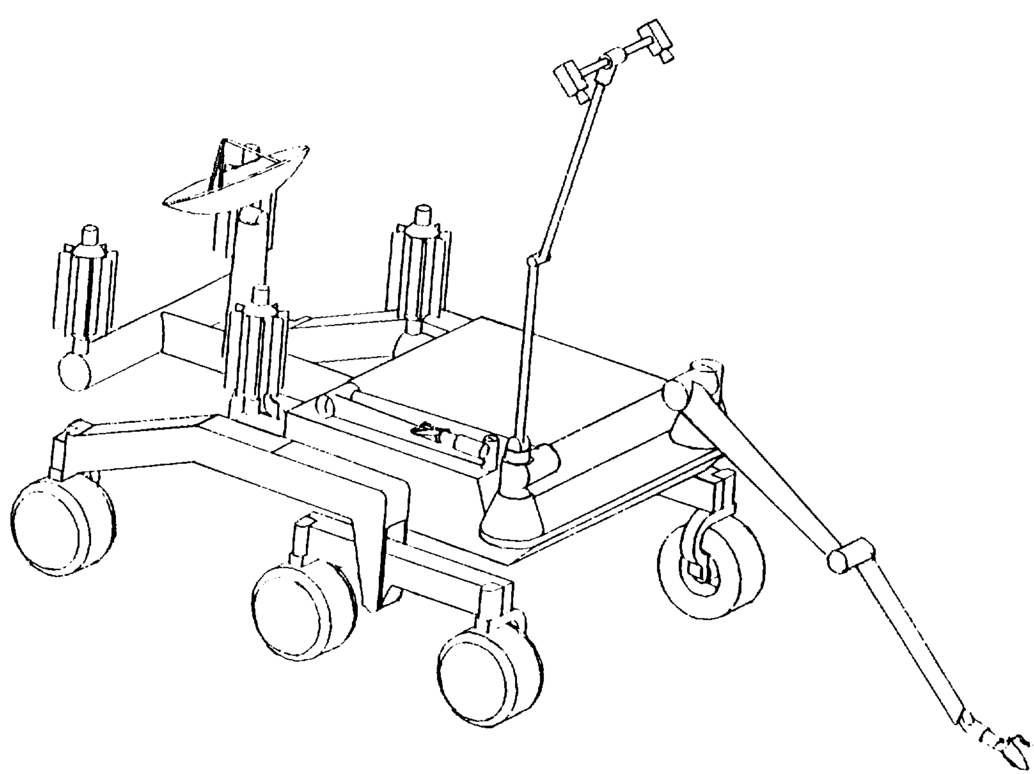


Figure 4 - Rocker Bogie

The configurations were also evaluated to determine what their mobility would be if their mass were restricted to 50 kg. For small rovers the Delta Goat and Rocker Bogie with Ackerman steering were clear leaders. Although light, the four-wheeled Clearance Car has very poor mobility.

A simple local rover design would be a Clearance Car with four "bicycle wheels" and harmonic drives. It would be unable to climb over obstacles larger than 20 centimeters or so, unless it could straddle them. If the rover is a cache retriever this should present no problem since a previous rover will have scouted a smooth site. If the mission is a "grab sample" the rover may be very limited in range and access to areas around the lander.

A more complex local rover was designed around the rocker bogie concept, to support the 5-km mission. See figure 5. This is a version with 40-cm wheels which is nevertheless able to surmount 1-meter obstacles. Mass for structure and mobility is 27.1 kg, and the structure is able to support a proposed 1.8-meter parabola for electromagnetic sounding.

3.4.1.4 Local Navigation - An innovative local navigation system concept for the 100-meter local rover was developed at JPL. In this concept the lander views the scene out to 100 meters' distance and an obstacle-free path is planned on Earth. The local rover would be small (100 kg total), therefore, the path might need to be fairly complex to wind around obstacles. The rover would be commanded to execute the path and would be monitored by the lander.

The location of the rover is determined with respect to the lander by beaming a laser from the lander to the rover. The laser beam reflects from retroreflectors mounted on a mast on the rover. The reflections are sensed on the lander by a star tracker and the location of the reflections in the star tracker field of view gives the location of the rover in azimuth relative to the lander. The distance apart of the reflections gives an indication of the distance that the rover is from the lander. The 5-km local rover would be driven by the Computer-Aided Remote Driving (CARD) technique (see 3.5.1.4) when away from the lander.

3.4.1.5 Sample Acquisition - All local rovers will have a simple scoop, and possibly a "micro-drill," for obtaining fresh rock samples.

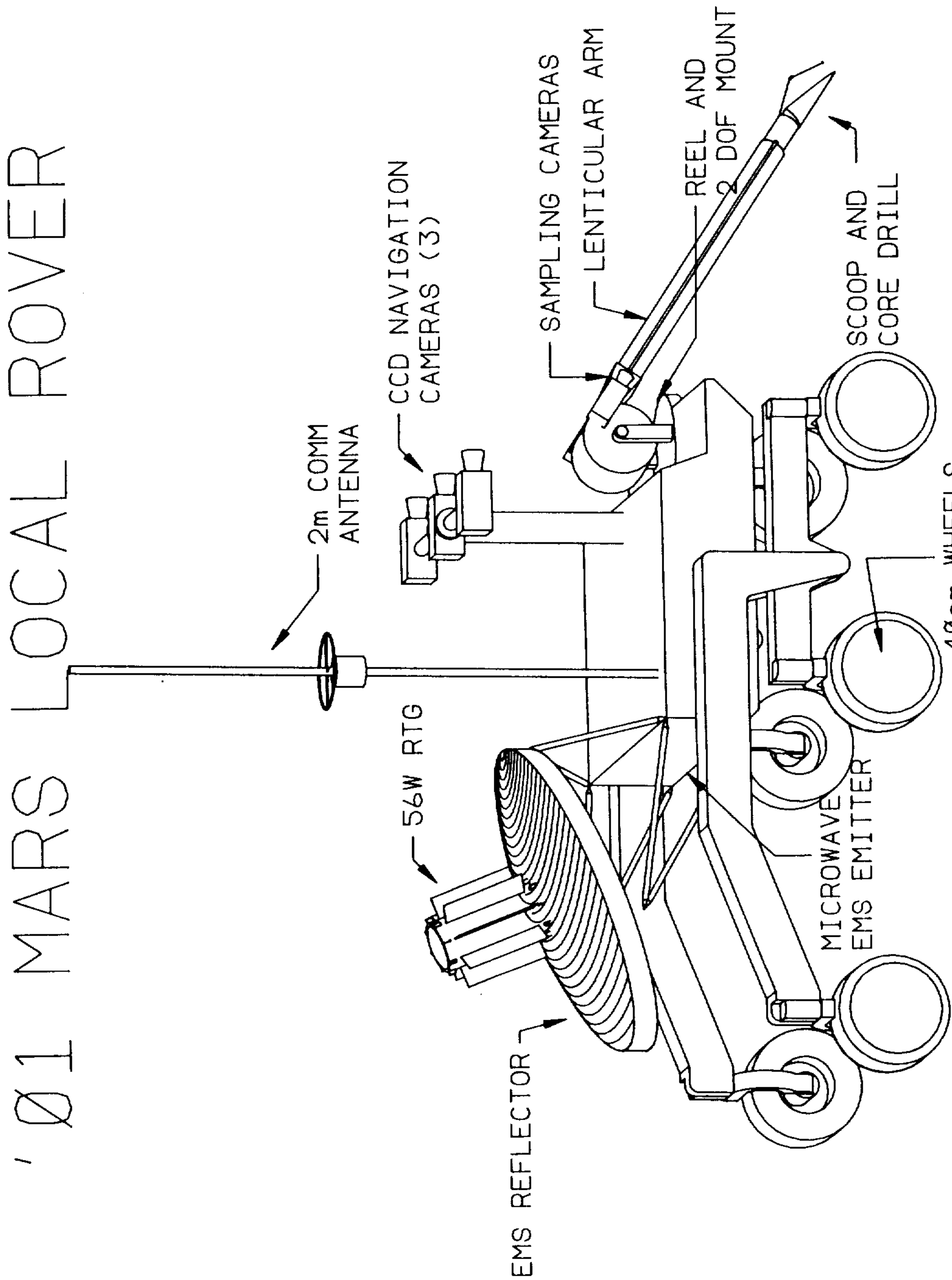


Figure 5 - Mars Local Rover with 5 Km Range

The cache collector will have special purpose manipulators and a carrier for grasping and carrying the cache container.

3.4.1.6 Vehicle Control - Both the 100-meter rover and the lander have a sun sensor, which in conjunction with inclinometers, provide rover attitude determination. The rover has passive obstacle detectors, although the path planned for the rover would be as obstacle-free as the lander cameras could show. The lander could have considerable automation so that the rover changes of direction could be guided by commands stored on the lander. Alternatively, the rover could be teleoperated, very slowly. Vehicle control for the 5-km local rover would be similar to that of the Moderate rover when distant from the lander.

3.4.1.7 Computation - The local rover would have minimal, off the shelf, onboard computation. Most computation and data storage would be on the lander. The 5-km rover would need to rely more on onboard computation than the 100-meter version, because of reduced data rates at longer distances.

3.4.1.8 Communications - There would be a low-frequency radio frequency (RF) link from the lander to the rover. Communications rates would be in the megabits/second range at 100 meters, but diminish to 5 kbps at 5 kilometers.

3.4.1.9 Power - Power is provided either by batteries/fuel cells (which have the problem of limited power or the need for recharging) or by 45 watt mini-RTGs adapted for the Mars surface. Solar power could also be used if the risk of being trapped away from the lander at night were accepted.

3.4.1.10 Thermal Control - The local rover will utilize passive thermal control techniques which include thermal control surfaces, multilayer insulation, thermal conducting control, and the probable use of thermal louvers. The thermal louvers will allow the system to control thermal rejection during the various phases of the mission. Thermal Radioisotope Heater Units (RHUs) will be used as necessary. With batteries or fuel cells, the RHUs may be necessary. With RTGs, a technique may well be developed (thermal switch) to turn on and off the energy source as needed.

3.4.1.11 System Characteristics - The 100-meter local rover would weigh about 100 kg or less and would use 45 watts of power. The 5-km rover would consume 56 watts.

3.4.1.12 Performance - The 100-meter local rover is projected to be able to collect about 60 samples from the circular area within a 100-meter radius of the lander over the course of 150 days. This will be very unlikely to result in more than one type of geological unit being returned to Earth, but may be sufficient to provide some information on possible toxicity.

A low-technology local rover would work in daylight only, and would require significant ground intervention in each sample acquisition. Samples would be selected mainly with imaging from the lander, acquired one at a time, and brought to the lander for analysis. Operations teams would function in parallel to save surface time. While one team is acquiring a sample, the other is working with the scientists in choosing and planning for the next acquisition.

It might require around nine interactions to acquire a sample. Interactions could take an average of three hours, and since the local rover works only during the 12.5-hour Martian day, it might come to 55 hours per sample acquisition, or 60 samples in a 150-day mission after a 10-day post-landing overhead is subtracted.

Sampling with the 5-km local rover would be similar to the 100-meter version discussed above. However it is envisioned that this rover would collect less samples and spend more time getting to them. Sample detection and final selection must be done from the rover, unaided by imaging from the lander. Emphasis would be on collecting data from the EM sounder, cameras and Neutron Spectrometer while the rover was rolling, and only collecting a few samples. Operations teams could not be used in parallel as efficiently as with the 100-meter rover.

3.4.2 <u>Lunar Site Characterization Small Rover</u> - The third type of small rover considered is for characterizing potential human landing sites on the Moon for their safety, "buildability" and possible resources. The study to define this rover is incomplete, and the following results are included as an indication of mission feasibility rather than for accuracy.

The Lunar rover scenario definition and concept design were done on the premises that: (a) human precursor engineering functional requirements superseded science requirements, (b) activity levels could be reduced but not eliminated during Lunar night, (c) the rovers would need to live at least one year. The requirement was assumed to be to methodically survey a circular proposed human habitation site of 0.5 km radius. The activities most vital to determination of habitability would be concentrated near the beginning of the survey (i.e. the first Lunar day), with more and more "nice to have" information as the survey progressed (i.e., through the third Lunar day), and culminating in a search for mineable resources (e.g., water, oxygen-bearing rocks, raw materials for propellant or construction) extending beyond the initial 0.5 km radius of the survey.

This site-surveying Lunar rover concept derived has a mass of just under 300 kg, six wheels, single-body construction, and depends on current technology RTGs for power. Commanding is direct from Earth, not through any kind of communications relay. With the rover moving at 10 cm/sec, navigation will be conducted from ground control stations which receive near-continuous video downlink of the area in front of the rover. This technique should allow for incremental commanding of the rover. That is, course corrections would be generated by using graphics in response to obstacles detected on the fly, so the rover can be kept moving continuously in an attempt to complete the most important aspects of the survey before the onset of the first Lunar night.

3.4.2.1 Science - Science instruments proposed for the Lunar rover emphasize knowledge useful for planning the human habitation, as well as planning science activities of the astronauts. Sample acquisition is not included among the science capabilities, as this would increase design and operational complexity at the expense of the main goal of the human precursor mission. Table 6 lists a strawman science payload.

3.4.2.2 System Control - Ground command and control will be as direct and as close to teleoperation as possible while still completing the job in the required time. Fairly standard types of onboard spacecraft fault protection will be used, where the craft utilizes very safe, well-tested, canned responses to out-of-bounds conditions sensed within the resources, and Earth provides most of the fault analysis and recovery.

TABLE 6 - LUNAR SITE CHARACTERIZATION INSTRUMENTS

	Instrument	Functions	Mass
Rover:	Point Spectrometer	Resource Analysis	5 kg
	Neutron Spectrometer	Resource Analysis	5 kg
	Geophones (10 ea)	Seismic Analysis	1 kg
	Simple Seismometer	Seismic Analysis	3 kg
	Simple Magnetometer		2 kg
	Gravimeter		10 kg
	Optical Microscope		2 kg
	total		28 kg
Lander:	Broad-Band Seismometer Station		50 kg

3.4.2.3 Mobility - A six-wheel, single-body rover with no gears is envisioned. The vehicle type was shown in Figure 4 and is a JPL design known as the Rocker Bogie. Mobility need only provide for 10 cm/sec top speed and the capability of surmounting 0.5-meter obstacles safely. One hundred kg has been allocated to structure. Figure 4 illustrates 4 RTGs mounted vertically on the aft structure. This orientation prevents dust from settling on the RTGs and provides a good angle for heat rejection.

3.4.2.4 Local Navigation - Six rover navigation cameras (massing about 6 kg collectively) are mounted on a pan-tilt platform (which generally does not need to be moved). The cameras point over a wide angle in the general direction of rover movement. Three pairs of stereo images are taken around once per second as the rover moves. One to three pairs are transmitted to Earth and displayed for operators on video screens which are refreshed at up to once per second. Operators command the vehicle by indicating a path in appropriate directions around obstacles they can see, using a cursor on the video screen. The vehicle has preset engineering limits which it enforces in real time by means of sensing accelerations and tilt angles, generally by simply stopping if sensed conditions get out of bounds. This is a low autonomy approach, but still relies on the vehicle more than teleoperation would. This is appropriate because the 3-second round-trip light time delay is too great for true teleoperation, in which all control is directly by the operator.

3.4.2.5 Engineering Tests - In order to determine subsoil obstacles and conditions affecting construction, the vehicle has electromagnetic sounding antennas weighing together about 4 kg. These collect 8 Gbits of data in the total survey, from which obstacles as small as 0.2 meters in size, up to 2 meters below the surface, may be reconstructed.

The EM sounding data should be correlated with data from a 2-meter probe for ground truth. The concept includes a reusable 1 cm-wide 2-meter long rod which is driven into the soil with about 12 ft-lb of force. Twenty kg has been allocated to this pile driver device. The impact of pile driving will also provide inputs to the seismic net for additional subsurface characterization.

3.4.2.6 Vehicle Control - Vehicle control is closely tied to the mobility subsystem and provides steering, proximity sensing for obstacles ("curb feelers"), pointing and directional sensing, and the computation for these controls. Forty-nine kg have been allocated to these functions.

3.4.2.7 Computation - Exact computing requirements have not been fully determined, however a version of the Comet Rendezvous Asteroid Flyby (CRAF) computer weighing about 20 kg would be adequate. Digital tape recording is presumed to not be required because of the near-continuous communication with Earth operators during all periods of high data flow. The computation requirement is well within current capabilities.

3.4.2.8 Communications - The site characterization mission is assumed to be on the Earth-facing side of the Moon. S-band communication from the rover direct to Earth at the rate of 2 mbps to a 34-meter Deep Space Network antenna is achieved by a hemi-directional antenna on the rover. This assumes that the rover is not tilted on a slope of greater than 15 degrees and is within 45 degrees Lunar latitude of the sub-Earth point. The communication system weighs about 17 kg.

3.4.2.9 Power - The power subsystem utilizes Galileo class RTGs to provide 150 Watts, and avoids batteries by use of a capacitor bank to aid in power management. The power in this first version of the rover may have to be increased as the study progresses because the initial performance assessment (below) shows a need for almost 200 watts during traverse. Forty-six kg are currently allocated for power. A

Lunar rover could also use solar energy if the thermal control problem could be accepted or be solved by the use of RHUs.

3.4.2.10 Thermal Control - Thermal control of a solar rover is difficult on either the Moon or Mars. Night-time temperatures on both bodies are very low, and on the Moon they last for two weeks. The Mars solar rover design (described below) is just able to provide heat for critical functions during the night. On the Moon a purely solar/battery system is infeasible. Either the rover must be allowed to freeze (as was Surveyor) and recover when the sun warms its batteries, or RHUs must be provided.

Since the current Lunar rover design uses RTGs, heat will be transferred from the RTGs to critical components on the rover. This would require the development of a thermal optical heat pipe (normal heat pipes will not work under the influence of gravity). This would allow night operation if Earth-light is sufficient for local navigation.

3.4.2.11 System Characterization - The rover weighs 289 kg and requires up to 197 Watts while roving.

3.4.2.12 Performance - Assuming the site to be surveyed is 0.5 km in diameter, and assuming that landing takes place as soon as possible after sunrise, we calculate the rover might be able to place the geophones and complete an initial surface imaging survey and subsurface electromagnetic sounding scan of the site in the ten days or so before the onset of Lunar night. This necessitates continuous movement, controlled by an Earth operator, at around 10 cm/sec. Sixty km would have to be traversed if the survey swath width was 10 meters.

In the second phase, consisting of the next two Lunar days, time could be utilized for more detailed imaging surveys of particularly interesting areas, emplacement of the heat flow experiment, and judicious use of the pile-driver/penetrator for collection of subsurface ground truth for better understanding the EM subsurface survey data. Thirty five km might be covered in these two Lunar days. Unlike the initial survey, there would be many times while the rover is idle waiting for Earth decision making and commanding.

In the third phase, consisting of the fourth Lunar day and beyond, the rover could conceivably cover up to 120 km/Lunar day in a wide ranging resource survey, by moving continuously at 10 cm/second. If the rover lived a year, this could amount to 1000 km. This would be much reduced if ground decision making processes caused the rover to stop often. It is possible the rover could be kept moving continuously in this mode, because the resource survey would emphasize the general detection of the presence of desirable resources using the point and neutron spectrometers, rather than their exact characterization or location, which would require accurate pointing of the instruments. That task would be left to the astronauts.

3.5 Large Rovers

As discussed previously, three classes of large rovers were studied: simple rovers, moderate rovers and complex rovers. This section defines examples of specific concepts for each class of rover, with some associated assumptions about mission requirements and constraints. Three of these concepts are directed to Mars sample acquisition. In addition, a common design was developed for a rover to perform science and site characterization at both the Moon and Mars. A simple, solar-powered rover was designed for Mars in an attempt to define a reasonably capable, but low cost sample return mission. A moderate rover was defined in FY88 and updated in FY89. Three distinct concepts for capable rovers were developed, one each by JPL, FMC Corporation, and Martin Marietta Astronautics Group. A common capable rover concept for the Moon and Mars was developed late in FY 89 by JPL. Each concept is described below.

Table 7 summarizes the characteristics of the three FY89 large Mars rover concepts, simple, moderate, and capable, as designed for a specific sample collecting mission. Mission constraints resulted in the specific rover designs violating the principle of all functions being simple, moderate or capable, especially in communications. The simple solar rover was defined in an attempt to minimize overall mission cost. Consequently, the rover was forced to have a fairly sophisticated system for direct Earth communication, because no communications orbiter was provided. The moderate rover was assumed to communicate both directly with Earth and through an imaging orbiter, requiring the most advanced antenna pointing system and complex, dual frequency transmitter. The capable rover was assumed to be aided by a dedicated, areostationary communications orbiter, and therefore has a simple, S-band omni antenna. Otherwise, the progression from low to high technology is fairly uniform.

TABLE 7 - LARGE ROVER CHARACTERISTICS

FUNCTION	FUNCTION TECHNOLOGY BASE		
	SIMPLE	MODERATE	CAPABLE
MISSION	Collect rocks, soil & pebbles, Cache or give to Sample Return	Same as simple plus fresh rock	Same as moderate plus volatiles
SURFACE RESOLUTION FOREKNOWLEDGE	Viking Level (10s-100s of meters)	Mars Observer Level (few meters in small, scattered areas)	1 meter topography over roving area by high res Imaging orbiter
DELIVERY SYSTEM	Viking-type, 20 km landing ellipse	10 km landing ellipse	1 km landing ellipse
INSTRUMENTS (See Table 4 - pg. 12)	Point Spectrometer	PS, OM, APXS, NS, EMS	IS, OM, APXS, NS, EMS, DSC/EGA
SYSTEM CONTROL	Earth based	Earth based	Onboard Executive
GROUND OPERATIONS	CRAF-based, Normal multi-mission ops development	10 time speedup over Galileo sequencing turnaround	Extensive validation during development and ops testing
LOCAL NAVIGATION	Computer Aided Remote Driving, Stereo vision	CARD, Stereo, "Curb Feelers", Emergency Stop	Semi-autonomous; Multi-sensor suite; Expectation generator & execution monitor
MOBILITY	4 wheels	6-wheels	Active wheels or walker
SAMPLE ACQUISITION	Rake or scoop, Low-level automation	Rake/scoop, Rock drill, Low-level automation	Dexterous Manipulation, Regolith core, Volatiles analysis, Onboard IS data selection
VEHICLE CONTROL	Sun sensor, Inertial guidance	Star tracker, Inertial guidance	Sun sensor, Inertial guidance, Speed sensor

TABLE 7 - LARGE ROVER CHARACTERISTICS (continued)

FUNCTION	FUNCTION TECHNOLOGY BASE		
	SIMPLE	MODERATE	CAPABLE
COMMUNI-CATIONS	Low data rate X-band to Earth	X-band to Earth & relay thru Imaging Orbiter (accurate pointing requ'd)	Simple omni S-band relay thru dedicated areo-stationary orbiter, X- or Ka-band direct backup link.
COMPUTATION	CRAF Inheritance MIP computer, Magellan Tape recorders	2-MIPS CRAF or VHSIC-based computers; tape recorders	5-10 MIPS parallel computer, special purpose sensor processing, optical data storage
POWER	Solar arrays, NiCad Batteries, Discrete power mgmt compon'ts (200W/470W-Hr)	Galileo RTGs adapted to Mars. The rest like simple rover (500W/470W-Hr)	Modular RTGs, Advanced Li Batteries, Power Integrated Circuits (500W/700W-Hr)
MASS	670 kg	880 kg	600-842 kg

3.5.1 Simple Solar Rover - This concept was developed to characterize the low-end extreme of the simple, large rover. (A more detailed study of the implications of using solar energy for powering a Mars rover was conducted by AeroVironment, Inc. for the Lewis Research Center [Hibbs89].) It was an attempt to minimize the development costs of a Mars rover and an assumption was also made that little funding would be available to develop new rover technology before project start.

The "solar rover" on Mars is handicapped by the low intensity of solar energy available, aggravated by occasional global dust storms which further decrease the surface insolation. The primary driver on this concept is the need for massive amounts of batteries to provide "keep-alive" power to survive the Martian night. Since no new technology development was assumed, heavy, state of the art Nickel-Cadmium (Ni-Cad) batteries were used.

Simple rovers all utilize Computer Aided Remote Driving (CARD) (described below) for local navigation, which requires two-way contact with the Earth each time the rover moves a few meters. The solar rover does not operate at night. The simple rover approach also assumes that there is no communications orbiter (to save cost), requiring a direct communications link from the rover to the Earth. This results in only 3 to 5 cycles of solar rover operations per day and severely limits the rover range. The solar rover is designed to collect only soil and pebbles, and to place these in "caches" which could be retrieved by a later sample return vehicle. (In this study the rover was assumed to launch in 2001, the sample return vehicle in 2005.) The rover uses only stereo cameras and a point spectrometer to select the samples.

The low-tech solar rover concept weighs between 700 and 900 kg depending on whether the nighttime keep-alive power is applied to all computers plus the high-gain antenna receiver, or whether only one computer is kept alive to wake the others up in the morning. (Either concept is considered to have a high risk of electronics failure.) The computer is assumed to be derived from that developed for the Comet Rendezvous Asteroid Flyby (CRAF) mission and provide minimal computational capability. The mobility design is a simple, four-wheeled concept, capable of traversing only 1/2 meter obstacles. The vehicle is as large as the delivery system will permit, to maximize the surface area available for carrying the solar arrays (12-20 square meters). Thermal control is by insulating the components and allowing them to run cold. Figure 6 shows a concept for the minimal solar rover with 12 square meters of solar array. It includes only one sampling arm to collect soil and pebbles.

3.5.1.1 Science Payload - Science instrumentation on the simple rover is limited to a Point Spectrometer (PS). The spectrometer is coordinated with the stereo navigation cameras, and provides information on the composition of the Martian surface. Characteristics of the Point Spectrometer (PS) are summarized in Table 4. In addition, the rover stereo cameras provide images that can be used for scientific study of the terrain. The PS is operated in conjunction with the stereo cameras, providing composition measurements in areas of the images.

3.5.1.2 System Control - The simple rover uses a preprogrammed sequence of events uplinked by the Earth and stored onboard to direct itself. This philosophy is very similar to current interplanetary spacecraft. There is a heavy dependence on the human controllers to integrate desired activities into a plan for rover actions, and to validate that the action plan will not endanger the rover. The

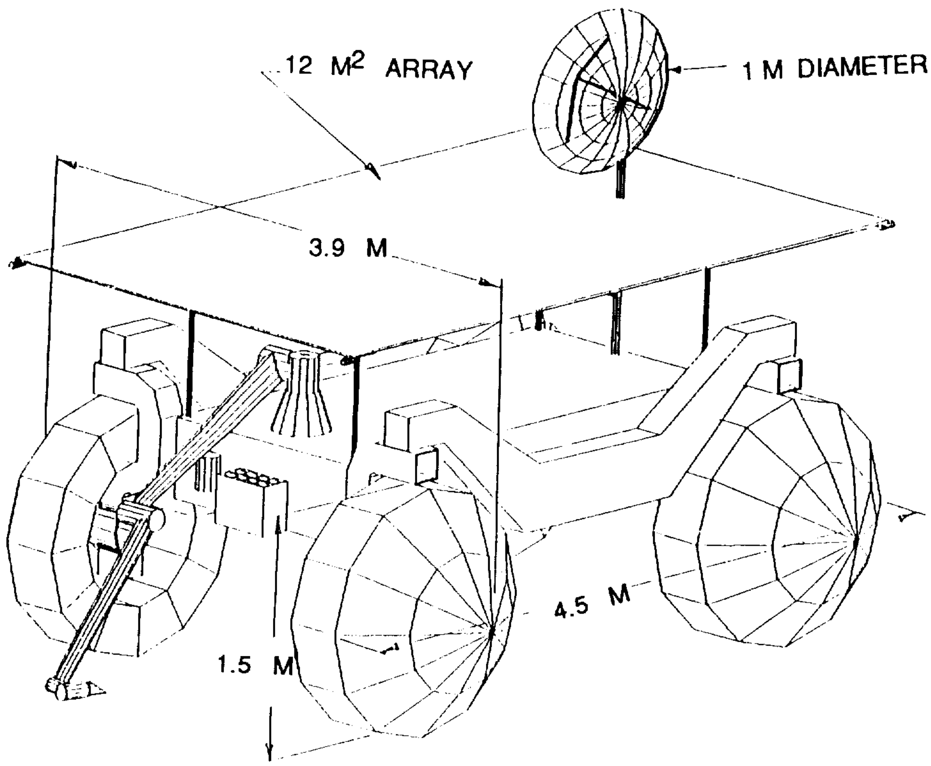


Figure 6 - Clearance Car with Solar Array

difference is that plans must be turned around very rapidly, compared to current spacecraft, because the rover is constantly interacting with an only partially predictable environment. In previous interplanetary spacecraft, interaction with planetary surfaces has been remote, or happens only once, on landing. System control of the rover, therefore, will have to have considerably more and faster simulation and verification of the rover's likely actions in interacting with the environment.

3.5.1.3 Mobility - The Clearance Car design was used for the Solar Rover to establish the lowest possible cost. However, it is clear that a modest investment in moving to a six-wheeled system would vastly improve the mobility.

3.5.1.4 Local Navigation - In the CARD-based local navigation used by the simple rover, its video cameras collect a set of images that form a stereo panorama of the terrain in front of the rover. The stereo images are downlinked to the Earth. (Onboard memory requirements can be minimized by shuttering the Charge-Coupled Device (CCD) cameras and storing the images in the cameras themselves, then reading out the data at the allowable communication rates.) Human operators view the terrain in a 3-D display, and designate a safe path using a 3-D cursor in the display. This path may be up to ten meters in length, depending on the presence and number of visible terrain obstacles and hazards. The turn angles and path segments that define the planned path are uplinked to the rover, which then executes the path. Violations of preset vehicle attitude and acceleration limits would cause path execution to be aborted. At the end of each path traversal, a new set of images is captured, and the process repeats.

3.5.1.5 Sample Acquisition - Two types of reduced function sampling arms have been proposed for a low-cost solar rover. The first is a single degree of freedom (dof) arm with a rake or scoop at the end. The arm may be dragged behind the rover all the time during traverse, or operated as a simple boom for limited control in the selection of samples. The manipulator itself would be located at the center of the rover. The second type is a 4 dof arm with a rake or scoop at the end. Starting from the base, the first joint would use low-speed indexing control, while the other three would use high speed servo-control.

3.5.1.6 Vehicle Control - The requirements for vehicle control differ little among the rover options considered. Vehicle control encompasses attitude determination, high gain antenna pointing control, camera pointing control, and guidance and control during locomotion.

Two types of attitude determination are required: Mars-local and celestial. Local attitude determination is required to know which way is up and to command camera pointing and steering. A strapdown inertial reference package is used to sense local attitude. With the vehicle at rest, precision accelerometers measure the components of the Mars gravity field and a set of Fiber Optic Rotation Sensors (FORSs) measures the Mars angular velocity vector–both in vehicle coordinates. The direction of the horizontal component of the angular velocity vector defines North.

Celestial attitude determination is required to accurately point an antenna at the Earth. For precision pointing, a star tracker is used to initialize the inertial attitude of the rover. For the simple solar rover, data rate requirements are reduced and 1° pointing accuracy is sufficient. This level of accuracy is possible without a star tracker. Knowledge of the Mars angular velocity vector and the Mars-sun line are sufficient to orient the rover with respect to celestial coordinates. A precision sun sensor in addition to the FORS gyro package mentioned above is needed. A single redundant unit will suffice if the sun sensor can be mounted on the camera platform. If the rover cameras are mounted pointing nominally forward, the sun sensor should be mounted pointing nominally up (at right angles to the cameras).

For antenna pointing control, stepper motors are used to control azimuth and elevation axes such that the antenna is pointing in the predicted direction of Earth relative to Mars.

For camera pointing control, a pair of stepper motors moves the camera platform to the commanded positions required to collect a panoramic view of the surrounding terrain. The two axes are commonly referred to as pan and tilt. All images are taken while the vehicle is motionless.

The rover uses inertial guidance to keep track of its current heading and location on the surface of Mars. The combination of FORS with precision accelerometers gives sufficient accuracy if a strategy of frequent zero velocity updates is used. In this strategy, the rover is allowed to move for approximately 100 seconds before stopping. It then remains motionless for 100 seconds in order to recalibrate its gyros and accelerometers before moving for another 100 seconds. The gyro integration algorithm will require the fastest rate group of any control algorithm, with a required update time somewhere between one and ten milliseconds.

Locomotion control responds to the error signals generated by the inertial guidance system and sends commands to the steering and drive actuators.

The simple solar rover assumed that high gain antenna pointing would be required, because a communications orbiter would not be available to save cost. Therefore, the Vehicle Control System for this "simple" solar rover is as complex as the VCS for a capable rover, or even more so. All of the VCS functions defined above were included in the solar rover.

3.5.1.7 Computation - The computational system for the simple rover will be very similar to that used on the Comet Rendezvous Asteroid Flyby (CRAF) mission planned for the mid 1990s. CRAF uses point processing (also called embedded processing); this is where every subsystem has its own computational resources. A subsystem so configured cannot use any computational resources from any other subsystem. A functional block diagram is shown in Figure 7. The system is block redundant at the subsystem level. Every subsystem will utilize one or more common computers. (The computers are "common" in the sense that they are the same for all the subsystems.) The various subsystems will also need to incorporate special purpose logic boards to perform functions which are specific to them. The number of common and special-purpose computer boards per subsystem are expected to correspond to CRAF's except for those subsystems that do not exist on CRAF.

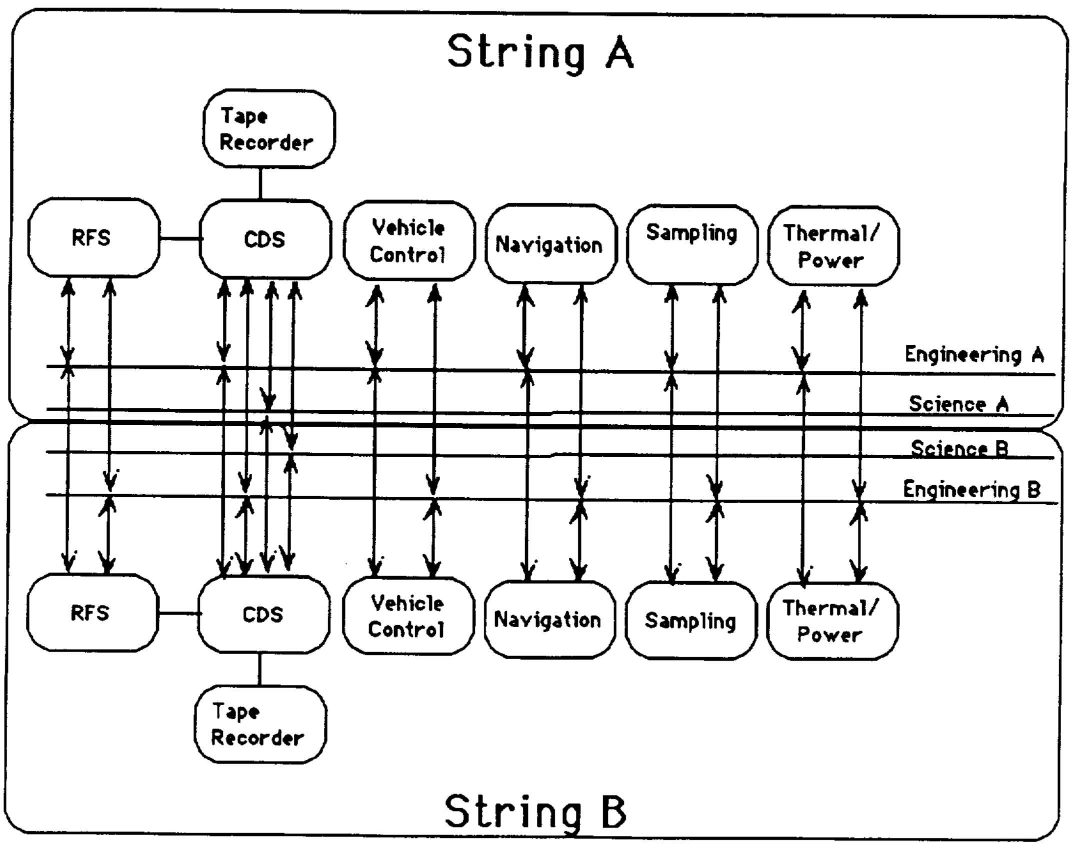


Figure 7- Simple Rover Computational Block Diagram

Engineering telemetry is transmitted on the Engineering bus and the science data is transmitted on the Science bus. Under normal operations a subsystem assigned to string A will not transmit or receive data from string B or vice versa. Each bus is serial and will probably be a 1553 specified bus. The aggregate data rate of each bus will be around 700 kbs, and this does not incorporate the project margin that is typically included.

The common computer board will be a direct inheritance from CRAF. Below is a summary of some of its characteristics:

- 32016 Processor
- 32081 Floating Point Processor Unit (FPU)
- 64 Kbytes of RAM
- 16K bytes of ROM
- 7 watts per board
- 1 kilogram per board

The data storage tape recorder for this system can be a direct inheritance from CRAF, or from Magellan.

In summary, it is expected that most aspects of the computational subsystems for the simple solar rover can be inherited directly from CRAF. The special purpose logic boards associated with each subsystem can be easily built using technology that is being used today. The mass/power/volume requirements for various aspects of the rover are shown below. Note that the mass/power/volume requirements for every computer in every subsystem were not included because those numbers are assumed to be incorporated in the overall requirements of the subsystem.

Data storage	One Tape Recorder	Two Tape Recorders
Mass -	22 lbs	44 lbs
Power -	22 watts	44 watts
Capacity -	2 Gbits	4 Gbits

Command and Data Subsystem

Mass - 20 KG
Power - 18 watts

3.5.1.8 Communications - An X-band downlink data channel concept was investigated for the simple solar rover. The data rate varies from 12.5 kbps to 170 kbps depending on the Earth-Mars distance. This means that the time to send one set of images for a navigation cycle varies from 8 to 34 minutes. These conclusions assume: (1) data required for one cycle of CARD is 6 Mbits (i.e., enough for three stereo image pairs with 2 to 1 data compression), (2) an antenna size of 0.7 meter, (3) 200 Watts DC power available, (4) use of a 34-meter antenna on Earth. An X-band uplink data rate would be 2 kbps, using the same hardware assumptions. The communications subsystem mass would be 50 kg. Pointing resolution of 0.67 degrees is required for 0.2 dB maximum loss due to pointing.

An S-band link was also investigated. This would provide for a much less stringent pointing requirement (3.5 degrees for a maximum of 0.2 dB loss), but would limit downlink rate to a much lower 950 bps.

3.5.1.9 Power - The power system for the simple solar rover consists of state-of-the-art silicon cells with super Nickel Cadmium (Ni-Cad) batteries (available in the near future) and flight qualified power management technology. The solar arrays for this rover are mounted on the rover body to minimize the mass of structure on the solar cell substrate. It is assumed that the solar cells, the coatings, and the substrate structure weigh about 1 Kg/m^2 for the portion of array that mounts on the rover and 2 Kg/m^2 for the overhangs. The power output of the solar array for a non-tracking silicon cell with optical depth of 2.0 around the Mars equator is about 15 W/m^2. The energy storage for the solar rover is super Ni-Cad which is currently under development. It is felt that the super Ni-Cad will be flight qualified by NASA for other programs by the rover launch date. The depth of discharge for super Ni-Cad is 40% and the specific energy is 30 Whr/Kg. The power management for the simple rover was assumed to be at the same technology level as CRAF which uses discrete power components for management and distribution.

To minimize the mass of the power subsystem, which is dominated by the mass for energy storage, the power usage at night was reduced to the bare minimum. The battery sizing was based on power usage at night for a 12.5 hour night cycle. The solar array was sized based on the total energy requirement and 12 hour daylight periods. This means that during some daytime activities, the batteries will be used and charged again while in the idle mode.

3.5.1.10 Thermal Control - Mars solar rover thermal control at night was assumed to be accomplished by keeping only a few, critical systems powered, and allowing the rest of the rover to be quiescent at low temperature. This system will require louvers and other standard thermal control materials and techniques. An alternative to this risky approach is to provide RHUs scattered throughout the rover.

3.5.1.11 System Characteristics - The simple solar rover is constrained to operate only during the day and when it has access to communications to receive commands. The power used in different modes ranges from 37.5 watts at night (in sleep mode) and 61 watts during daytime idle, rising to as much as 440 watts during traverse. The mass of the rover is driven primarily by the batteries needed to provide keep-alive power in sleep and idle modes. The total mass of the simple solar rover is therefore surprisingly high, about 670 kg.

3.5.1.12 Performance - Sample acquisition traverse performance for the simplest rover was estimated to be 80 km and 30 samples in 1500 days. This assessment (and all subsequent performance assessments below) was accomplished by estimating the number, duration and productivity of interactions between Earth and the simple rover. Since active periods are limited to daylight only, and commandability limited to direct Earth view periods from the rover, the opportunity for productive activity is limited to a daily window that varies in length from 9 to 12 hours per sol depending on the Sun-Earth-Mars angle. The one-way light time delay per interaction also varies from 4 to 20 minutes depending on the Earth-Mars distance. Assuming 90-minute Earth decision periods between interactions, 3-5 (average of 4) interactions per day were estimated under these circumstances. If the rover can move 15 meters per interaction, that would yield 60 meters/day. Also, it would take a number of interactions to acquire a sample with low autonomy, not to mention images from several angles, so 5 days/sample acquisition, or 150 days for 30 samples, was estimated.

Simple rover performance assumptions are summarized as:

Traverse:	75 2-hour engineering interactions/km; 1 8-hour science interaction/km
Sampling:	10 2-hour engineering interactions/acquisition; 1 8-hour science interaction/acquisition
Survey:	Not needed: considered part of traverse

3.5.1.13 Technology Levels, Risk and Cost - The low-tech rover mission assumes that a low-tech delivery system technology will be used. For the solar rover study this means a Viking-style system which uses propulsive capture at Mars and which has a landing accuracy of no better than plus or minus 10 kilometers from a desired landing point. There is assumed to be no contiguous, high resolution imagery (only Viking and Mars Observer images). Therefore, the rover landing is relatively risky, and the rover will have to do an unknown amount of backtracking to avoid untraversable (greater than 1/2 meter) obstacles. Figure 8 shows a possible rover traverse in the East Mangala area, with the arbitrary assumption of 40 percent backtracking (out of 80 Km total).

Two caches of pebble and soil are dropped in "smooth" areas suitable for a sample-return mission landing, and a third cache is retained by the rover. This figure illustrates a 3-sigma "bad" landing away from the interesting (shaded) sampling areas. In this case two major types of geology could be sampled, provided that the rover could access them without traversing obstacles larger than 1/2 meter. However, obstacles of this size would not be seen before landing.

Very preliminary cost estimates for the solar rover mission were made by JPL, the Johnson Space Center and Science Applications International Corporation. These estimates indicate that the solar rover cost in 1989 dollars is approximately $1B, the delivery system is about an additional $1B, and about $0.5B additional is required for project management, systems integration, mission operations development, etc. Reserves to account for the poor level of definition add another billion, for a total of $3-3.5B for the mission.

3.5.2 Improving Performance - Most people's immediate reaction to the relatively poor performance and high risk of the solar rover mission is to want to add capability. Figure 9 shows a "tree" featuring examples of how various levels of capability could be added to the solar rover, increasing its performance and cost. (Note: The reader can "design" his or her own rover by selecting these or other capabilities to achieve a desired level of cost and performance.) Mobility (and access to interesting areas) can be improved by using one of the concepts defined in the following sections on moderate and capable rovers. RTGs substituted for solar arrays add safe survival and operations capability at night, and can reduce the mass of the system. If constant power is available redundant elements can be added and utilized.

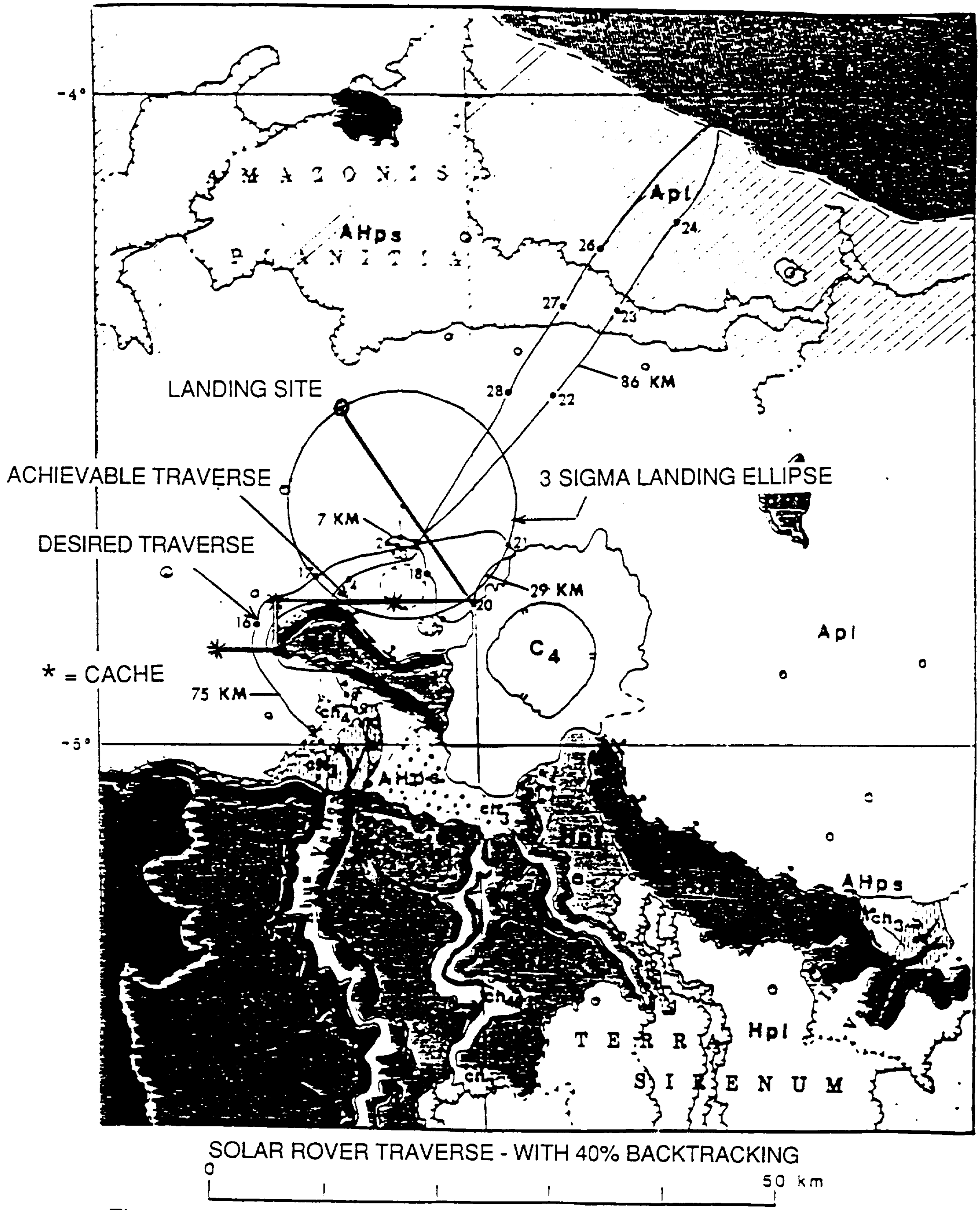


Figure 8 - Solar Rover Traverse with Viking-Class Landing (adapted from [SSED87], pg. 15)

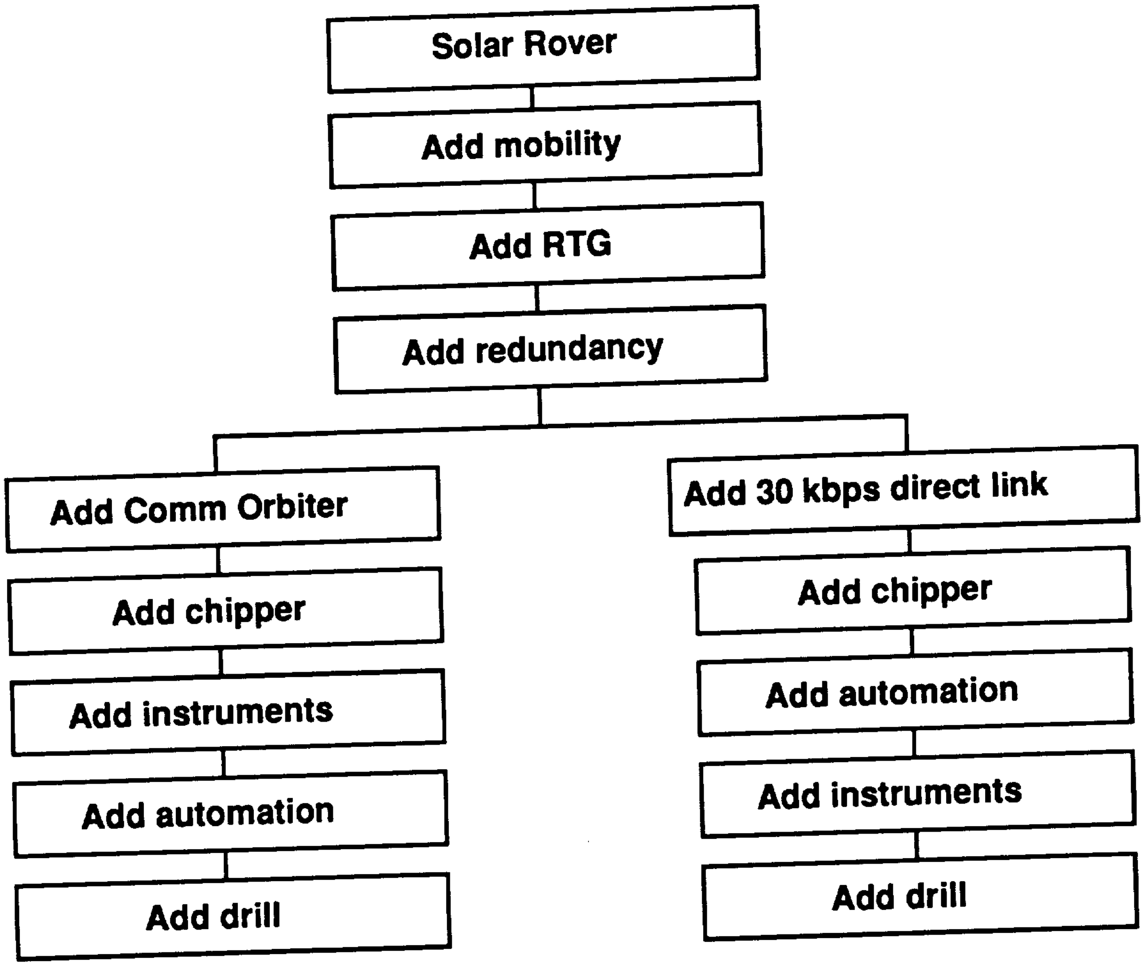


Figure 9 - Rover Delta Tree

A major improvement in performance ('round the clock operations) can be achieved with the addition of a communications orbiter. Since this is an expensive item, the direct link could be improved instead, allowing faster transmission of stereo images to Earth for navigation and sampling control.

The tree branches at this point. On either branch fresh rock could possibly be acquired for only a little increase in automation by adding a simple rock chipper or core drill. In the absence of a communications orbiter (the right branch), the range of the rover could still be dramatically increased by increasing the level of automation, provided that the rover were allowed to operate for a number of hours unsupervised by humans. On the other hand, the sample selectivity can also be greatly increased by adding instruments to the rover with 24 hour communications capability, even without an increase in automation (the left branch). The combination of automation and sophisticated sample analysis instruments, in addition to a regolith drilling capability, brings the rover to a "fully capable" status on either branch, although the right branch involves more acceptance of risk to utilize the full capability.

Figures 10 and 11 show the performance improvements attributable to the various additions, and the estimated cost of these improvements. These Figures show that a fully capable, semi-autonomous rover, operating around the clock can traverse about 1000 km and collect at least 100 carefully chosen samples. The cost of these additions is less than $0.5B for the rover. Adding a communications orbiter to provide 'round-the-clock supervision of the rover can not only reduce risk and add range, but it can increase the amount of science data available for sample selection, and simplify rover operations. The cost of this orbiter has been estimated at less than $0.5B.

3.5.2.1 Measurement of Improved Performance - Rover performance improvements at each increment in Figure 10 were estimated as deltas to the simple solar rover performance, discussed above.

Adding an RTG - This yields a 10% improvement in performance over the solar rover, raising it to 90 km and 30 samples. It allows the rover to take advantage of the 0- to 3-hour seasonal dark interval when direct communication to Earth is available, when the solar rover would otherwise be idle.

Following the left branch of the tree:

Add Comm Orbiter (CO) - This slightly more than doubles performance to 200 km and 30 samples, by providing 24 hours of commandability.

Add chipper - This reduces return to 160 km and 30 samples, since it adds complexity. It takes much longer to gather a chip sample (especially without the aid of more automation) than a surface pebble. Of course, chip samples would be more useful scientifically. The measurement of the return allows additional time for 10 acquisition failures or throwaway of undesirable samples.

Add Instruments - Like the chipper, this reduces mission return because it adds operational complexity. The ground decision making process becomes more complex which adds to rover idle time.

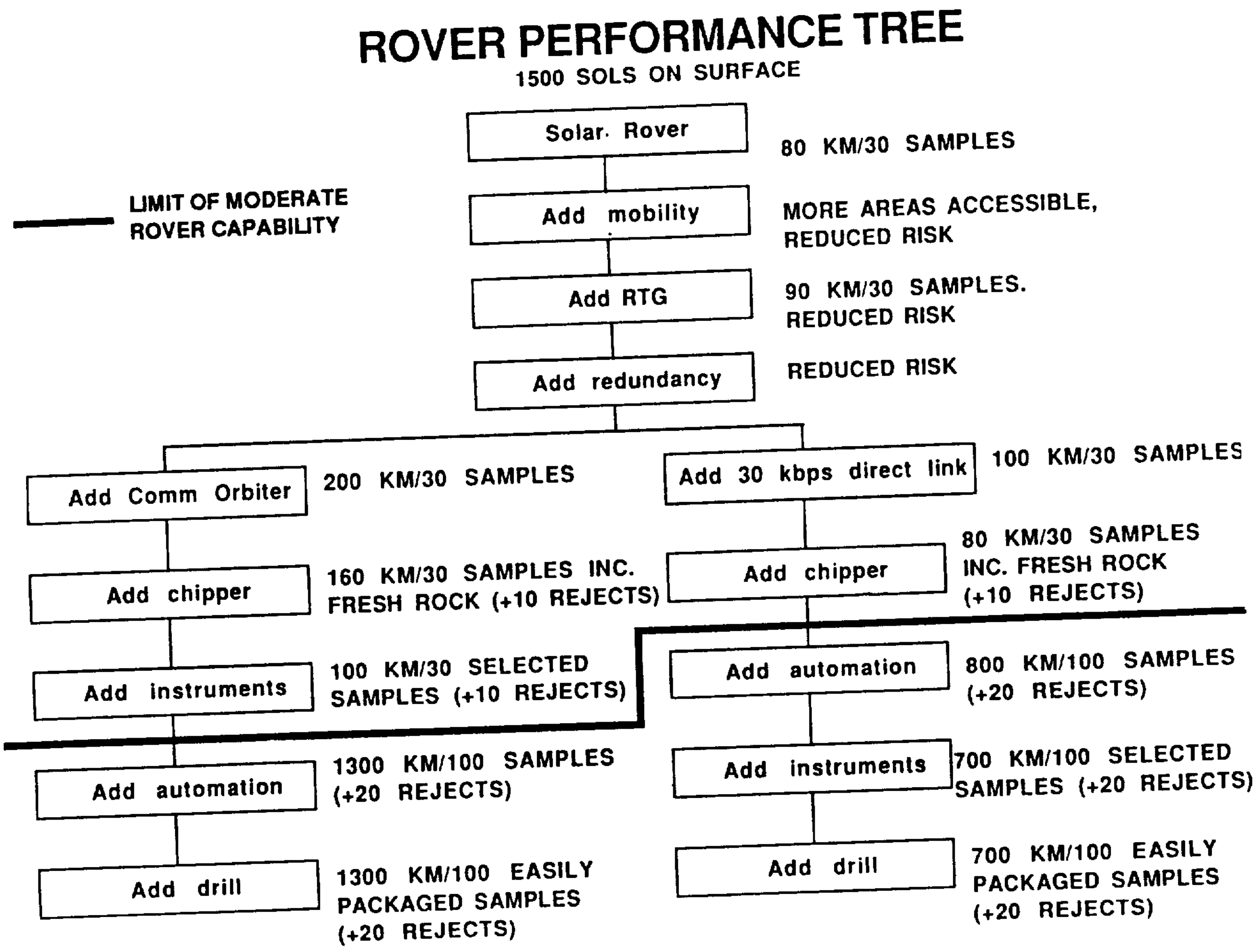


Figure 10 - Rover Performance Delta Tree

An estimate was made of 100 km traverse, 30 samples acquired and kept, and 10 sample acquisition failures or rejects. Of course, the samples acquired with a lot of instruments to aid in selection might be more meaningful, however it's important to bear in mind that distance covered is being given up while instruments are used and results analyzed.

Add Automation - Adding automation sufficient to bring about more autonomy drastically improves performance. If automation can bring about a 1 km/day traverse, then over 1000 km could be covered in 1500 days while still acquiring 100 samples.

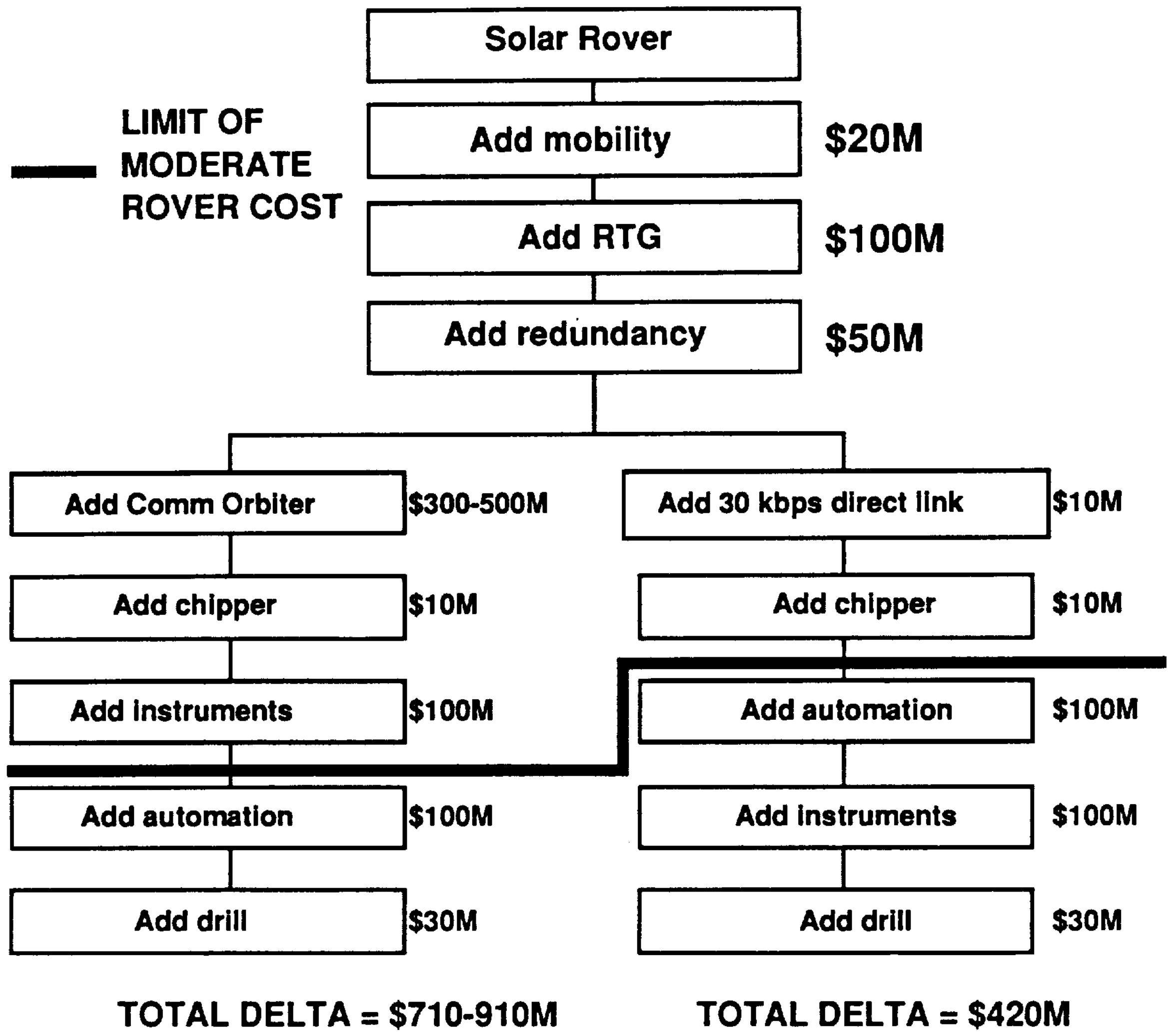


Figure 11 - Rover Cost Tree

Add Drill - Adding a drill neither adds to nor subtracts from performance. Presumably some chip samples would be replaced with core samples, but both might require the same amount of time.

Following the right branch of the tree:

Add 30 KBPS Direct Link - Adding a better direct link to an RTG rover would only slightly improve performance - it is estimated to add 10 kilometers to the range. This is because communications time is not the bottleneck. It is dwarfed by light time delay and the ground decision making time.

Add Chipper - Adding an operationally complex item like a chipping tool with no automation to assist in operation would reduce return by about 20%, to 80 kilometers and 30 samples.

Add Automation - As in the case with the Comm Orbiter, automation drastically increases presumed return. By being able to cover a kilometer a day, such a rover might cover 800 kilometers and still collect 100 samples. The reason that the rover cannot cover over 1000 km, as it could with the CO, is that sample acquisition and site surveying are still somewhat interactive, so the rover will be idle when out of Earth view while performing those functions.

Add Instruments - Adding instruments slows down operations, but less so than on an unautomated rover. A 10% performance decline was estimated, to 700 kilometers and 100 samples acquired.

Add Drill - Does not affect performance in terms of number of kilometers or samples. Seven hundred kilometers and 100 samples are estimated.

3.5.2.2 Other Improvements - Other options exist for performance improvement. Lewis Research Center intends to address the use of better integrated power/mobility designs and improved batteries to determine if the solar rover can be made efficient enough to be attractive. Lower mass mobility systems are being investigated by JPL, and if the mass of the power subsystem can be substantially reduced, great improvements in mobility and structural efficiency appear possible. Lower mass, higher performance computational systems are possible with sufficient lead time and investment in technology development.

3.5.3 Moderate Rovers - If one stops part way along the "rover additions tree", a moderate level of performance can be defined. Getting to the branch point is probably required for an acceptable level of risk, given the heavy investment in even a low-capability rover. This rover would use a level of automation equivalent to today's planetary spacecraft, providing preprogrammed fault protection and using the ability of the system to automatically switch from a failed subsystem element to a healthy element.

For Mars Rover Sample Return missions the addition of a communications orbiter more than doubles the capability of a "CARD" level rover. Alternatively (or as a backup) a 30 kbps direct link allows stereo images of the rover's surroundings to be transmitted in a reasonable period of time for use in ground-planned local navigation, and in sample selection. A moderate Mars rover has some means of gathering fresh rock (a low-automation chipper or drill) and includes a larger set of analysis instruments than a simple rover. Although the right branch of the tree shows that automation would be added before additional instruments, some instruments would enhance the ability of the rover to gather diverse samples without requiring a great deal of automation. Following this line of reasoning, a moderate rover can be defined by deltas above the heavy lines in Figures 10 and 11.

A moderate rover was also defined for Lockheed for a Lunar mission by Battelle Columbus [Battelle89]. This rover would be used to emplace a network of radio astronomy antennas on the back side of the Moon. Sufficient communications support was assumed so that the rover could be operated from Earth in the Computer Aided Remote Driving mode. Simple manipulation was required to emplace the antennas, and RTGs were assumed for power. The Battelle design is, in fact, very similar to the moderate MRSR design. The remainder of this section, and the next, focus on the MRSR rover design.

3.5.3.1 Science - Science instrumentation on the MRSR moderate rover includes a number of instruments for viewing and compositional measurements. In addition to the point spectrometer (and the stereo cameras) for the simple rover, the moderate rover includes an Alpha, Proton, X-ray Spectrometer (APXS), a Neutron Spectrometer (NS), and an Optical Microscope (OM). Characteristics of these instruments were summarized in Table 4.

The Alpha, Proton, X-ray Spectrometer (APXS) determines major, minor, and in some cases trace element chemical composition of samples and outcrops. The instrument measures the radiation emitted from a sample bombarded by alpha-particles from a radioactive source.

The Neutron Spectrometer (NS) detects scattered neutrons from the rover RTG. The scattering is very sensitive to the amount of hydrogen (presumably as water ice) present in the subsurface.

The Optical Microscope (OM) provides very high resolution imaging of samples, allowing characterization at the scale of mineral grains. Some spectral capability is desired.

3.5.3.2 System Control - Moderate rovers have the onboard control capability equivalent to current spacecraft for fault protection. In addition, they have the ability to sense anomalous conditions while traversing or sampling, and can take simple actions (such as stop). In order to exploit the more robust mobility and sampling capabilities the ground control system must be able to process and uplink commands much more rapidly than current practice. A target of an order of magnitude speed-up in ground operations turnaround has been selected.

3.5.3.3 Mobility - JPL designed two configurations which are simple enough to be appropriate for moderate rovers, but which could also be candidates for capable rovers. The design process and results are described below.

3.5.3.3.1 Analysis Tools for Wheeled Designs - In FY89 significant gains were made in the ability to compute vehicle performance and optimize vehicle configurations. At JPL mathematical models were written for step and bump climbing by wheeled vehicles with two-dimensional (2D) suspension geometries. A step is defined as a rise in elevation with horizontal dimensions greater than the vehicle length. A bump is an abrupt rise which fits horizontally between the axles. These math models use quasi-static force analysis based on classic friction with ridged wheels. This work is similar to that published by Jindra [Jindra66] in the 1960s. The most significant finding of this work is that bumps are more difficult (require a greater coefficient of friction) than steps.

No three dimensional analysis of these problems was found in the literature. Three-dimensional (3D) mathematical models are complicated by the simultaneous interaction of forces which shift weight forward or backward and to one side. The vertical forces resulting from these interactions determine the resulting friction forces (traction) at each wheel. There are two forces at each wheel contact, a perpendicular force and a friction force. Both the direction and magnitude of the friction are unknowns. For a six-wheeled vehicle this requires 18 independent equations to solve the 18 (three times six wheels) unknowns. The most important relationship is the distribution of forces as viewed from above the vehicle. With an obstacle against one wheel there is an eccentric load. Classical analysis (used in the elastic regime) distributes the reaction as forces perpendicular to radial lines from a moment center of forces. The magnitude of each reaction force is proportional to the radius from this center. This situation creates a paradox if the reaction forces are to be equal to their normal force times the coefficient of friction.

This problem was overcome with the invention of a "strain center". This new center has all the reactions perpendicular to radial lines from it while the magnitude of each reaction is determined by the out-of-plane (normal) force. The "strain center" concept is a NASA new technology item.

The complex 3D mathematical models were solved using commercially available software (EUREKA and MATHMATICA). The result of using the programs was checked by ADAMS, a commercial 3D dynamic mechanism software package. The vehicle, with its suspension pivots, was modeled in 3D using ADAMS and the forces resulting from the other programs. The vehicle was shown to be stable, with the forces giving a satisfactory solution in ADAMS. One of the most significant findings was that for a given obstacle size, having both wheels in the same axle position against obstacles is a more severe challenge than having one wheel against the obstacle and the other wheel on a flat surface. This result is true regardless of vehicle width. It was feared that very wide vehicles would slide and rotate around the obstacle rather than climb it. But this was shown to not be the case. This means that the 2D analysis is the worst case (neglecting, for the time being, complex, multiple obstacles at random axles).

Because these analytical tools are valid for different gravity forces, they can be used for the Earth, the Moon, or Mars. Variation in gravity alters the sinkage of wheels in the planet's surface. These traction forces can be simulated by picking the proper scale size for the model being tested. Worst case sinkage conditions occur when the surface particles are near spherical and do not interlock to a significant degree. The roundness of the grains is determined by the geological processes which formed the material, and these vary from planet to planet.

3.5.3.3.2 Vehicle Designs - Since 2D analysis appeared to be the worst case, a systematic analysis was done toward optimizing six-wheeled vehicles. In order to maximize vehicle obstacle climbing ability with the simplest, most reliable characteristics, JPL designed a suspension system with the following attributes:

- Equal (or design specified) weight on each wheel.
- Constant weight distribution throughout a range of vertical deflection over obstacles.
- Stable vehicle body.
- Passive suspension (no actuators).

A system of bogie links was invented which used six wheels and satisfied these four attributes. A significant feature is that the left and right sides of the vehicle are independent. There are no axles coupling a wheel on the right with a wheel on the left. The system uses a single body which tilts slightly when a single wheel is significantly displaced. Effectively, a mechanical averaging of wheel position determines the body position. There are no springs or other elastic elements which would change force with displacement. As a result the body is rigid to the limits of the linkage structure, which creates a very stable instrument platform when the vehicle is stopped. The bogie link pivots for this design are at axle height. As a result, the pivots interfere with obstacles larger than one half of the wheel diameter.

Another version of the bogie link suspension was designed which uses virtual pivots to avoid the pivot interference problem. This is accomplished by four parallel linkages which resemble a pantograph, hence the name "Pantograph" was uncritically applied. The Pantograph was shown in Figure 3. The pantograph-like system carries the wheel torque reaction at a different link than the previous system and is therefore different in performance. The Pantograph has very high ground clearance (equal to the diameter of the wheels).

Still another type of bogie linkage is being studied. This system has only two links on a side (compared to nine links per side for the Pantograph). The most significant aspect of this new "Rocker Bogie" system (shown in Figure 4) is that the wheels are 5/8 of the diameter of the Pantograph's, while retaining the ability to climb the same step height (one and 1/2 Pantograph wheel diameters). The newer system performs much better than the Pantograph over bumps. A disadvantage of the Rocker Bogie, however, is that there is again a link pivot between the wheels at a level slightly higher than the original bogie link system. By adding another two links per side this pivot can be made virtual as with the Pantograph. A motorized scale model of this newer design is being tested to compare actual performance with computed performance.

3.5.3.4 Local Navigation - In a moderate rover, CARD-based navigation is still used. However, the execution monitoring function can be made more sophisticated, resulting in increased rover safety. From the downlinked stereo imagery, a computer model of the terrain geometry near the rover can be constructed. Traversal of the human-operator designated path can be simulated on Earth, producing a set of sensor expectations linked to specific steps along the path to be executed. This set of sensor expectations is uplinked to the vehicle along with the desired path. Given these dynamic sensor expectations, rather than preset sensor limits, the rover can recognize anomalies before they become serious. With sensor limits matched to the type of terrain to be traversed, the rover can react appropriately; e.g, the rover might stop if it hits an unexpected rock while driving over a supposedly smooth expanse, yet would continue traversing over several larger (though traversable) rocks that had been anticipated along a path through rough terrain.

3.5.3.5 Sample Acquisition - The moderate rover sample acquisition system will consist of a 6 dof manipulation arm and a 3 dof fresh rock acquisition arm. The manipulation arm will collect loose surface samples such as sand and pebbles, and transfer fresh rock samples from a specialized chipper to containers. The acquisition arm will perform simple drilling operations up to a depth of not more than a few centimeters, and set specialized chipper tools on rock faces. For the latter operation, the acquisition arm may be aided by the manipulation arm.

All of the sampling operations will be planned on the Earth and commands will be shipped up to Mars. While CARD technology for local navigation implies that each uplink would consist of a single command for the navigation subsystem, this is not a reasonable assumption for the sampling system because of the granularity of the problem domain. So, it is assumed that the entire sampling operation will be planned on Earth as a single sequence, and uplinked to the sampling system. If execution is successful, such a report is sent back to the Earth. However, if failure occurs, then the sampling system executes simple reflexive actions, and ships the errors back to Earth for replanning. This is not expected to involve a very high degree of sophistication since the only operation that could fail in a catastrophic manner is the rock drilling operation, and drilling depths will be constrained to a few centimeters at most.

3.5.3.6 Vehicle Control - The vehicle control subsystem for the moderate option differs little from that described above for the simple option. Night operations require the addition of a strobe to illuminate the scene for the cameras, and the change from four to six wheels adds two actuators to be controlled during locomotion. The most important change is the addition of higher precision pointing requirements for the direct-to-Earth communications antenna. For pointing accuracies tighter than 0.25°, a star tracker is chosen to initialize the celestial attitude of the rover. The inertial attitude of the rover is then propagated by the gyros from the time of the star sighting to the time of direct rover-Earth communication.

3.5.3.7 Computation - The moderate rover computation concept is very similar to that of the simple rover. This architecture inherits a large amount from CRAF. In order to meet the additional performance required for execution monitoring and fresh rock acquisition, more computer boards will probably be needed for local navigation and sample acquisition. The tape recorder may need to have a higher capacity to handle the additional instrument data.

3.5.3.8 Communications - The primary communication link for the moderate rover is at S-band through the CO. Downlink rate is 30 kbps through a hemi-directional antenna. A solid state S-band power amplifier requires 8.5 watts unregulated DC power, assuming the CO is areosynchronous (17,000 km above the Martian surface). X-band uplink rate for the primary system is 2 kbps. A backup direct communications system was assumed for use in case the CO failed. A 30 kbps X-band downlink to a 70-meter dish could be used which would require a 0.6-meter dish on the rover, 200 watts regulated DC. The total system (primary and backup) would weigh 53 kg.

3.5.3.9 Power - The power system for the moderate rover consists of RTGs modified for Mars operation, super Ni-Cad batteries for energy storage and discrete components for power management and distribution. All the technologies assumed for this rover have either been space qualified or will be qualified by rover launch date by other programs at no expense to MRSR.

A 500-W power system was designed for the moderate rover, although later performance analysis indicates that this is conservative. Primary power is provided by Radioisotope Thermoelectric Generators (RTGs). These RTGs use the General Purpose Heat Source (GPHS) that has been qualified for the Galileo and Ulysses missions. The heat of GPHS is converted to DC power by thermoelectric unicouples that have been used on the Voyagers and Galileo and are scheduled to fly on Ulysses. Therefore, no new technology is required for this class of RTGs. However, the GPHS-RTGs used on Galileo and Ulysses are designed for space operation and some engineering modifications are required to make them suitable for Mars surface operation. The thermopile (thermoelectric converters and multifoil insulator) has to be isolated from both the Martian atmosphere and the He produced by the heat source.

This modification is necessary because the multifoil insulation that is used in the RTG to minimize system heat loss degrades in the presence of these gases. In a study funded by DOE, Fairchild Space Company developed a concept [Schock89-1] [Schock89-2] whereby the entire housing of the RTG is sealed to keep the Martian atmosphere out of the RTGs. The heat source blocks are placed inside a Molybdenum canister. The He produced by the heat source is contained in the canister and is vented out.

The super Ni-Cad battery storage system is a near term technology under development by NASA. The super Ni-Cad improves the depth-of-discharge (DOD) of Ni-Cad batteries, which have a long history of space flight. The performance of super Ni-Cad assumed for this rover is 30 Whr/Kg, capable of 40% DOD.

3.5.3.10 Thermal Control - The major thermal control issue on Mars is keeping the rover systems warm at night. For the moderate rover this is expected to be by the use of waste heat from the RTGs, rather than by the use of auxiliary electric heaters. Further, other thermal control devices such as thermal louvers and insulation will be used. Small RHUs may also be used. On the other hand, for efficient operation the RTGs must have a cold environment to radiate heat to. There is a risk that improper location of the RTGs on the rover may block their radiation. A thermal analysis conducted at JPL shows that the Fairchild RTG design can be kept within acceptable temperature limits while mounted in reasonable positions on the rover.

Another thermal control issue is dissipation of the waste heat from the rover during its delivery from Earth to the Mars surface. The moderate rover is assumed to be captured propulsively into Mars orbit, so the landing aeroshell can be open for heat dissipation during interplanetary cruise and orbit capture. During descent the rover will probably be enclosed in an aeroshell, and a heat sink for the RTG will have to be provided during the few minutes of aerodynamic heating.

3.5.3.11 System Characteristics - The performance of the moderate rover was estimated by creating a scenario for a low-autonomy traverse lasting 24 hours. This traverse is a repeating cycle of Move, Image, Downlink and Idle (wait for a new set of commands). Figure 12 shows the power consumption and battery state for the moderate rover. This rover is powered by a 500 watt RTG and has 470 watt-hours of battery storage available. The rover power consumption line in Figure 12 is identified by the square data points and reflects the total power output of all the subsystems on the rover. When the rover is in Mobility mode, the power required to operate it jumps to over 900 watts. The battery energy line is identified by diamond shaped data points and accounts for the battery

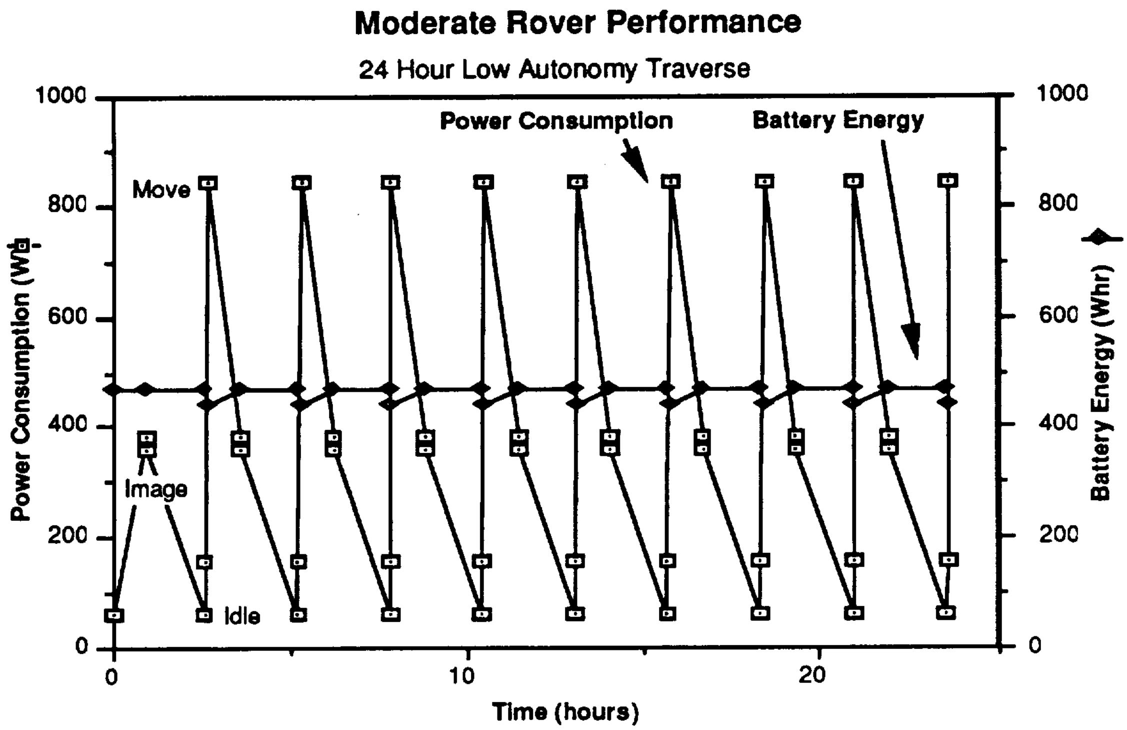


Figure 12 - Moderate Rover Power Consumption

energy needed to provide the make-up power. During the mobility mode the rover moves 30 meters through sand at a climb angle of 30 degrees. These conditions were considered to represent the most stressing case the rover could encounter.

The moderate rover mass is estimated to be 878 kg, again driven primarily by the power subsystem mass, which includes 79 kg of batteries. The result of a low technology approach, designed to save up-front technology development costs, is therefore a large mass penalty which may drive the cost of other elements (i.e. the delivery system) more than the savings to the rover.

3.5.3.12 Performance - The moderate rover performance is estimated to be about 100 km and 30 samples in 1500 days. The assumptions behind this are shown below.

Moderate Rover Assumptions:

Traverse:	75 2-hour engineering interactions 1 8-hour science interaction/km traverse
Sampling:	10 2-hour engineering interactions/sample acquired 1 8-hour science interaction/sample acquired
Survey:	Not needed: considered part of traverse

A large amount of this movement is likely to be backtracking if the terrain is known only at Viking and Mars Observer (MO) resolution. If an Imaging Orbiter were included in the mission, capable of mapping the rover traverse area at resolutions equal to the scale of the rover itself, backtracking could be reduced, efficient traverses to interesting, but reachable areas could be planned on Earth, and the range of the rover could be greatly increased because of confidence of Earth operators that the traverses are safe.

Figure 13 illustrates the effect of a plus-or-minus 1 km landing accuracy capability and good terrain knowledge on a 100 km traverse in the East Mangala area. (This assumes that the imaging shows that the terrain is indeed traversable.) The addition of spectrometry to the Imaging Orbiter would aid in sample site selection and traverse planning, increasing the value of the mission. The Imaging Orbiter is estimated to cost between $0.5-1B.

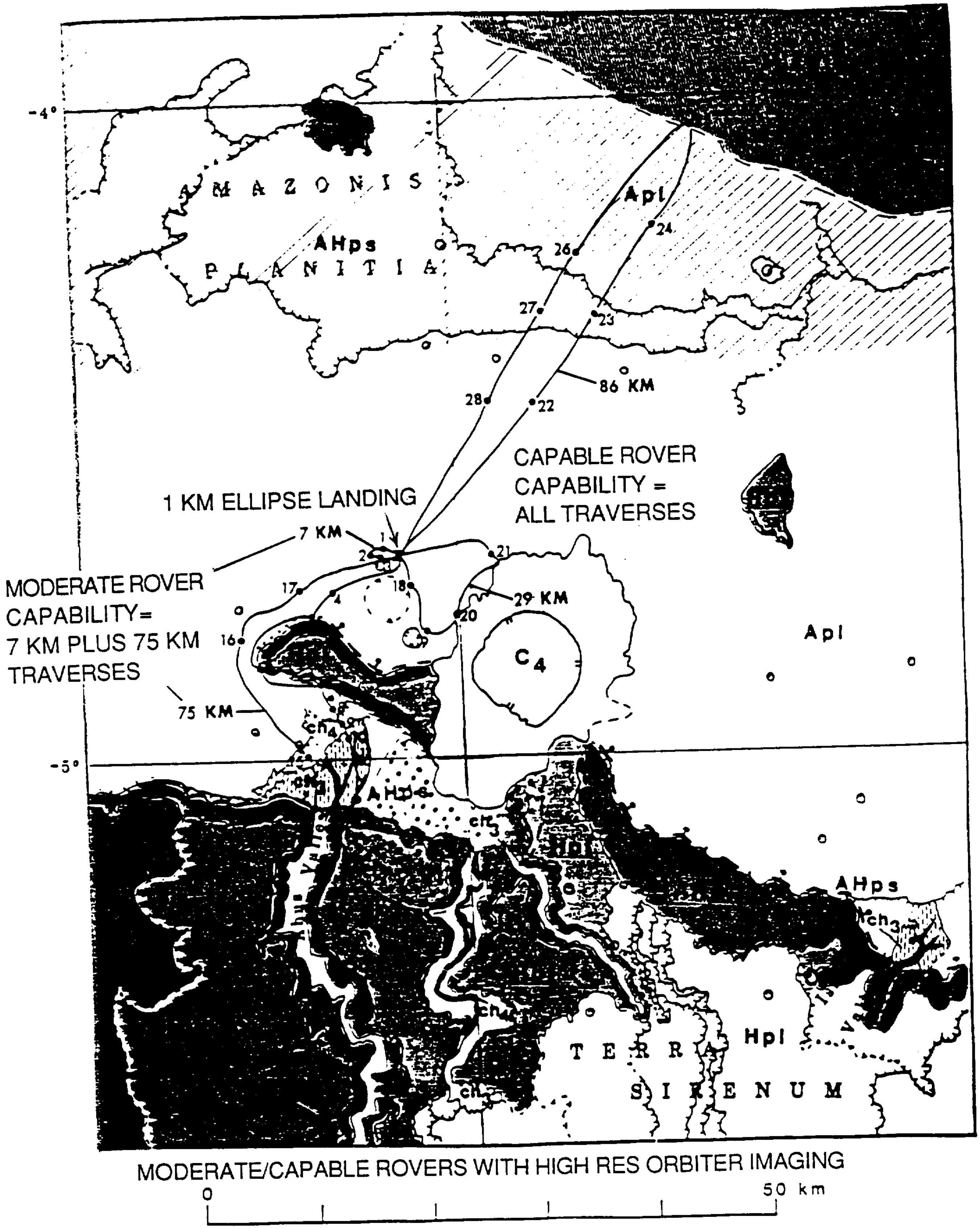


Figure 13 - Traverse with Terrain Foreknowledge and Accurate Landing (adapted from [SSED87], pg. 15)

3.5.4 Capable Rovers - The Mars Rover Sample Return baseline mission in FY89 was to launch the rover and sample return both in 1998. This minimizes the rover time on the surface, perhaps to as little as 215 days. In order to accomplish an acceptable mission, this rover must be highly automated, highly capable, and employ advanced technology. Therefore, the FY89 studies focussed on these capable rovers. The feasibility of these rover concepts is dependent on 1) the continued/expanded funding of the OAST Pathfinder Planetary Rover and OAST Pathfinder Sample Acquisition, Analysis and Preservation, 2) the development of Mars-surface operable RTGs by DOE, 3) and the continuation/expansion of OAST programs in space-qualified, high-speed computing and power component improvements. The availability of flight qualified versions of these technologies is also dependent on the rover launch schedule: technology readiness (brassboard demonstration) is required by 1992 for a 1998 launch, and by 1994 for a 2001 launch. In 1988/89 capable rover concepts were developed at JPL and two contractors addressed mobility and local navigation concepts and performance. Numerous universities (most notably Carnegie Mellon University, with funding by OAST) have developed rover concepts as part of their research, or as student projects. The remainder of this publication summarizes the current capable rover concepts of JPL and its contractors, FMC Corporation and Martin Marietta Corporation (MMC).

3.5.4.1 Science - Science instrumentation on the capable rover includes the instruments on the moderate rover, with the addition of a Differential Scanning Calorimeter/Evolved Gas Analyzer (DSC/EGA) and an Electromagnetic Sounder (EMS), as well as an Imaging Spectrometer (IS) instead of the Point Spectrometer (PS). Characteristics of these instruments were summarized in Table 4.

The Differential Scanning Calorimeter (DSC) provides primary phase identification of minerals. It can determine low temperature mineralogy of samples. The Evolved Gas Analyzer (EGA) is a Gas Chromatograph (GC), a Mass Spectrometer (MS), or both (GCMS). The EGA is used to analyze the composition of volatile components, including organics. It can also be used to analyze atmospheric samples.

The Electromagnetic Sounder (EMS) detects variations in electrical properties of materials beneath the rover traverse path. It can be used to determine subsurface structure and watch for subsurface hazards to navigation. The EMS requires special purpose data analysis electronics to process the data and reduce its volume for return to Earth.

The Imaging Spectrometer (IS) provides multispectral images of Martian surface at high spatial and spectral resolution. The information is used to determine and map compositions of the surface, and aid in sample selection. The IS will use special purpose data analysis electronics and algorithms to identify minerals and reduce data volume for return to Earth.

3.5.4.2 System Control - Because of the complexity of a highly automated rover, a concept for a top-down systems approach to control of the system was developed by Smith and Matijevic [Smith89] based on their previous work in spacecraft computation and robotic control. Rover concept activities in FY89 focussed on defining the rover system in terms of the control architecture, and on allocating control among functions and among the system executive and the lower level functions.

3.5.4.2.1 System Control Architecture - Figure 14 views the rover control system as a set of virtual computers, with processing, sensors and actuators connected by information and command flows. The normal spacecraft functions of system control and "subsystem" control are displayed on the front face of the cube in a hierarchical fashion, with commands flowing down from a high level to the actuator control level. State/status information flows up from the lowest (mechanical) level to the higher levels for use in monitoring command execution. Activities appropriate to each level are performed by control loops at that level. High-speed, closed control loops are executed at a low level for actual vehicle and manipulator motion actuation. Slow control loops are exercised for high level planning, e.g. of a traverse sequence.

Fault protection is exercised by a monitoring function (shown on the side face of the cube in Figure 14) which monitors the information/telemetry stream, and can interrupt the command stream to correct or react to anomalies in the expected order of events. That is, commands flow down through the hierarchy, while information flows up.

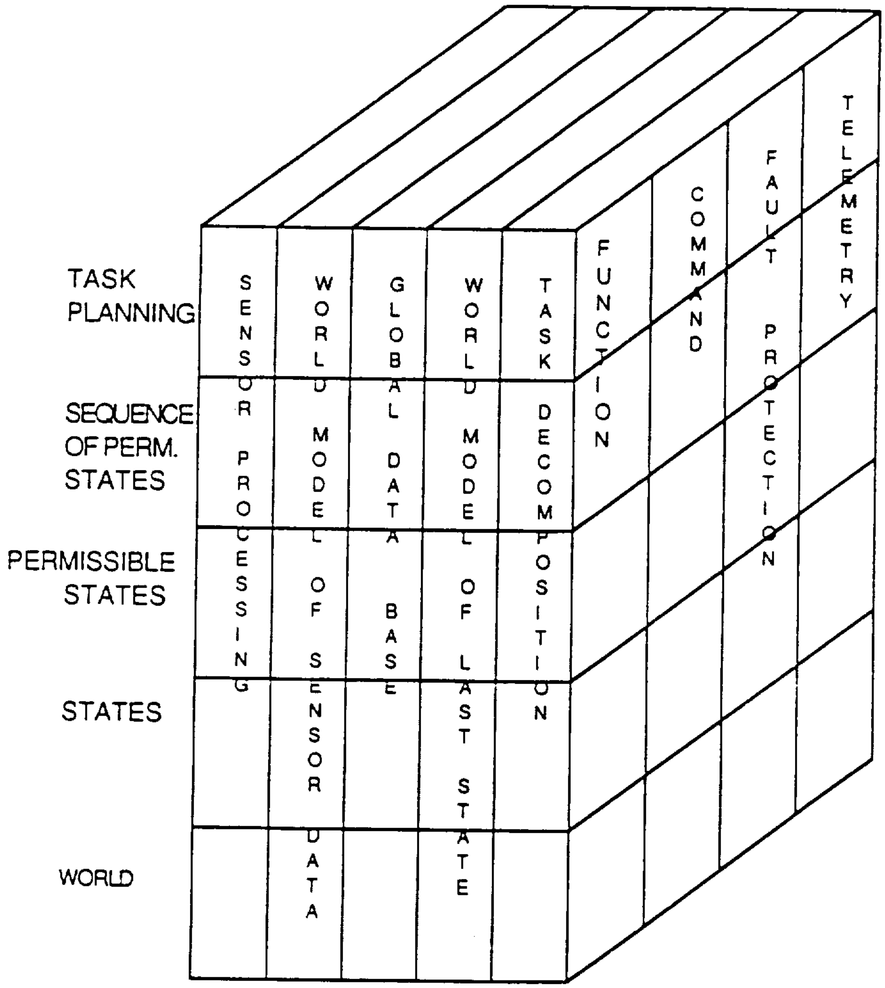


Figure 14 - Rover System Control Architecture

The fault protection function monitors performance and compares it with commanded performance and actual events and conditions. If a condition is out of spec the fault protection function can interrupt the command stream to deal with the fault. For example, if an unexpected rise in temperature occurs at a component level, the fault protection function can switch to a backup component to avoid a catastrophic failure while higher level fault diagnosis is occurring.

The system control architecture approach was used to allocate control authority and boundaries to various rover functions, and to address which control functions should be on board the rover and which should be retained by the ground system. A prototype computer model called ROSA (ROver System Architecture Analyzer) was developed which allows detailed functions to be input to each cube of the architecture. Information and command flows can be traced through links between cubes, and thus command and control loops and sequences of commands can be developed. A descendant of this tool will be used in future years to design and evaluate integrated control and information system architectures.

3.5.4.2.2 System Executive - The issue of system-level control of a quite autonomous roving spacecraft was addressed at the functional level in FY89. The complex nature of a capable rover with 6 or more quasi-independent functional elements mandates some form of central control process or system executive (SE). The SE's functions provide services in two areas: resource management and activity planning and monitoring. Resource management includes fault protection. The general hierarchical relationship among the major elements is shown in Figure 15. For the capable rover it is assumed that ground communication provides a set of events, goals and constraints rather than a step by step timed sequence. It is also assumed that the resources have some level of intelligence, generally at the level of a disk controller. The functions of the SE are illustrated by an example for a traverse with a number of science objectives.

1. The ground uplinks a traverse description including a map for the navigation subsystem. The description includes the positions of sites where science objectives are to be undertaken.

2. The Planning function of the SE incorporates constraints from the global state of the vehicle and expands this description into a set of tasks that the components of the rover can perform. A command stream is generated by the interaction of the SE and the activity managers, which are responsible for detailed planning. Included in this command generation procedure is the creation of a set of event tokens (expected values) that the SE can monitor throughout the plan's execution.

3. The SE monitors the events and the regular reports from the resource controllers. Various methods, such as the application of a Blackboard model [Pearson88] are under consideration for supporting this feature of the SE. If the events indicate that the plan has encountered the unexpected, the plan is resequenced to avoid the difficulty. If the resource controllers report a failure condition the SE returns the rover to a known state and waits for ground interaction.

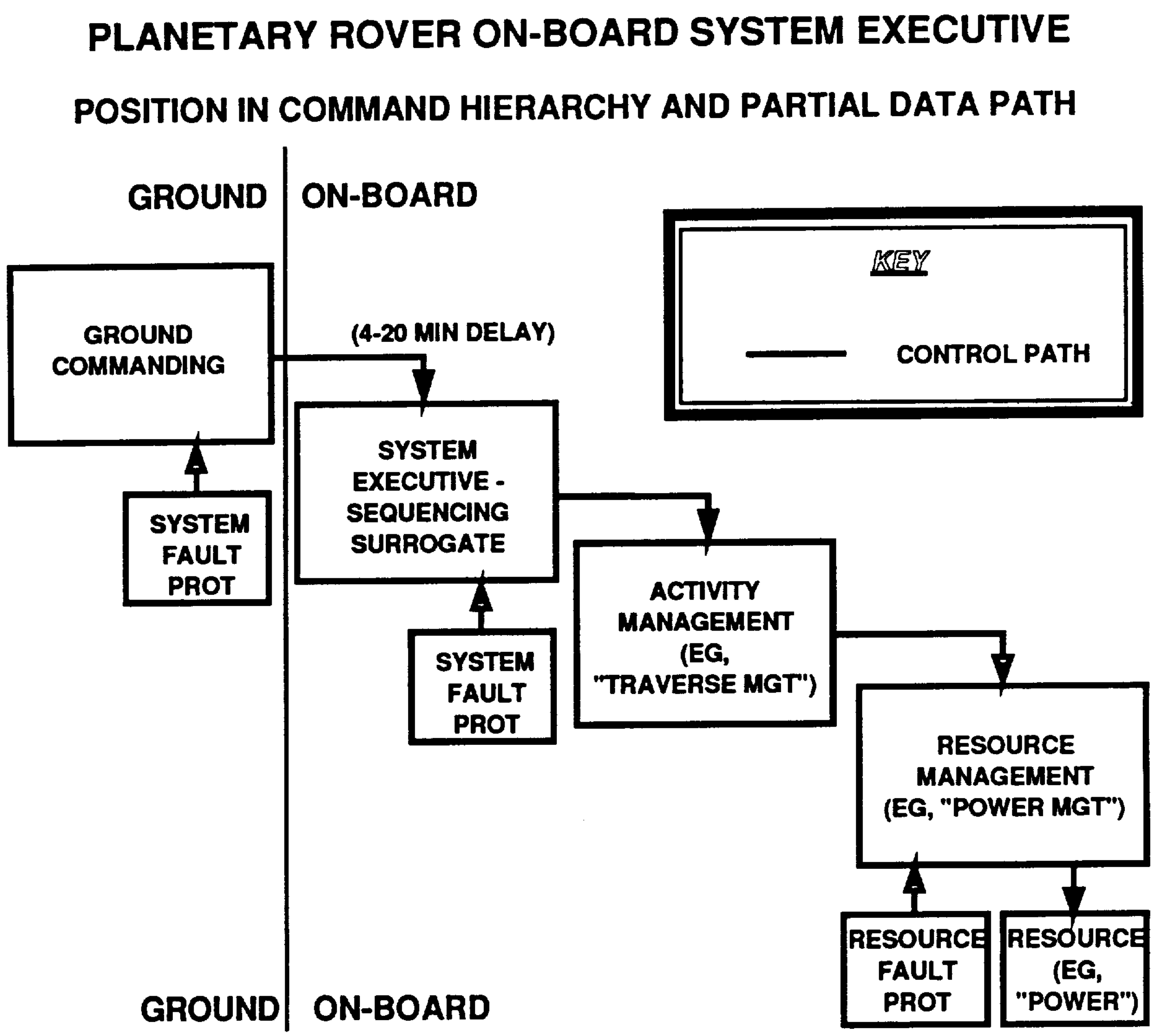


Figure 15 - System Executive Architecture

4. At the end of the traverse the SE collects the overall state of the vehicle from the resources and functional components, sends downlink to Earth at the prearranged time, and waits for the next ground communication.

The concept described above is one approach. Some work based on other ideas is in progress at Carnegie Mellon University [Simmons89]. Many issues remain to be addressed. System executive concepts were studied for a capable Mars Rover rather than for the less complex rovers. System control concepts for the less capable rovers could likely be based largely on existing spacecraft control methods, but the higher degree of autonomy in the capable rover is incompatible with those techniques. Subsystems, especially for local navigation and sampling, must be relatively autonomous to function efficiently. The system executive must be capable of managing these automated subsystems (e.g., an autonomous traverse path finder and planner), so that the actions taken by such a subsystem in response to the unpredictable terrain will be in accord with equally dynamic system and mission goals for science, distance covered, resource control, communications, etc. A traditional, low-autonomy approach to system control would either be constantly and unreasonably overriding the autonomous subsystems or would give them too much latitude for security.

Uncontrolled subsystem autonomy could be risky (witness the dangerous autonomy of a human two-year old) whereas over-supervised subsystem autonomy could bog down the whole rover. A balanced approach, perhaps incorporating principles from management of people such as "management by exception" and "management by objectives" is advocated. The point is, any reasonable solution implies an intelligent onboard System Executive (SE).

An issue identified, but not completely resolved in FY89, concerns how to define a fault and at what level of control faults should be corrected. In particular, the execution monitoring functions of the local navigation system are designed to keep the rover on track by sensing when accelerations and tilts, for example, deviate from those predicted by the planner. Normally, the local navigation function would replan to correct for slight deviations. For large discrepancies the desired response might be to stop. On the other hand, the discrepancies may be caused by a faulty sensor, which would be detected by the Vehicle Control function fault protection. The response would still be to stop while the cause of the discrepancy is diagnosed. But should the System Executive make the stop decision? The VCS? Or the local navigation subsystem?

Such issues will be a major focus of future years' rover designs.

3.5.4.3 Mobility - Three versions of a highly automated rover were studied in FY89. All are designed to move over rocks and steps at least 1 meter high, and across crevasses at least 1 meter wide. They can climb 30 degree slopes and maneuver in soft sand. They collect soil and pebbles and drill or chip rocks to acquire fresh, unweathered mineral samples. Both FMC and MMC developed concepts which incorporate active mobility elements, whereas the JPL design incorporates passive elements.

3.5.4.3.1 JPL Mobility Concepts - Either the Pantograph or Rocker Bogie described in the Moderate Rover Section (above) may be appropriate for a capable rover.

3.5.4.3.2 FMC Mobility Concept - FMC Corporation was awarded a contract by NASA's Jet Propulsion Laboratory in October, 1987 to study Rover mobility and surface rendezvous issues for the Mars Rover Sample Return Mission. FMC developed an extensive, innovative set of mobility and navigation concepts for a Rover planetary exploration vehicle. The Rover system concepts comprised a carefully balanced integration of navigation and mobility and spanned the full spectrum of navigational autonomy. The concepts were subjected to a rigorous, structured evaluation process to derive the most promising candidate Rover systems.

In FMC's evaluation of mobility concepts in FY88 the wheeled, three bodied, articulated Attached Scout concept shown in Figure 16 received the highest evaluation score. Wheels are one meter in diameter, one half meter wide, and are equipped with aggressive grousers. Each wheel is conical in shape with interior drives and high connecting axles. The center body has a mechanism to move the center axle forward and backward, allowing either end to become a stable platform for raising or lowering the axle at the opposite end. This function finds its primary use in crossing faulted terrain. Wagon type axles are used, thus the rover is steered by driving the wheels on either axle end at different speeds. Front and rear pivots are powered on demand to provide backup steering in case of drive motor failure. This mode of steering can yield to rocks or other obstructions, thus reducing loads and stresses within the structure. The front and rear bodies are connected to the center body by powered roll joints. In addition, the pitch of the front body is powered.

Pivot, pitch, and roll axles are all free during normal movement to allow conformity to the surface and to keep all wheels driving. The governing philosophy of the scout vehicle is to test the terrain ahead with the lead body before committing the complete vehicle to potentially unstable terrain. The powered pitch and roll joints enable

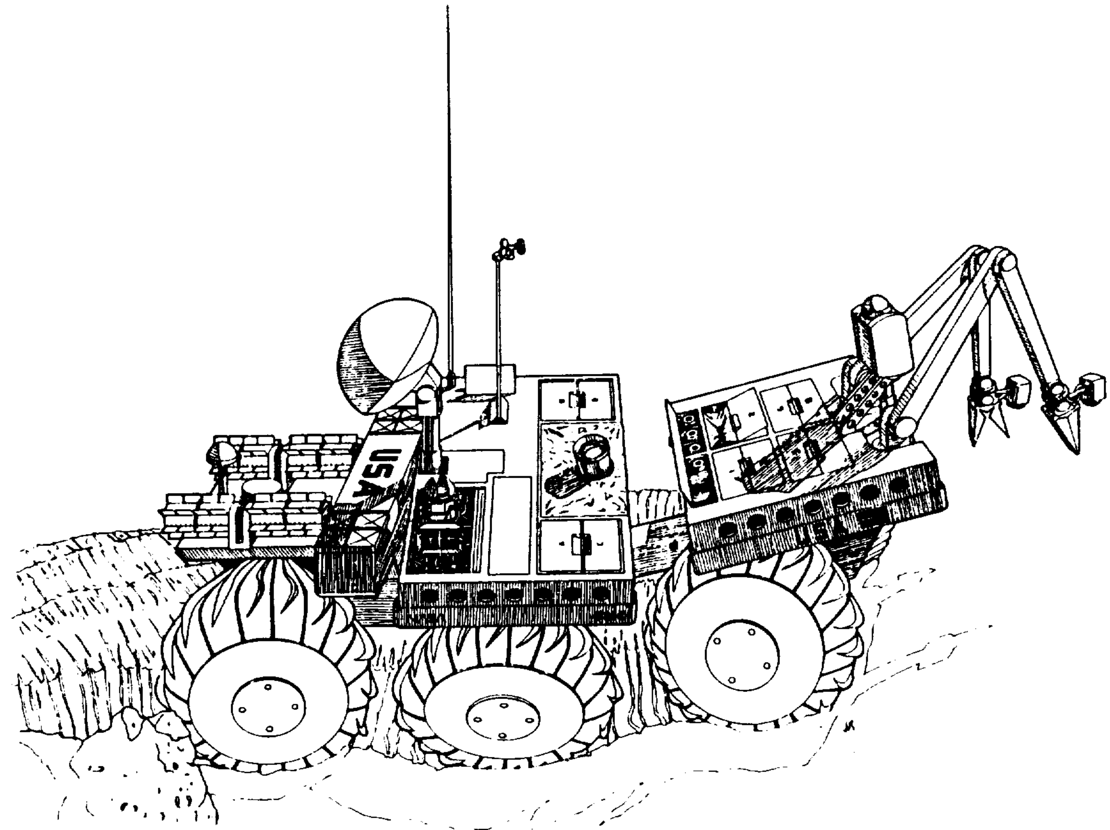


Figure 16 - FMC Attached Scout Configuration
(used by permission, L. McTamaney, FMC Corp., 1989)

the vehicle to cross crevasses and climb steps, and to hoist itself back to an upright position should a rollover occur. The powered pitch joint in conjunction with the axle shift facilitates packaging of the chassis into its aeroshell for transport to Mars.

3.5.4.3.3 MMC Mobility Concept - One of the vehicle concepts being considered by Martin Marietta as a candidate MRSR rover is the Walking Beam design shown in Figure 17. The Walking Beam is a collapsible seven-legged vehicle that consists of two platforms joined along the central beam, each with its own set of legs. It propels itself by alternately moving one set of legs with respect to the other. Rotation of the outer T-beam tripod while the vehicle is supported by the inner four-legged platform provides vehicle steering. Translation is achieved by level, nearly frictionless rolling on a central beam. Foot placement is vertical; this minimizes soil work and vehicle slip, which are major sources of power consumption and odometer error, respectively, for rolling vehicles. Since the vertical and horizontal motions of the vehicle are decoupled, actuator conflict (a major source of parasitic loss in conventional walking vehicles) is also eliminated.

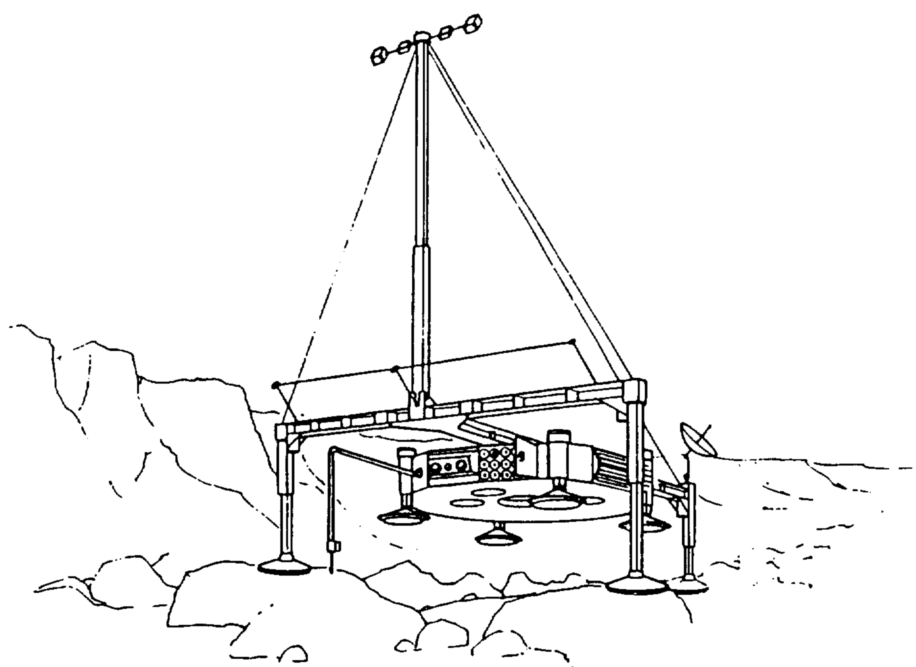


Figure 17 - MMC Walking Beam Configuration
(used by permission, A. Speissbach, Martin Marietta Corp., 1989)

The choice of a walking vehicle was primarily driven by two considerations: science return and safety. Legged locomotion provides increased traversability over the rough terrain inherently associated with scientifically interesting exploration sites. Since the traction elements need not be in continuous contact with the ground during motion, as is required for a rolling vehicle, the choice set of acceptable paths is far less constrained. With regard to safety, a passively balanced walker is both statically and dynamically stable. The low aspect ratio of the vehicle further enhances stability. In fact, the center of mass can be shifted in both horizontal and vertical directions to adapt the vehicle's geometry to the specific challenges of slope climbing, obstacle negotiation and other potentially destabilizing terrain conditions. The dual platform configuration ensures minimum risk of tipover and minimal shock and vibration to the payload. It also provides a highly stable base for an elevated sensor platform and a motionless antenna base for communication during half of each step cycle. Since the vehicle is always supported by one of the platforms during motion, it also has the ability to use its feet to test the bearing strength and traction of the terrain before committing the vehicle to a situation that could lead to accidental damage or entrapment.

The theoretical performance and safety advantages of legged locomotion are often offset in practice by the severe mechanical and computational complexity associated with the coordination of a very large number of independent, actively controlled articulations. The Walking Beam, however, does not require the complex articulations found on the majority of walking vehicles. It is designed to be simpler, more robust, less computationally intensive and more power efficient. There are only nine powered degrees of freedom, and the vertical and horizontal motions are decoupled. Decoupling of the motions also eliminates any possibility of leg interference, and greatly simplifies the coordination problem. The vehicle's ability to step over terrain eliminates the need to consider surface roughness and small obstacles explicitly. The capability to test the soil strength incrementally before putting full weight on it reduces the terrain classification problem to simple geometric consideration and simplifies path planning.

The outer tripod body is a simple deployable three-beam structure in a "T" configuration providing a long stable track on which the inner platform can translate. The inner platform contains power supplies, computers, science instruments, two sampling arms and an articulated sensor turret. Each of the vehicle's seven legs is a three segment telescoping cable-pulley drive with a single, triple-coil-geared motor and brake. The Kevlar cables will retain flexibility at low temperatures, will be automatically tensioned and will be sheathed to render them insensitive to dust. The footpad has the general shape of an inverted saucer, the same as a camel's foot. This shape compresses loose material underneath for more efficient locomotion. It also permits shedding of loose material collecting on the top surface during operation. A boot-sealed, spring-centered, ball and socket joint at the ankle lets the foot respond to uneven terrain.

3.5.4.4 Local Navigation - Three basic concepts of semi-autonomous local navigation have been addressed using three sensor approaches: stereo vision by JPL, structured light vision by FMC and laser ranging by MMC.

3.5.4.4.1 JPL Local Navigation Concept - The semiautonomous navigation (SAN) approach being investigated by JPL [Miller89] is being primarily developed as part of the NASA OAST Pathfinder

Planetary Rover Program. The concept follows this scenario: An imaging orbiter acquires stereo images of the Martian surface with approximately 1 m resolution; these images are downlinked. The images are used to construct high resolution (3 m) height maps of the regions over which the rover is expected to traverse. On Earth, a rover route (with a length on the order of kilometers) is planned; this route, along with a portion of the high resolution map, is uplinked to the vehicle. The rover acquires stereo images and other sensor data, matches what it sees against the uplinked map, then plans a local path (up to 10 m) that avoids local obstacles. The local path corresponds as closely as possible to the Earth-planned route, with deviations as necessary due to obstacles and conditions not resolved in the uplinked map. On board, the rover simulates the execution of the planned path, producing its own set of sensor expectations to be used during traversal. The rover executes the path while monitoring its sensors for anomalous conditions. Once the short path traversal is complete, the rover acquires a new set of images and performs the processing necessary to traverse another short path. The process repeats until one of two events occurs: 1) the rover reaches the end of the uplinked route and requests a new route and map be uplinked, or 2) the rover encounters a situation beyond the capability of its onboard decision making resources and waits for the next available communications window to downlink a CARD-type panorama, rover status, and a request for Earth intervention.

3.5.4.4.2 FMC Local Navigation Concept - The navigation system for the FMC Mars rover maximizes the rover's transit speed and minimizes the amount of communication which is required with Earth. A robust semi-autonomous design reduces the time the rover sits and waits for limited communication opportunities and, thus, optimizes the utility of an unmanned rover concept. The flexibility of this semi-autonomous rover is enhanced by establishing levels of control which vary from full autonomy for most common functions to detailed teleoperated control of all rover functions. The common functions which can be executed autonomously include normal driving, sensor data collection and communication with Earth. Several special operational modes are also available which can be executed autonomously under operator supervision to maneuver in close quarters, to extract the rover from entrapment and to recover from rollover situations.

The navigation system design takes advantage of functional redundancy in path finding and position estimation to maximize system robustness and minimize the number of sensing, control, and computational components. The local terrain geometry is characterized with a combination of structured light vision and stereo vision and the nongeometric characteristics are identified by actively testing the terrain surface with the attached scout and onboard manipulators. The rover's relative position and orientation are measured through wheel encoders, an inertial navigation system, a heading sensor, inclinometers and local terrain tracking. The rover's position and orientation in Mars coordinates are estimated through RF beacon navigation, optical beacon navigation, orbiter imaging of the rover, and very long baseline interferometry from Earth.

The major computational modules communicate and cooperate by using a blackboard paradigm. This minimizes the required amount of onboard memory and enables the navigation computing to be done on fault tolerant computing systems of standard design. The blackboard paradigm is extended to the problem of coordinating the rover from Earth by implementing a parallel blackboard on Earth which is coupled to the communications resources and to an Earth-based simulation of the rover. The blackboard model of interaction between Earth and the rover also permits the rover to be programmed with an extended rule based language. This programming approach provides a natural interface to an autonomous rover and makes expectation driven programming easy.

3.5.4.4.3 MMC Local Navigation Concept - The Walking Beam rover Navigation and Mobility function has four major elements: Sensing, Perception, Reasoning, and Mobility Control. The inputs are a global map, a global position update, and a task specification. It is assumed that Navigation is presented with one or more global maps of corridors through which the rover will travel in the accomplishment of the task. That is, the navigation and mobility task is described in part by a sequence of corridors that defines the route to be traveled by the rover. Corridor maps are digital elevation maps with approximately 5 meter or better resolution, with a specification of known obstacles (i.e., regions of the map which are designated as containing known non-traversable areas). Corridors may be of variable shape and size, but should be roughly equivalent in area to a 100 meter by 100 meter square. Within the corridor a starting position and a goal position must be specified, and way-points (intermediate goals) may be specified. The specification of the start point must include position as well as orientation (the global position update), while the way points may contain only position or approximate position specifications. The specification of goal points may be positional, or may consist of an approximate position specification coupled to a functional or procedural specification. In the latter case, the vehicle is directed to an approximate position, with the achievement of the goal determined by the ability of the vehicle to accomplish some function or procedure (e.g. to reach out and touch a soil or rock formation).

It is also assumed that the specification of the task may be more complex than the specification of a simple traverse. The specification may include functions that, although not within the purview of navigation or mobility, require interaction or synchronization with navigation or mobility. For example, the specification may include directives to acquire imagery or sensor readings during a particular segment of the traverse. This interaction with other system elements will be provided through the status and goal achievement outputs.

Once the navigation function has received these inputs the various elements within navigation and mobility perform the functions of sensing, map generation, navigation planning and actuator control.

Planning for navigation and mobility is performed at three levels. The highest level plan is provided to the rover in the form of the global corridor map or maps and goal points. The navigation system plans an a-priori path through the corridor to the goal point. There is a laser ranging system high on a mast above the base of the vehicle. Based on the initial vehicle orientation and the direction of the a-priori path, the perception function points the mast sensor and makes a local map from the mast data. Perception also processes the local map data to determine all allowable vehicle positions within the local map area. These positions become vehicle placement options that the reasoning function can use to replan over the local map area, based on local map data. The replanning done at this level is thus based on the more detailed data provided by the mast sensor. The replanning uses the original path location, just outside the local map, as a goal point.

Once a path has been computed based on the mast data, Perception is directed to produce a line scan sensor map, and mobility is directed to slide the rail in the direction indicated by the path. During rail movement Perception collects the line scan sensor data and creates a map. This map is in higher resolution than the local map, and will be used for determining exact footfall locations. Perception processes the footfall map to determine valid footfall locations for both the outer and inner legs, and passes the footfall map to the reasoning function. Reasoning selects among the valid footfall locations found by Perception, to produce a trajectory for the next pair of inner and outer leg placements. The trajectory includes specification of all movements needed for mobility , including rail movement, rail angle movement, leg retraction, and leg extension. Mobility executes the actuator control functions and monitors for mobility exception conditions, such as excessive force/torque to the legs.

3.5.4.5 Vehicle Control - The vehicle control subsystem functions may be described in terms of two cubes of the system control architecture discussed above. If the faces of the cubes in Figure 14 are rotated 90°, the control architecture structure can be overlayed with block diagrams for the control system. Figures 18 and 19 show block diagrams for the attitude control and traverse portions of the VCS respectively. The attitude control portion includes estimation, attitude determination, position determination, antenna and camera platform commanders and motor control. The traverse portion receives data on vehicle attitude and location from the attitude control cube, and performs the locomotion guidance and control functions. Several direct Earth-link antenna-pointing options are available. For the low data rate communications planned for this option, coarse Earth pointing of the antenna is possible with the FORS gyro, a clock, and a precision sun sensor. For higher data rates, a star tracker would be added to give more precise pointing. If no Earth pointing at all were required, the complex celestial attitude determination and propagation could be deleted from the subsystem.

3.5.4.6 Sample Acquisition - The NASA OAST Pathfinder Sample Acquisition, Analysis and Preservation (SAAP) effort has developed an initial system, subsystem and component architecture, requirements and conceptual design for a capable rover sampling function. This concept is shown in Figure 20. SAAP is also developing a breadboard acousto-optical tunable filter (AOTF) imaging spectrometer with autonomous hierarchical classification of minerals for sample identification in the 0.4-0.9 micron range. Surface sample acquisition experiments are being conducted, including chipping, sawing and autonomous coring, all using representative rock specimens to characterize tool design and control issues. Conceptual designs of sampling tools and end effectors, such as a "micro-drill" are also being developed. Results of the SAAP

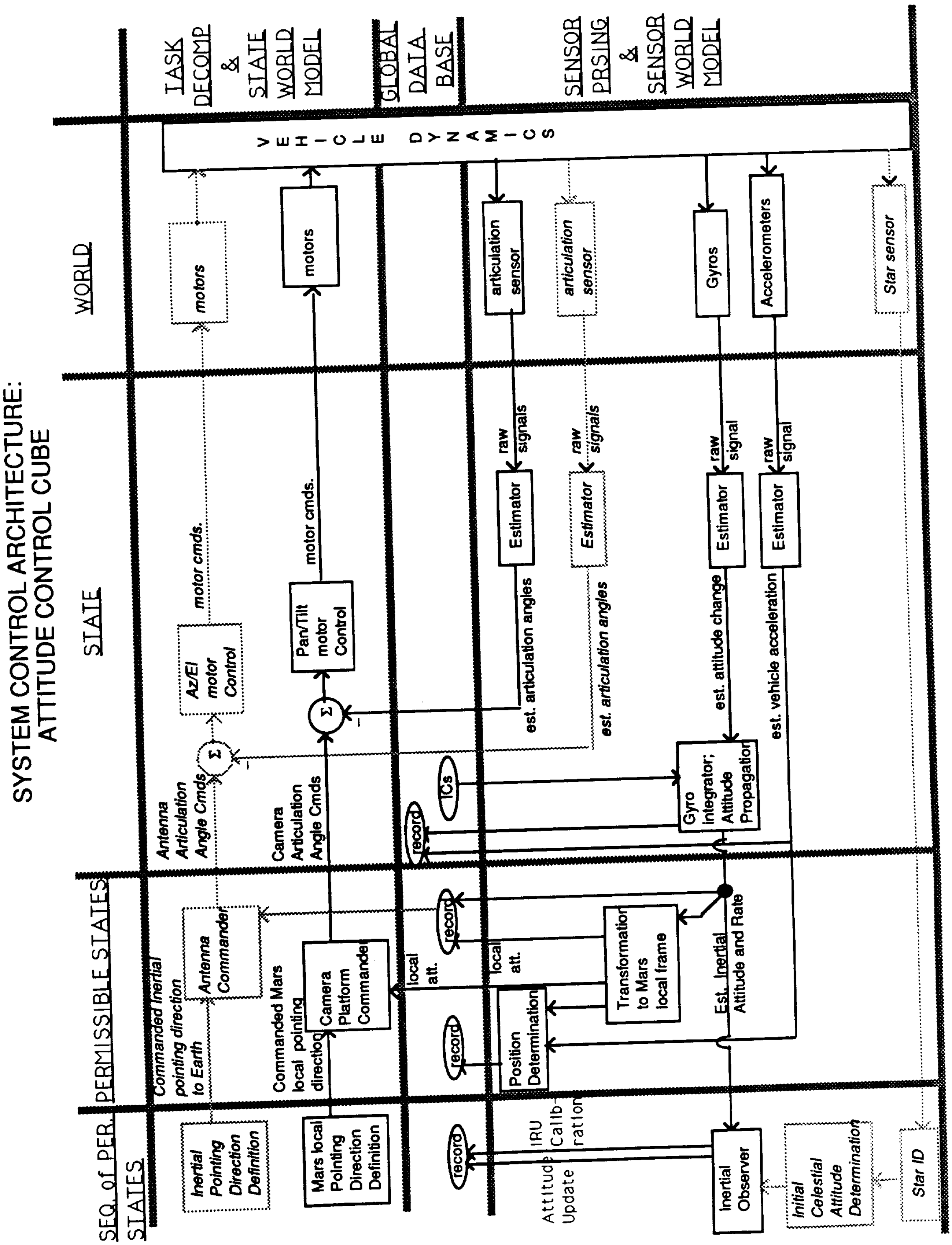


Figure 18 - Vehicle Control Attitude Control Architecture

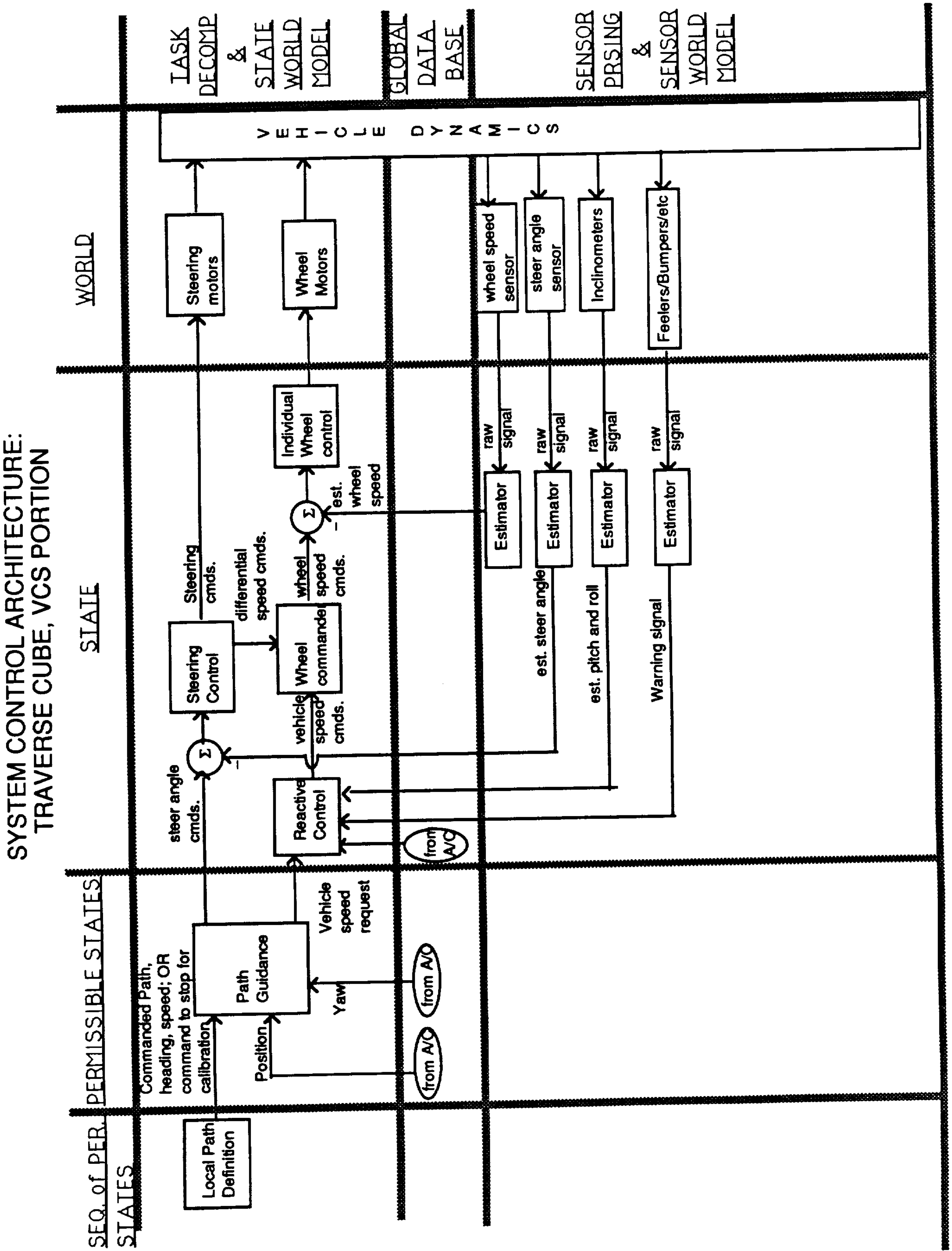


Figure 19- Vehicle Control Traverse Architecture

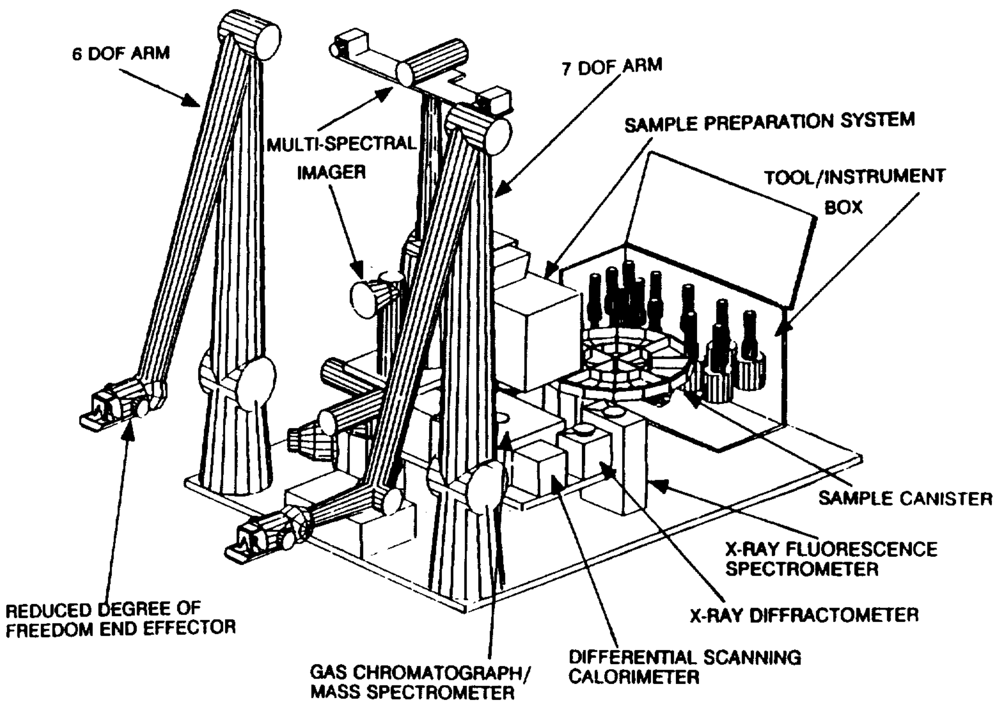


Figure 20 - Sample Acquisition, Analysis and Preservation Concept

effort since December 1988 have been incorporated into the rover designs described in this publication.

For a fully capable semi-autonomous rover it is assumed that scientists would pick sampling sites and uplink a single command for sample acquisition. On Mars, the Rover would plan and execute (i) vehicular motions necessary to place the sampling site within the sampling system's work space, and (ii) an entire suite of actions required to extract the required sample and containerize it.

The sampling system would consist, once again, of a 6 dof manipulation arm and a 3 dof acquisition arm. Each arm will contain appropriate position, velocity, force, vibration, and thermal sensors. The acquisition arm will also have the ability to exchange tools and perform chipping or coring. Typically, chipping may be expected to be more complex to execute for the following reasons:

- Since chipping involves impact, there is a greater probability of damage to sensors and other instruments from shock.

- The probability of tool slippage during impact is higher than that during core drill entry into a rock face. Impact may result in large velocities (and therefore, control problems) in the least, and collision between the sampling arm and rock face at the worst.

- In addition, containerization of samples acquired using chippers is significantly more complex than for those acquired using cores. In fact, with disposable core drills, the core bits themselves may be used as containers.

The sampling system must have the ability to plan and execute abstract sampling commands, as well as have extremely efficient sensor-based reflex mechanisms to quickly retract or adjust tools and avoid system-level damage. The system must be able to recalibrate its instruments and sensors prior to any sampling operation. It must also have the ability to transfer samples to containers, and exchange tools on the acquisition arm.

Salient features of the sample acquisition architecture proposed for fully capable rovers are as follows.

- The architecture reflects a decomposition from high level abstract sample acquisition tasks all the way down to low level actuation signals.

- At each level of the architecture, a task at the corresponding level is planned and executed.

- Execution implies either an instantiation of lower level tasks (in the nominal path) or a reflex action (if fast recovery is required).

- Sensory information commensurate with the level of abstraction is assumed available from the perception portion of the architecture.

At the lowest level, the architecture deals with actuation. At the next level, executions in joint space (for a manipulator, and at the steering and wheel axis for a vehicle) are considered. At the third level of abstraction, cartesian tasks such as free or fine motion are considered along with force/motion constraints that have to be met with during execution. The next level of abstraction deals with the sample acquisition task space. Here, for example, a coring task would be scheduled into a free motion of the arm to reach the tool box, a guarded motion of the arm to acquire a tool, a free motion to carry the tool to sampling site, and a fine motion to execute the actual coring operation. At levels more abstract than this, various sample acquisition tasks may be considered at a particular site, and scheduled.

3.5.4.7 Computation - A flight computer required for a semi-autonomous rover demands unique attributes. It needs to be able to address not only the processing problem associated with most automated robots, but also the classical high reliability and data acquisition functions of planetary spacecraft. Based on traversing 1 Kilometer using the time line in Table 8 (which is based on an operational scenario described in Section 3.5.4.12, below) a traverse cycle will require a processing load as shown in Table 9.

The computing requirements for the traverse mode call for about 4 MIPS of real-time processing. The compute mode requires about 11 MIPs of processing -- only about 3 MIPs of it is real-time processing, the rest is dependent on the time required to get the task completed which is about 3 minutes. If more time were given to the compute mode, the processing requirements could be lowered. Other estimates have been around 10 to 25 MIPs [FMC88].

In past designs pragmatic issues were typically overshadowed and forgotten when efforts were concentrated on meeting the performance and reliability requirements. In this case a concerted effort was made at addressing other issues such as testability and flexibility which are critical to the development cycle.

Even though much more work is needed in determining the complete computer system for a Mars rover, initial analysis of the criteria (cost, performance, reliability, and spacecraft usage) and possible architectures has led to a parallel system which is loosely coupled and message based utilizing high speed point to point serial links. Data flow will be used to address the problem of process synchronization. An example of such a system can be seen in Figure 21.

Table 8 - Capable Rover 1 - Km Traverse Time Line

AN OPERATIONAL SCENARIO

MODE	TIME
Idle	Variable
Communications	17 minutes
Image	0.5 minutes
Compute	3 minutes
Traverse	2 minutes
Science	5 minutes
Downlink	3 hours

one kilometer/day

Table 9 - Capable Rover Computational Requirements (MIPS)

	Idle	Comm	Image	Compute	Traverse
Focused based range	0	0	0	1.38	0
Path Planning	0	0	0	1.38	0
Terrain Match	0	0	0	2.77	0
Traverse Sim.	0	0	0	1.11	0
Execution Mon.	0	0	0	0	2.0
Sequence Gen.	0	0	0	1.38	0
System Mon.	0.2	0.5	0.5	0.25	0.5
Vehicle Con.	0.2	0.2	0.2	0.2	0.3
Telemetry	0.075	0.075	0.075	0.075	0.075
Command	0.1	0.2	0.2	0.2	0.2
Power/Therm.	0.05	0.05	0.05	0.05	0.05
Sys. Fault Prot.	0.125	0.2	0.2	1.7	0.625
Total	0.75	1.23	1.23	10.59	3.75

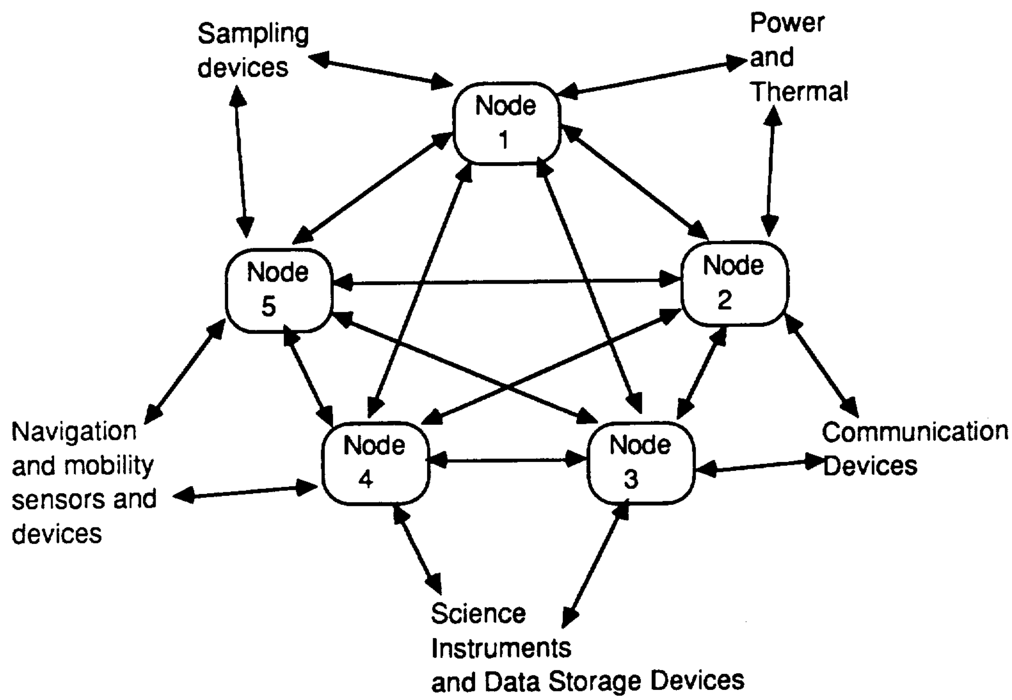


Figure 21 - Data Flow Computational Architecture

Each node can be a self contained computer with high speed bidirectional serial ports (10 Mbps) connecting it to the other nodes [Ras87]. Standard microprocessors and memory can be used as well as symbolic processors if at some later date it is determined necessary.

The mechanism used for communications to an instrument, sensor, or device is dependent on the response time required. But in most cases bidirectional serial links running at 10 Mbps are probably sufficient. At this rate a message could be generated, sent and received in milliseconds. Since the intelligence required by an instrument is also dependent on the response time required by the instrument, most of the intelligence required by an instrument can reside in the nodes (unless an instrument requires a response time under about 10 milliseconds). This would leave the instruments with a very small and inexpensive interface.

With the development of faster processors and data links, it is becoming apparent that most events can be addressed in a timely manner, using a remote multicomputer node. In perspective, the only thing being done is moving the digital control outside the instrument black box. This alternative can benefit the project enormously on cost savings not only on the scarce spacecraft resources, but also on development cost. It is expensive to develop, test, and maintain custom/unique hardware and software for every instrument. The more commonality in the processors the lower the initial fixed cost (development and testing cost). An ideal system from a development standpoint would be one which has a large amount of commonality so that the project resources (personnel, equipment, parts, etc.) can be shared and minimized. This commonality would also inherently provide a more thorough checkout. If all subsystems going through system and subsystem test used a common processor, that processor would have a more thorough testing by virtue of higher use.

While many studies have been done on data flow machines, one of particular interest is the success of a NASA funded research project called MAX [Ras87]. From its inception, this project had as its main objective development of a system which will address the computing needs expected for future NASA flight projects. Not surprisingly they concluded that a loosely coupled data flow machine would optimally address this need. The preliminary results from the testbed are impressive.

Another study was performed at Martin Marietta - Denver. It was found that using a similar meshwork type architecture was superior for flight applications. The topology they examined was set accordingly: each node x is connected to node ((x+1) mod N) by the forward loop and to node ((x-h) mod N) by the backward loop, where h is the square root of N [Jambor88]. They performed some simulations and compared it to the Fiber Distributed Data Interface (FDDI) token ring network, which has gained some popularity, and concluded that the meshwork architecture was superior to the FDDI network in the following ways: 1) The response time is shorter for similar loads and even for some heavier traffic conditions, 2) using standard complementary metal-oxide semiconductor (CMOS) technology the meshwork could carry six times the traffic of an FDDI for a 15 node network, 3) the meshwork offers a much wider range of reconfiguration capabilities which makes it a desirable solution for dynamically reconfigurable networks.

Such an architecture may not excel at all of the requirements, but it more than sufficiently addresses every one of the key requirements: reliability, performance, cost, and conservation of spacecraft resources. These requirements may seem straightforward independently, but addressing them collectively is much more difficult.

3.5.4.8 Communications - An advanced rover communications subsystem for a relay link would be identical to that of the moderate rover. The rover would carry an S-band system of 10 watts DC which transmits through a hemi-directional antenna to supply 30 kbps to the communications orbiter.

The rover is equipped with a low data rate direct emergency link and a redundant high data rate emergency relay link. The direct link is supported through a moderate or low gain antenna which means that the attitude control system can be simplified by eliminating the star tracker. Because the direct S-band moderate gain antenna would be used only in case of a major failure, its data rate can be very low, little more than engineering data. Therefore, off-boresight pointing would be permissible, and the accurate antenna pointing would not be necessary.

3.5.4.9 Power - The power system for the advanced rover utilizes the emerging power technologies that will reduce the mass and volume of the power system. The advances in thermoelectric conversion technology, secondary Li batteries and power integrated circuits will drastically improve the performance of the power system. The power system for the advanced rover consists of modular RTGs utilizing advanced thermoelectric material, high density secondary $LiTiS_2$ batteries, and power management and a distribution system utilizing the power integrated circuits.

The modular RTG, currently under development by Department of Energy (DOE), utilizes multicouple technology (instead of the traditional unicouple used in the current RTGs) and advanced insulators to maximize the specific power of the RTG. This improvement in the engineering design along with the use of high efficiency thermoelectric material, under development by NASA, will provide twice the power of the current RTGs, or it could reduce the mass to half [Schock89-1] [Schock89-2].

Similarly to the General Purpose Heat Source (GPHS) RTG for the moderate rover, this modular RTG needs to be modified for Mars operation. The modification will be similar to the GPHS RTG where the entire RTG housing is sealed and the heat source modules are placed inside a Molybdenum canister that is vented.

The energy storage system for the advanced rover uses advanced secondary $LiTiS_2$ batteries capable of delivering 100 Whr/Kg with depth of discharge of 50%. This battery is currently under development by NASA. The power management and distribution of the advanced rover utilizes the emerging Power Integrated Circuit (PIC) technology where the power and logic components are integrated into a single monolithic substrate. PIC technology reduces the required number of parts for a given system by 40%, the mass and volume by 50%.

3.5.4.10 Thermal Control - On the Mars surface the capable rover thermal control problem is the same as for the moderate rover. The capable rover mission design assumed that the rover and its lander will be aerocaptured into Mars orbit, rather than propulsively captured like the moderate rover. This means that the rover with its RTGs will be inside an aeroshell. The Johnson Space Center and its contractors are developing concepts for active and passive cooling of the RTGs during flight. One method is to use a radiator on the surface of the aeroshell and to use a water-loop passing through the fins of the RTGs to the radiator for heat transfer. Such a water loop is normally used to cool spacecraft RTGs before launch. The major problem is that, during aerocapture, aerodynamic heating will require the use of a heat sink for RTG heat.

3.5.4.11 System Characteristics - The capable rover power requirements were estimated by modeling two types of activity: a 24 hour autonomous traverse, and an autonomous site survey with sample collection, analysis and storage.

The autonomous traverse is a repeating cycle of Move, Image and Compute. The computation is to process the image, plan a traverse path and generate a new set of commands. Figure 22 shows the power consumption and data stored for the capable rover. It is powered by 500 watts of RTG and has 700 watt-hours of battery storage available. When the rover is in mobility mode, the power required jumps to over 900 watts. The battery energy line is identified as "charge level" in Figure 22, and accounts for the energy required to provide make-up power. Each cycle uses about 6 watt-hours of battery energy. During stops to collect or downlink data this loss is made up quickly. During the mobility mode, the rover moves 10 meters through sand at a climb angle of 30 degrees. These conditions were considered to represent the most stressing case the rover could encounter.

When the capable rover performs an autonomous site survey, the rover moves 20 meters (2 autonomous traverse cycles), images the site thoroughly in visible and a variety of other wavelengths, and downlinks the data to Earth. The multi-spectral images are processed on board to extract information rather than sending down the many megabits of raw data. The rover is then commanded to collect rock samples by drilling (worst case power consumption). The samples are tested and stored for Earth return. Figure 23 shows the power consumption and battery energy used for such activities.

The traverse cycles require far more than the 500 watt RTGs can produce, but the duration is so short that little battery energy is needed. Drilling for sample acquisition requires only about 10% more energy than the RTG puts out, but over a long period of time (as much as 4 hours). The battery is needed to provide make-up energy for this operation.

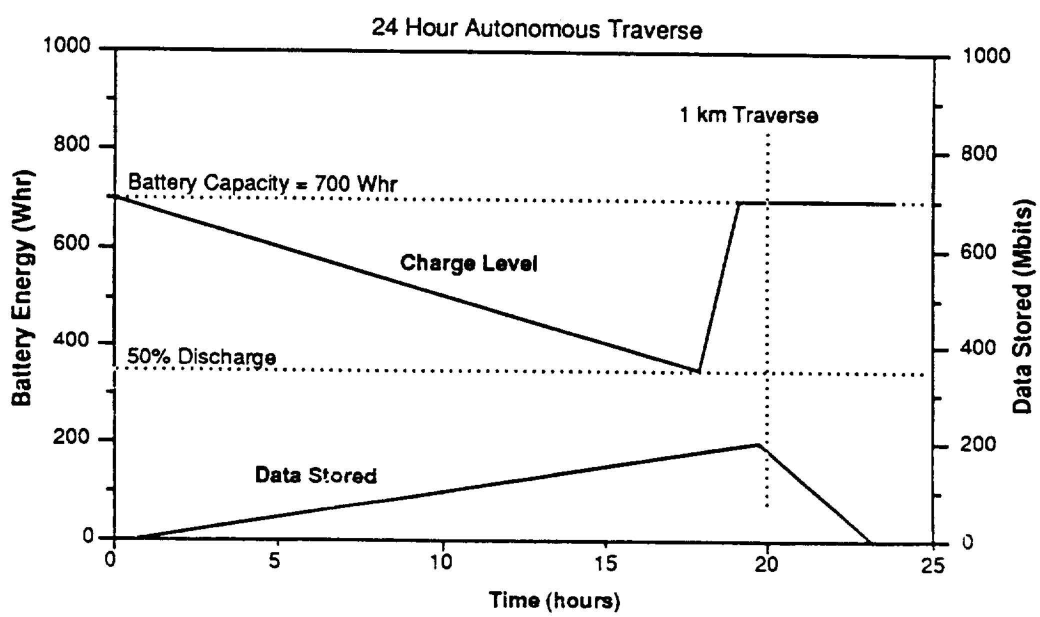


Figure 22 - Capable Rover Power Consumption and Data Storage

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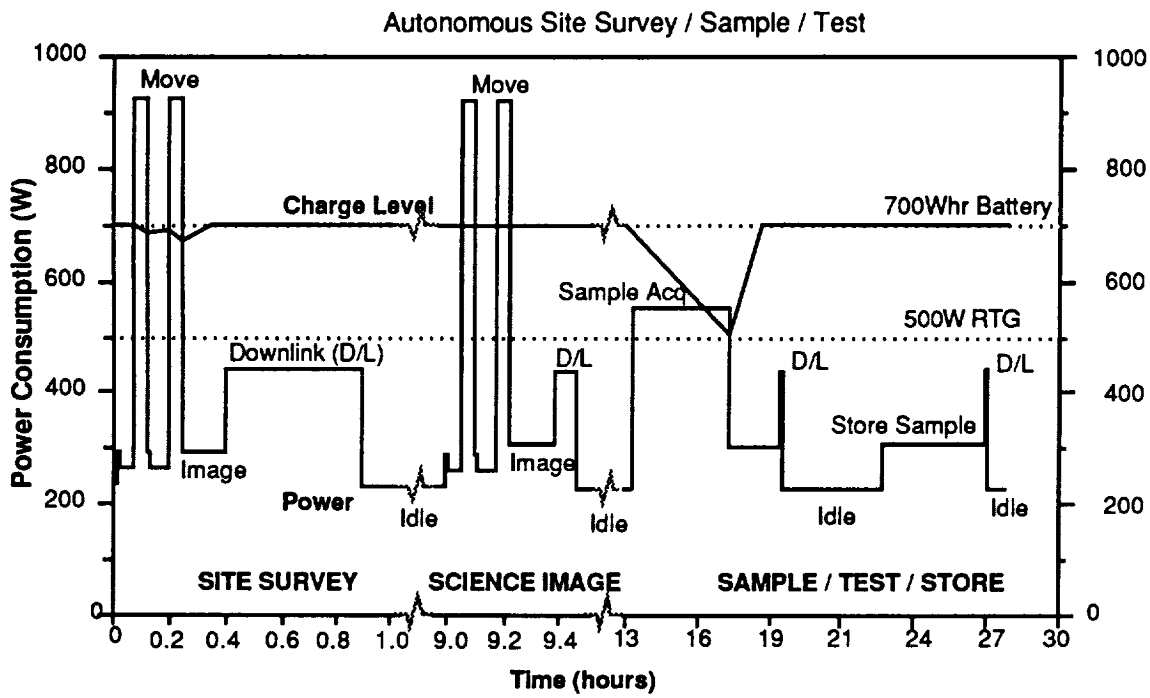


Figure 23 - Capable Rover Power Profile

The mass of the capable rover is estimated to be 842 kg. This is less than the moderate rover because of the high level of technology assumed, primarily in the power subsystem. The capable rover also carries more instruments than the moderate rover and has far better overall performance (see below).

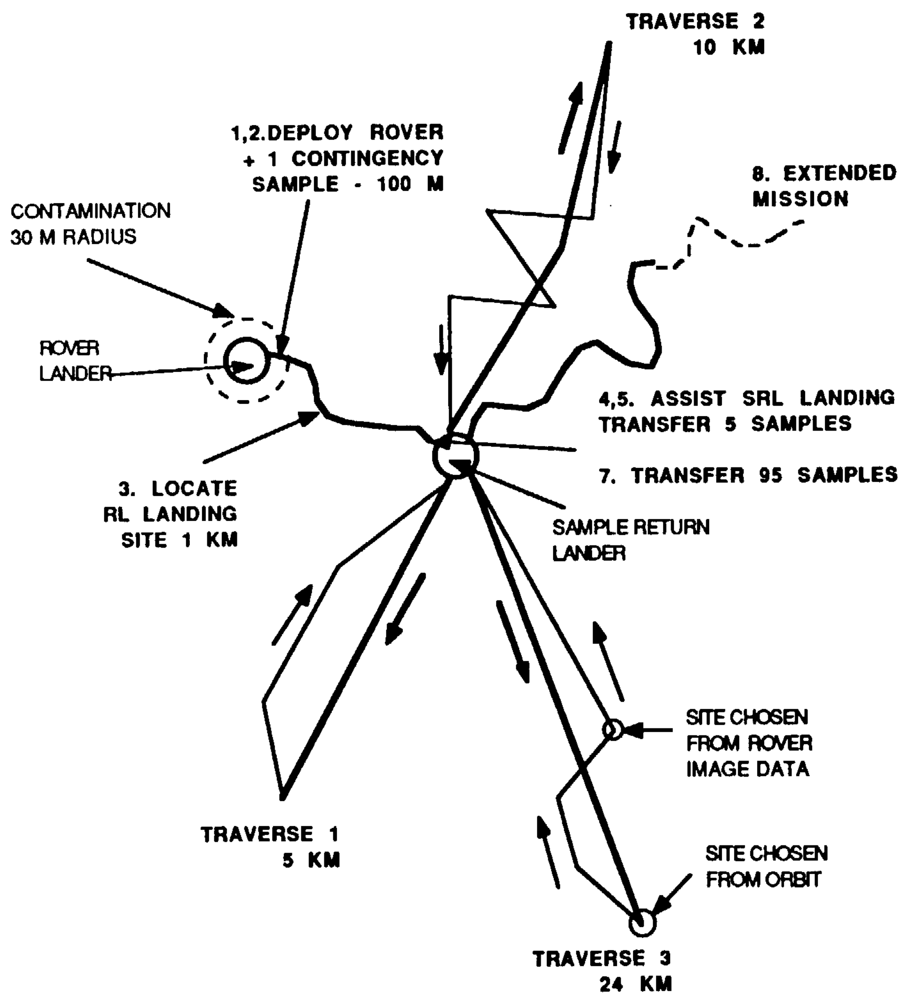
3.5.4.12 Performance - Figures 10 and 11 showed the performance improvement and cost impact of adding automation and additional instruments to the "rover tree" for a 1500-day mission. The most capable rover considered could collect 100 samples and cover 1000 km with aid of a comm orbiter, or 100 samples and 200 km without that assistance in 1500 days.

However, as shown in Figure 24, with only the 215 days on the surface allowed for the FY89 reference mission, even a capable rover could cover only about 40 km and obtain 100 samples. That requires continuous support by a comm orbiter.

ROVER ACTIVITY PATTERN

215 DAYS AVAILABLE SURFACE TIME (7 MONTHS)

100 SAMPLES AND 40 KM COVERAGE IN 211 DAYS (2 % MARGIN)



0.	7 DAYS	POST-LANDING PHASE, DEPLOY
1.	1 DAY	CHECK OUT ROVER
2.	7 DAYS	MOVE 100 METERS, COLLECT 1 SAMPLE
3.	17 DAYS	MOVE 1 KM, COLLECT 4 SAMPLES FIND AN SRL LANDING SITE
4.	1 DAY	ASSIST SRL LANDING
5.	1 DAY	TRANSFER 5 SAMPLES TO RSCA
6.	174 DAYS	PERFORM 3 ROUTINE SAMPLING TRAVERSES 39 KM, 95 SAMPLES STORED DEPLOY 2 MGPS TRAVERSE 1 - 20 DAYS, 5 KM 15 SAMPLES - 0 CERTIFIED, KEPT 5 ACQUISITION FAILURES 4 SITE SURVEYS TRANSFER (TIME INCLUDED UNDER 7) TRAVERSE 2 - 41 DAYS, 10 KM 30 SAMPLES - 0 CERTIFIED, KEPT 10 ACQUISITION FAILURES 8 SITE SURVEYS DEPLOY 1ST MGP TRANSFER (TIME INCLUDED UNDER 7) TRAVERSE 3 - 113 DAYS, 24 KM 50 SAMPLES - 45 CERTIFIED, KEPT 20 ACQUISITION FAILURES 10 SAMPLES CERTIFIED, REJECTED 16 SITE SURVEYS DEPLOY 2ND MGP TRANSFER (TIME INCLUDED UNDER 7)
7.	3 DAYS	TRANSFER 3 SAMPLE BATCHES TO RSCA
8.	? DAYS	EXTENDED MISSION

Figure 24 - Capable Rover Activity Pattern

Figure 24 depicts a stage by stage summary of the surface mission activities, from landing and initial contingency sample collection through several traversals and sample transfers to the return vehicle. Like other performance calculations, these conclusions are based on bottom-up addition of times for the basic activities being performed, in this case 1 km/day for autonomous traversing, 12 hours to acquire a sample without testing (such as use of a time-consuming DSC/EGA or APXS test), 24 hours to acquire and test a sample, and 30 hours for site surveys to initially detect samples. Those activity times are in turn based on assumptions such as the number of Earth interactions required (1/km for traverse, 3/untested sample acquisition, 4/tested sample acquisition, 3/sample survey), and the length of the Earth interactive decision processes (7 hours for science decisions, 1-3 hours for engineering decisions and command generation). A full description of the surface mission plan and underlying assumptions is contained in the MRSR Operations Concepts document [Ops89]. The assumptions on Earth interactions are summarized below.

Capable Rover Assumptions:

Traverse:	1	7-hour ground interaction / km traverse
Sampling:	2	2-hour engineering interactions / sample acquired
	1	7-hour science interaction / sample acquired
Survey:	3	7-hour science interactions / survey
	3	2-hour engineering interactions / survey

The cost of a high-technology rover mission, including aerocapture at Mars and an accurate entry and landing system, has been estimated at $4-5B. The capable rover is about $1.5B of this. A communications orbiter and high resolution imaging orbiter would maximize performance, but would raise the total mission cost to about $6B.

3.6 Lunar/Mars Common Rover

Two classes of rovers were addressed in the Human Exploration Precursor Task Team study in late FY89 [90-DAY]: a 100 kg local rover associated with the Sample Return missions, and a science/human-precursor rover capable of traversing great distances and conducting a variety of surface operations. A single rover concept was developed for the latter missions, which could conduct science and site certification operations on either Mars or the Moon with minimal modification. This section deals with the larger rover and does not apply to the local rover which is addressed in Section 3.4.1. The strategy for the large rover was to design to an envelope covering both the Moon and Mars. This included sizing the mobility system and structure for Mars (1/3 g, twice the gravity of the Moon). The thermal control system was sized for the Moon, which has extremely high daytime temperatures, as well as severe nighttime cold, as does Mars.

The Lunar/Mars Common Rover is a rover concept which is capable of meeting the mission requirements of both the Lunar robotic exploration and Mars robotic exploration missions which are intended to precede Human missions. This rover design is based on that of the Capable Rover (Section 3.5.4), and the following description will make reference to that design.

Common interfaces with the Lunar and Mars rover delivery systems are a goal, although the Lunar rovers will be delivered as part of cargo or piloted flights, while most of the Mars rovers will be delivered on separate, Titan IV/Centaur launches and aerocaptured at Mars. Although the onboard computation for Lunar operations can be simpler than for Mars, because of the shorter round-trip light time, a common, multi-processor computation architecture was selected which will be expandable as Lunar operations are extended to the back side of the Moon, and for semi-autonomous operations on Mars.

Each rover will attempt to be made at least 75% common with the preceding rover, whether it is for the Moon or Mars. The success of this strategy will depend partly on the grouping of rover missions, with missions close together providing more opportunity for synergism and block buys.

All rovers will be procured under a single system contract and an on-going advanced technology development program will be maintained to allow for smooth upgrades of capability throughout the life of the program. The current mission set for Mars precursors and Lunar outpost science includes 9 rovers:

2002 or 3 = Lunar rover delivered as cargo for the first human outpost,
2005 = Precursor Mars site survey rover,
2006 = Second Lunar outpost rover,
2007 = Second Mars precursor rover,
2009 = Third Mars precursor rover,
2010 = Third Lunar outpost rover,

2015 = Mars site survey rover launched with the first human Mars expedition,
2017 = Mars site survey rover launched with the second human expedition,
2024 = Mars site survey rover launched with the third human expedition.

3.6.1 Baseline Lunar Rover (2002 or 3) - For this study a quick synthesis of previous rover designs was done with the target of a 600-700 kg mass concept. This baseline is targeted at the capabilities required of the first Lunar rover in 2002, and is capable of being improved for subsequent missions to both the Moon and Mars. Because the Moon is much closer to the Earth than Mars, a modified CARD local navigation concept can be used to drive the traverses of the Lunar rovers. Therefore the computation for the baseline rover is equivalent to that of the moderate rover (Section 3.5.3), while most of the rest of the design is similar to that of the capable rover (Section 3.5.4). The following characteristics are those of a feasible, but almost certainly not optimal, general-purpose rover concept.

3.6.1.1 Mission - The baseline Lunar rover is intended to conduct scientific operations up to 1000 km away from the human Lunar outpost. These operations should be quite similar to those required for the sample collecting science rovers on Mars. (In the Human Exploration studies the assumption was that the baseline Lunar rover would be dedicated to science, and that the Lunar site characterization activities described in Section 3.4.2 would be performed by a multi-purpose mobile vehicle dedicated to the Lunar outpost site.)

3.6.1.2 Payload - The baseline rover carries the payload shown in Table 4 (Section 3.2.1.1) with the exception of the Differential Scanning Calorimeter and Evolved Gas Analyzer, which are believed to be unnecessary on the Moon. In addition, the payload may include only a point spectrometer instead of a scanning spectrometer. The instruments are for allowing scientists on Earth or at a Lunar base to select samples for return to the base, where they can be analyzed further and/or returned to Earth.

3.6.1.3 Sample Acquisition and Preservation - Two 6-degree of freedom manipulator arms have a set of interchangeable tools (scoop, rake, rock drill, etc) to acquire fresh rock, soil, pebbles, and dust.

The baseline concept provides for shallow regolith sampling, but not for deep coring. Sample acquisition, like local navigation, is supervised by operators who, for instance, designate a sample to be collected. The rover accomplishes low-level robotic control for the manipulators automatically, to grasp (for example) a designated pebble. Samples are labeled and preserved individually and are typically carried by the rover back to the Lunar outpost.

3.6.1.4 Subsurface Characterization - The rover may use electromagnetic sounding to a few meters' depth to detect subsurface characteristics. The rover may deploy a localized seismic network and pound a penetrometer into the regolith to excite the seismometers and physically verify subsurface obstacles detected by electromagnetic sounding. The rover may also deploy one 50-kg seismic station for deeper seismic sounding.

3.6.1.5 Mobility - The baseline rover is a 6 wheeled, single bodied vehicle using a system of passive levers to allow the vehicle to surmount 1 meter obstacles and climb 30 degree slopes, with a design speed of 10 cm/sec. The "rocker bogie" described in Section 3.5.3.3.2 was selected as the baseline for the common rover.

3.6.1.6 System Control - The Lunar rover will be supervised from Earth or by astronauts on the Moon. The rover will be directed using CARD-type control, in which it can automatically execute low level traverse and sampling functions in response to moderately high-level goals from the human operators. (An example is to follow a path designated by the operator.) If astronaut control beyond line-of-sight is desired, a communications orbiter will be necessary. The Earth (or Lunar outpost) control system includes software and procedures to allow quick turnaround decisions and to provide the capability for continuous traverse.

3.6.1.7 Local Navigation - Operators designate a path through a stereo image transmitted from the rover's cameras. The rover automatically executes the path by calculating necessary wheel turns and steering angles. An execution monitoring and emergency stop/backup response is included to protect the rover. Using operator supervised control and continuous communications, the rover will be able to move continuously, depending on its slow speed and execution monitoring/emergency response, to avoid problems in the 2.5 seconds between Earth command and Earth perception of the executed response.

3.6.1.8 Vehicle Control - The vehicle uses inertial navigation, a sun sensor, and low-speed distance sensors to maintain the designated path, accelerometers for execution monitoring, and inclinometers to measure surface slopes.

3.6.1.9 Computation and Data Storage - 1 to 2 MIPS of general purpose processing capability will be provided on the rover to support the human supervised local navigation and sampling functions. The current design assumes inheritance from CRAF/Cassini of the processors and of tape mass storage. The rover will, however, feature a new distributed processing architecture.

3.6.1.10 Communications - The rover will incorporate an S-band, omni-directional low gain antenna for a 20 megabit per second direct Earth link. If over-the-horizon astronaut control is required an S-band relay link through a libration-point communications orbiter is probably needed.

3.6.1.11 Power - Power will be provided by one modular RTG providing about 400 watts (or 2 200-watt RTGs), with a Z of 1.0 (somewhat beyond the current state of the art). Power integrated circuits were included for power management and distribution as opposed to heavier discrete components. This concept depends on power management to stay within the 400 watt RTG capability, and therefore does not include batteries. This is the concept used on the Galileo spacecraft.

3.6.1.12 Procurement Strategy - A single general purpose rover plus a flight-ready spare would be procured as the first block in a rover project starting in FY95. Subsequent rovers would be developed under the rover project, with the flight spare rolling over as a spare for the 2006 Lunar rover.

3.6.2 2005/07 Mars Rovers - In 2005 the first rover of the next "block" of three will be launched to Mars. This second block will include the 2006 Lunar rover, and the 2007 Mars rover. A flight spare will also be procured for this block to back up the 2005 and 2007 launches, with the 2005 Mars spare being rolled over to 2007 if it is not needed in 2005. The Mars rovers will be adapted for Mars conditions in that the RTGs will be sealed against the Mars atmosphere, the thermal control system will be modified as necessary to handle the overall colder average temperatures, and a Ka-band phased array will be added to provide a direct Earth link. A

Mars-dedicated 34 meter antenna network will be added to the DSN to provide conflict-free communications. Some structural and thermal modifications to the rover may be necessary to permit packaging in the Mars entry and landing aeroshell.

The onboard computation subsystem and ground control system will be upgraded to permit semi-autonomous operation, including the addition of approximately 10 MIPS of onboard general purpose processing capability. The computer architecture of the first block will permit the addition of additional processors without a major overhaul of the data buses or operating system. Advanced data storage for map and onboard sensor data may be required, for example, optical disk storage.

Additional instruments will include a multi-spectral imaging system, and a DSC/EGA for the in-situ analysis of volatiles. The rover will also emplace caches of samples for possible later return by human missions.

3.6.3 2006 Lunar Rover - The second Lunar rover will utilize the flight spare from the 2002 Lunar rover. Upgraded instruments will be added based on the experience gained with the 2002 rover. In addition, the Lunar rover will be upgraded with the same computational improvements as the Mars rovers, to allow semi-autonomous operation and to enable longer traverses away from the outpost. A capable Lunar outpost facility for astronaut control of the rover, plus the necessary communications satellites, will be in place.

3.6.4 2009 Mars Rover/2010 Lunar Rover - The 2009 Mars rover and 2010 Lunar rover will be procured as a third block, with the rolling spares from 2007 and 2006, respectively. These rovers will include revised payloads based on the experiences from the previous blocks. The power subsystem will be upgraded to include a high efficiency conversion technology such as AMTEC (advanced direct thermal to electric conversion for an RTG) or DIPS (Dynamic Isotope Power System). Laser ranging will be added to the stereo vision system for local navigation, and the rovers will be able to do regolith coring to several meters. Ground operations upgrades on the Earth and Moon will provide efficient support of semi-autonomous rover operations.

3.6.5 2015/17/24 Mars Rovers - The final rovers in this scenario are three which accompany human expeditions to Mars. They would be separated from the human vehicle before landing and sent to another part of the planet's surface, to survey sites prior to the next human expedition. In this scheme, the 2015 human mission would land at one of the sites surveyed by the 2005, 2007 and 2009 Mars rovers. The 2015 rover would explore a fourth site, which could then be visited by the next human expedition. This expedition would send a rover to explore a fifth site. The 2017 expedition's automated rover would certify a sixth site. The Mars outpost mission would then have a choice of six sites to establish a long duration base.

These rovers would continue the Mars rover product line, with the 2015 and 2017 rovers and a rolling spare constituting the fourth block; the 2024 rover and spare would be the fifth block. The rovers would require an extended advanced technology development (ATD) program to bridge the gap from the 2010 Lunar rover and to take advantage of synergy with technologies (e.g. miniaturized electronics) developed for human missions. The rovers could also make use of human mission ground control and communications facilities.

4.0 CONCLUSIONS AND SUMMARY

The Rover concept work in FY88 and 89 has shown that a range of feasible rover concepts can be defined for a variety of missions. Since the majority of the effort was devoted to defining sample-collecting Mars rover missions these are the best defined and understood. It appears that most of the principles of Mars rovers can be applied to automated Lunar rovers. The Lunar performance at lower levels of automation will greatly exceed that on Mars because of the ability for short-time commanding of rovers.

4.1 Lunar Rover Conclusions

The brief JPL study of a site certification rover has shown that a fairly simple rover can perform most of the functions needed to determine, in situ, that a Lunar site is safe and attractive for human habitation. The exception is that exploration for possible deeply buried resources would be beyond its capability unless water were revealed by the neutron mass spectrometer or electromagnetic sounding. A simple rover cannot do deep drilling. Lunar rover missions have not yet been costed but should be much cheaper than Mars rover missions performing the same functions.

The Battelle Columbus study [Battelle89] has illustrated that a moderate rover can also perform a complex science mission on the

Moon, in this case, assembly of a large radio astronomy array. It is apparent that fairly simple rovers can perform important science and human exploration functions on the Moon.

The common Lunar/Mars rover design allows a single product line rover to conduct remote operations on both the Moon and Mars. Rovers landed with humans (or as part of a cargo mission supporting humans on the Moon) can conduct scientific explorations very similar to those on Mars.

4.2 Mars Rover Conclusions

The performance of Mars rovers depends on level of technology, time on the surface, and amount of support from other mission elements. Mars rovers suitable for sample collection can be adapted readily to perform site characterization and resource assessment. A sample collecting Mars rover can traverse from tens to hundreds of kilometers, and collect tens to hundreds of geological samples. The mineralogical diversity of the samples depends both on the rover range and on the amount of instrumentation and sample acquisition capabilities carried by the rover.

4.2.1 Traverse and Sample Collecting Performance - The performance of different sample collecting Mars rovers illustrates the importance to all Mars rovers of advanced technology, especially in computation to support a high level of autonomy. Because Mars has many unknown characteristics, and because highly autonomous surface rovers have never been flown, there is difficulty in predicting the exact performance of a rover. An attempt was made to identify and quantify some of these unknowns, and it was used to adjust expectation of mission return. Five of these variables were used in a trade-off study and are discussed below. These are :

1. degree of autonomy;
2. degree of confidence in autonomy;
3. degree of surface obscuration;
4. amount of science interaction in traverse;
5. time on the surface.

Figure 25 shows the results of the performance trade-off study between high- and low-autonomy rovers over two different surface mission lengths. A short surface mission of 5 months (150 days) would occur if the first opportunity for sample return after

SINGLE-ROVER PERFORMANCE RANGE OVER 900 DAYS FOR HIGH VS. LOW AUTONOMY

WIDE PERFORMANCE RANGE DUE TO: (1) VARIATION IN ASSUMPTIONS ON CONFIDENCE LEVELS (HIGH VS. LOW), (2) VARYING PENALTY FROM SURFACE SPECTRAL OBSCURATION (25-100% SAMPLE RETENTION), AND (3) VARYING STOPS FOR GROUND SCIENCE DECISIONS (0-7 HOURS/DAY).

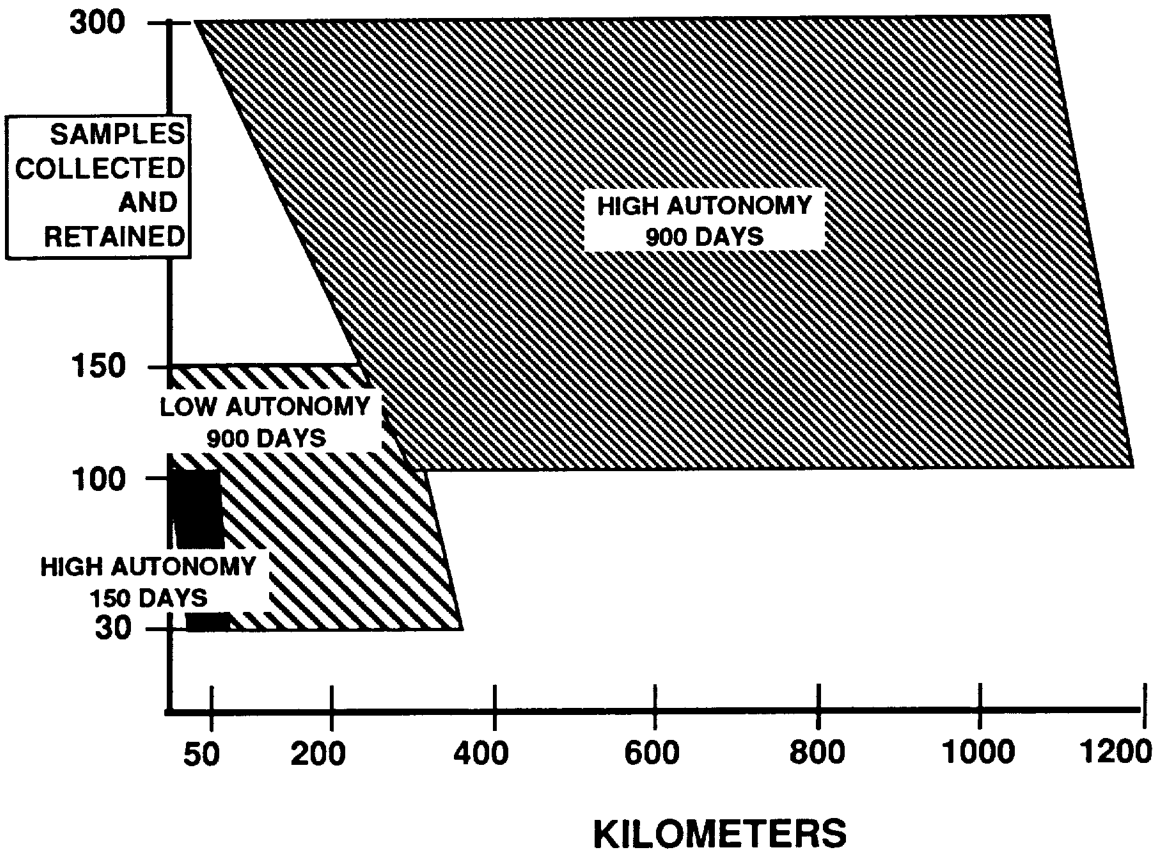


Figure 25 - Rover Traverse and Sampling Performance Summary

rover landing were exercised. A much longer mission - with increased risk and return - would be possible by waiting 32 months (900 days) for the next sample return opportunity.

Degree of Autonomy - More autonomy means less time is needed for the overhead of spacecraft management, so more productive time is available for sample acquisition and getting from place to place. More autonomy means fewer and shorter interactions to accomplish a given piece of work such as a sample acquisition.

Degree of Confidence - It was desired to measure not only the degree of autonomy but the degree of confidence in that autonomy. This is because it was perceived that unforeseen (and unforeseeable) environmental conditions could negatively affect mission return after landing, if these caused unexpected conservatism. This is an entirely separate effect from that of the autonomy itself, however it is measured similarly. That is, increases in confidence result in fewer and faster ground interactions required per unit of rover work, whereas decreases in that confidence would increase the number of interactions for verification of rover status.

Degree of Surface Obscuration - Surface weathering or dust coating could seriously reduce mission return. In the best-case situation, one can fully determine what a potential sample is and whether it is desirable just by looking at it before manipulation. There is no wasted manipulation of samples which turn out to be duplicates. However if the surface is very weathered or heavily covered by dust, this would not be the case. Not only would some samples turn out to be duplicates, but extra manipulation would be required to deobscure them. The effect of this possibility was studied by varying the number of acquired samples which had to be thrown away from 0% to 75%.

Amount of Science Interaction in Traverse process - If the location of desirable sample locations is known to within a few tens of meters from orbital imaging, then the traverse process to get from site to site can be conducted without analyzing science desirability of surrounding areas during traverses, increasing the distance which can be covered. If sampling locations are not known or known only generally in advance, the rover must be stopped frequently to debate whether interesting samples are nearby. This effect was estimated by assuming that the number of hours per day the rover would spend parked waiting for science decisions could vary from 0 to 7 hours. (Of course, much longer decision times are possible!)

Additional assumptions are that the overall sampling success rate is 60% and that the rover is able to work at full capacity during Mars night.

High-Autonomy, High Confidence - In this scenario, samples can be acquired in 2.1 hours with only three interactions. If the surface were obscured, that would stretch to 6.3 hours and add a decision. Up to 1.4 km/day could be covered in traverse mode, if desirable sample locations were all known in advance. If these need to be discovered en route, the rate would be 1 km/day.

High-Autonomy, Low Confidence - In this case 7 hours would be required per sampling attempt due to longer decision times, with effects from surface obscuration stretching the process out to up to 20 hours per sample. Up to 0.7 km/day could be covered in traverse mode, but only 0.5 km with a daily science wait period in unfamiliar areas.

Low-Autonomy, High Confidence - In this case, many more decisions are needed per sample, because Earth must provide the adaption to the surface environment as knowledge is gained and changes occur. Twelve interactions in 25 hours were felt to be required per sample. That number stretches to 75 hours if the surface is obscured, because of manipulation to deobscure samples before acquisition, and throw-aways. Traverse could proceed at from 300 up to 450 meters/day, at the rate of 50 interactions/km, with very short decision times. The lower number assumes daily science decision periods.

Low-Autonomy, Low Confidence - Decision times are longer than with the high-confidence analog, with the result that sample acquisition attempts take 45 hours. That stretched to 130 hours if the surface is obscured. Traverses might require up to 200 interactions/km, to satisfy ground elements about terrain uncertainties, with the result that as little as 40 meters/day might be covered if there were also daily science interaction periods.

Combining all these sources of uncertainty results in the performance variations revealed in Figure 25. As shown, an increase in the number of samples acquired (varies from 30 to 300) results in less distance covered. A very autonomous rover, collecting 100 samples, might go anywhere from 300 to 1000 km in a 32-month mission. Collecting 300 samples would be difficult even for a very autonomous rover in a 32-month mission, if all the other factors were working against the mission.

A low-autonomy rover could be expected to yield a fair return in a 900-day mission. It might be desirable to reduce the number of samples to 30 in order to cover more ground, if operational factors such as surface obscuration turned out to be negative. A high-autonomy rover could yield up to 100 samples and 50 kilometers' coverage in a short, 150-day mission, not nearly as much as in the 900-day mission. However, it is unlikely one could cover large distances even by reducing the number of samples. This is largely because the early phases of the mission would have to be conducted with lower autonomy and confidence, because of unknowns, and there would be little time to catch up before the end of the 5 months. A low-autonomy rover does not even show on the chart as having a feasible 150-day mission. Return could be very low if the various factors discussed wound up arrayed against such a rover after landing.

Another factor in the number of samples vs distance trade-off is the degree to which the surface is known by orbital imagery before the rover attempts to traverse it. Currently, only two sites on Mars have been seen at resolutions relevant to rover traverses (~1 meter real resolution). If an imaging orbiter can provide topographic maps at 1 meter resolution, a rover capable of scaling 1 meter obstacles can have high assurance of being able to execute planned traverses. If the resolution is greater than about 3 meters, the rover may be landed in areas which have chasms preventing it from reaching the desired sampling sites. Also, the poorer the surface foreknowledge, the more likely that Earth-planned paths will lead to "box canyons" at the rover scale, requiring backtracking.

Therefore, the chances that the distances traveled in Figure 25 are productive are greatly increased by high resolution orbital imaging before the rover begins its mission. Availability of a full time communications capability also increases mission productivity by as much as 25%.

4.2.2 <u>System Characteristics and Cost</u> - Mass estimates for the large, independent Mars rovers range from about 700 to 900 kg, depending largely on the sophistication of the power system. Costs for the independent Mars rovers studied range from $1B to $1.5B, and Mars rover mission costs from $3B to $5B.

Cost savings achievable by having a common Lunar/Mars rover product line should be considerable and will be calculated in FY 90.

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