MARS MICRO ROVER
PERFORMANCE MEASUREMENT AND TESTING

by

Kenton R. Lietzau


Submitted to the Department of Aeronautics and Astronautics
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February, 1994

Signature of Author

Department of Aeronautics and Astronautics
February, 1994

Certified by Professor Joseph F. Shea
Thesis Supervisor

Accepted by Professor Harold Y. Wachman
Chairman, Departmental Graduate Committee
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ABSTRACT

Future Mars research missions will most likely include micro rovers to assist in planetary exploration and characterization. Universities, laboratories, space agencies, and members of the aerospace industry are developing various micro rover design concepts. This thesis proposes performance measures and an accompanying test plan which permit the grading and ranking of the performance of these micro rover designs.

First, this thesis develops specific design and performance requirements in the following areas: mobility, navigation and control, scientific support, autonomy, and environmental stress resistance. Second, a list of rover capabilities necessary to satisfy the developed requirements is established, and pertinent performance metrics are proposed. Third, the design and performance requirements, necessary capabilities, and performance metrics are integrated into a series of proposed rover tests.

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Mars Rover Program Director
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Thesis Supervisor: Dr. Joseph F. Shea
Adjunct Professor, Aeronautics and Astronautics
Massachusetts Institute of Technology
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[Signature]

Kenton R. Lietzau

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This thesis is divided into three main sections and a summary. Chapters 1 through 3 consist of micro rover introductory and background material. Specifically, these chapters provide a general description of micro rovers and their utility, current mission plans and general rover requirements, a description of the planet Mars, and a discussion of other related background research accomplished previously.

Chapters 4 through 8 describe the five fundamental categories of rover performance selected for study, namely: mobility, navigation and control, scientific support, autonomy, and environmental stress resistance. In each of these chapters, a general description of the category is followed by a discussion of pertinent design criteria and/or performance measures. Each chapter is concluded with a table matching the developed design/performance requirements with specific, measurable capabilities. The table also includes a reference matching each measurable capability to a specific test in the proposed test plan (chapter 9). Chapter 8 (Environmental Stress Resistance) additionally includes a description of the Delta II (7925) launch vehicle and other predicted stress environments.

Chapter 9 consists of a proposed test plan drawn specifically from the five performance categories described in chapters 4 through 8. Each test description includes: a list of measured capabilities (cross-referenced from the tables in chapters 4 through 8), a brief test scenario description, a list of
test variables, a list and description of the proposed measured parameters, and a proposed test location.

Chapter 10 provides an overall summary, recommendations, and a description of future plans.

The reader should note that nomenclature has been developed to facilitate the easy referencing of the tests described in chapter 9. Rather than refer to each test by its full name, an abbreviation is used which indicates the general category and relative sequencing of the test in question. For example, the abbreviation MOB.1 refers to the first proposed mobility test. MOB.2 refers to the second mobility test, and so on. In a similar manner, the prefix NAV refers to navigation and control tests, SCI refers to scientific support tests, AUT refers to autonomy tests, and ENV refers to environmental stress tests.
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CHAPTER 1
THE MICRO ROVER MISSION

Introduction

The idea of designing and building intelligent, autonomous miniature rovers ("micro rovers"), launching them into space, landing them on Mars, and using them to travel to Mars' unseen and unexplored reaches is undoubtedly radical. But using such rovers could prove to be an inexpensive means by which to greatly enhance the scientific utility of unmanned missions to Mars.

Investing for the Future

"Exploration is one of the hallmarks of a great nation. Turning inward is a sign of a nation in decline. Engaging the world brings in new ideas, new vitality."

Daniel S. Goldin
NASA Administrator

By pursuing innovative ideas and having the courage to explore and take risks, our world has reaped great rewards from its space programs. Our knowledge of our universe has greatly expanded as a result of our space exploration programs. Earth observation satellites have voluminously enlarged our data base of the Earth and its atmosphere. Weather satellites, navigation satellites, and communication satellites have revolutionized
Chapter 1: The Micro Rover Mission

global weather prediction, global navigation, and global communication. And there is much more to anticipate in our future.

But where there is now return, there was once risk. And where there is risk, there will be failure. Unfortunately, past failures are having a crippling effect on current space programs and priorities. Events such as the space shuttle Challenger explosion, the Hubble Telescope fiasco, and even the very recent Mars Observer failure have resulted in policies which inadequately support the development of advanced technologies. Investment in our future is becoming a thing of the past.

Vision: The Exploration of Mars

Mars has been an object of wonder for thousands of years. It has inspired imagination and scientific speculation since its discovery. Human travel to Mars is one intriguing and enticing challenge which man has not yet met. This challenge serves to fuel the motivation behind continued exploration.

"We shall not cease from exploration and the end of all our exploring will be to arrive where we started and know the place for the first time."

T.S. Eliot

In 1989, President Bush put forth a call to return to space. His vision included the construction of a major space station, a return to the Moon, and finally, a manned journey to Mars. President Bush could not predict the future social, political, and economic tides. But he did believe that achieving such noble goals would provide inestimable benefit in our future.
Chapter 1: The Micro Rover Mission

"The bravest are surely those who have the clearest vision of what is before them -- glory and danger alike -- and yet notwithstanding, go out to meet it."

Pericles

Dan Goldin has called NASA to pursue "smaller, faster, cheaper" space programs. Programs the size of Apollo are no longer being undertaken. New technologies are being pursued to make very small programs possible. Plans call for future spacecraft to weigh hundreds, not thousands of pounds, with launch costs of millions, not billions of dollars (Goldin 2, 5). Amidst international program cost reductions and program down-sizings, the idea of using miniaturized machines and robots for space applications becomes much more attractive. The stage is set for the entrance of the planetary micro rover.

Micro Rovers: Description and Utility

What before was an impossibility is now an opportunity. Improved micro-processor technology, advances in small robotics, and the miniaturization of science and navigation instruments make the task of designing and building a useful planetary micro rover possible. All of the same fundamental capabilities of a large, non-flyable prototype rover designed in the 80's -- intelligence, mobility, and scientific versatility -- can now be contained in a rover which is less than one-tenth the size.

Micro rovers are small (on the order of 10 kg), mobile, self-guided robots. These robots can negotiate rugged, hazardous terrain by relying on a combination of mobility and navigational capabilities. Micro rovers can
autonomously navigate to designated locations, providing scientific utility at any attainable desired location.

Although the Lunar Roving Vehicle (LRV) used in the Apollo missions was considerably larger than a micro rover and was designed with a different purpose (namely, to transport people), the concept of vastly improved scientific utility from enhanced mobility is nevertheless obvious. The Apollo 15 mission with the lunar rover provided scientific measurements over distances approximately four times greater than those covered during the previous three Apollo lunar landing missions combined (Costes, 1); a rover's mobility may become essential to propitious planetary exploration.

**The Mars Micro Rover Mission and MESUR Pathfinder**

The Mars Environmental Survey (MESUR) is a major NASA program involving a series of missions designed to greatly improve our knowledge of Mars. The first of these missions is the MESUR Pathfinder mission. Launch is planned for 1996, with surface operations scheduled to begin in November of 1997. The primary purpose of this mission is to demonstrate Mars entry and landing technology. It is also a precursor to the MESUR Network Mission which will set up between 8 and 16 small surface stations on Mars (dependent upon future NASA budget allocations). These stations will conduct meteorological and seismic measurements over two Mars years (≈ four Earth years) to determine global weather patterns and to attempt to measure the internal structure of Mars. Each station will include a small rover to emplace science instruments and examine characteristics such as rock and soil chemistry.
Chapter 1: The Micro Rover Mission

A micro rover is under development to fly to Mars as part of the MESUR Pathfinder mission. Many organizations throughout the world are exploring ideas for competing micro rover designs including the Jet Propulsion Laboratory (JPL), aerospace industry companies, various universities, and foreign space agencies.

In order to demonstrate the technology of such a rover, the Office of Aeronautics and Space Technology (Code R) at NASA is sponsoring a rover development experiment to test a micro rover on Mars. This experiment will:

1. Evaluate the performance of an experimental micro rover on Mars
2. Evaluate a micro rover's capability of examining the Martian soil and rock characteristics
3. Provide a better understanding of the interaction between rovers and the surface environment of Mars

The information collected will be used in the design of future rovers.

For the purposes of this research, the current and most probable MESUR Pathfinder missions and requirements have been assembled, and are used as a baseline from which to develop general and specific micro rover requirements and pertinent performance measures. A description of the Pathfinder baseline landed mission scenario is included in Chapter 6 -- Scientific Support.
**Chapter 1: The Micro Rover Mission**

**Systems Design and Evaluation**

**The Systems Design Challenge**

Rover design engineers must make prudent systems design choices from multitudinous design trade off options. How can current technology and projected requirements be assimilated into the best rover design? Of the myriad design options available, decisions must be made regarding that which is most beneficial for a rover, and that which is feasible, balancing cost, schedule, and performance.

**The System Performance Measurement Challenge**

Rover performance measurement is not a simple task. A relatively detailed systems level understanding of the interrelationships of the various subsystems in a micro rover is necessary to be able to establish meaningful performance measures.

For example, consider the design trades between a rover's mobility and navigational capabilities. The development of a mechanically superior rover able to traverse the most rugged terrain appears beneficial. However, such a design is more likely be large, heavy, and complex. Conversely, a highly developed navigation and hazard avoidance control architecture could eliminate the need for such mobility performance by demonstrating the ability to command a rover to successfully circumnavigate hazardous terrain features. This would enable a rover to be much smaller, lighter, and mechanically simpler. Ultimately, an engineering compromise must be reached by the rover designers.
Chapter 1: The Micro Rover Mission

As another example, consider the performance of a rover's central processing unit (CPU). The size, speed, and storage capacity of a rover's CPU can be measured and compared to other rover's CPU's. However, such measurements and comparisons are inadequate. A more capable CPU will probably cost more, require more power, and use less proven and less reliable technology. In addition, the adroitness and efficiency of the control logic the processor uses will have a much larger effect on the overall performance of the rover than any specific capability of the CPU. Thus, other, perhaps less obvious factors must be considered to meaningfully measure CPU performance from a systems perspective.

Thesis Objective and Outline

To best characterize a rover's capabilities, the goal of this research has been to assess micro rover performance from a systems level. First, the most fundamental requirements of a micro rover deployed on Mars are defined. These fundamental requirements are subdivided into more specific requirements which emphasize a rover as a useful tool for the exploration of Mars. Next, a set of specific rover capabilities and accompanying performance metrics to measure rover performance are developed. All of these are assembled in a proposed test plan which measures and tests each desired/required rover capability.

Fundamental Micro Rover Requirements

Certain capabilities are fundamental to a rover's practicality and effectiveness as a tool on Mars. Following is a listing and description of top level necessary rover capabilities.
Chapter 1: The Micro Rover Mission

Requirement #1:

Survive the Environments (Launch, Transit, Landing, and Martian Surface)

The rover must survive the launch loads, vibrations, and stresses associated with the launch phase. It must survive the radiation, vibrations, and temperature cycling associated with transportation to Mars orbit. Finally, the rover must be able to deploy from the lander and survive the rugged terrain, thermal cycling, winds, and dust deposition on Mars.

Requirement #2:

Rove Across/Through Mars Terrain

A rover must be capable of traversing through a spectrum of challenging Martian terrain types ranging from drift material to regions with large, jagged volcanic rocks. Martian terrain is discussed in detail in Chapter 2 -- The Planet Mars.

Requirement #3:

Navigate to Specified Locations on Mars Terrain

A rover must be capable of navigating from one location to another specified location. Such navigational capability helps rovers achieve the necessary degree of autonomy for top level commanding from Earth. Navigational capability is also fundamental for accomplishing experiments which are highly dependent on a specific location or terrain feature such as alpha
proton X-ray spectrometry or imaging of the lander, rocks/soil, or other terrain features.

**Requirement #4:**

Conduct and Support Science and Technology Experiments

A rover must be capable of conducting and supporting experiments on Mars. The specific experiments a rover will have to accomplish on Mars will change in accordance with changing scientific needs, desires, and available financial budgets. However, there are certain capabilities which a rover should have which will make it most useful as a general instrument of science and technology support. These include any or all of the following: storing experiments on the rover and transporting them wherever needed; deploying experiments; conducting and monitoring experiments; providing electrical power for experiments; collecting, storing, and processing experiment data; transmitting experiment data to the lander; and providing any other as yet undetermined support for future proposed experiments.

**Requirement #5:**

Conduct All Operations on Mars Semi-Automatically

A rover must demonstrate a relatively high level of autonomy. The Earth to Mars communications delay, depending on planetary positioning, is between 6 and 41 minutes, making real-time Earth-based rover control a virtual impossibility. Earth-Mars line of sight restrictions, daylight
Chapter 1: The Micro Rover Mission

operating restrictions, communications system limitations, and Earth-based command and control decision analysis requirements make long and frequent transmissions from Earth impossible. Thus, a rover must be able to operate on its own for extended periods while on Mars.

Each of the above requirements are discussed separately in chapters 4 through 8 of this thesis. Performance measurement approaches for each are also discussed within each chapter. Environmental testing, due to its unique nature, is discussed last. A summary of the above requirements, their corresponding proposed methods of performance measurement and testing, and chapter references are provided in table 1-1.

Table 1-1. General Micro Rover Requirements and Performance Measurement Approach.

<table>
<thead>
<tr>
<th>Requirement Description</th>
<th>Performance Measurement Approach</th>
<th>Chapter Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survive the environments (launch, transit, landing, and Martian surface)</td>
<td>Environmental Stress Testing</td>
<td>8</td>
</tr>
<tr>
<td>Rove across/through Mars terrain</td>
<td>Mobility Testing</td>
<td>4</td>
</tr>
<tr>
<td>Navigate to specified locations on Mars terrain</td>
<td>Navigation &amp; Control Testing</td>
<td>5</td>
</tr>
<tr>
<td>Conduct and support science and technology experiments</td>
<td>Scientific Support Testing</td>
<td>6</td>
</tr>
<tr>
<td>Conduct all operations on Mars semi-autonomously</td>
<td>Autonomy Testing</td>
<td>7</td>
</tr>
</tbody>
</table>
CHAPTER 2
THE PLANET MARS

History

Early Studies of Mars

Mars has always been an intriguing object of study and speculation by scientists and astronomers. However, for the purposes of planning missions with autonomous rovers, the information we currently have about Mars is far from complete. A brief examination of the history of Mars research helps establish the credibility (and, in certain areas, the lack thereof) of our current knowledge of Mars.

Three men who contributed significantly to our knowledge of Mars were Flammarion, Schiaparelli, and Lowell. The French scientist Flammarion compiled two exhaustive volumes on Mars which summarized telescopic observations through the 19th century. His works were referenced extensively into the twentieth century. In 1877 Schiaparelli added significantly to the knowledge of Mars by mapping the Martian surface. His work inspired a greater interest in Mars by both professional and amateur astronomers, and his mapping nomenclature evolved into the one in use today. Lowell was known for his claimed sightings of constructed canals on Mars and his speculations and theories of intelligent life. His widely believed theories, although blatantly incorrect, did help to motivate and advance the cause of Mars study and research.
Chapter 2: The Planet Mars

It was not until the 1960's that a more accurate understanding of the Martian surface and atmosphere developed. Telescopic observations and photographs revealed many previously unknown Martian features. Scientific and technological observation improvements led to more accurate surface and atmospheric characterizations. Carbon dioxide was correctly conjectured to be the primary constituent of the Martian atmosphere, and Mars' surface pressures were accurately estimated to be approximately 10 mbars (Kieffer).

The single most important element of our expanding knowledge of Mars has been provided by spacecraft exploration, especially by the Viking orbiters and landers. Table 2-1 lists highlights of the eventful, and sometimes lamentable history of our quest for information about Mars.
## Chapter 2: The Planet Mars

### Table 2-1. Chronology of Mars Mission Attempts (Kieffer, 74, et al)

<table>
<thead>
<tr>
<th>Year</th>
<th>Name</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>None</td>
<td>Failed to reach Earth orbit</td>
</tr>
<tr>
<td>1962</td>
<td>None</td>
<td>Failed to leave Earth orbit</td>
</tr>
<tr>
<td></td>
<td>Mars 1</td>
<td>Passed Mars June 19, 1963; telemetry failed</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>Failed to leave Earth orbit</td>
</tr>
<tr>
<td>1964</td>
<td>Mariner 3</td>
<td>Shroud separation failure</td>
</tr>
<tr>
<td></td>
<td>Mariner 4</td>
<td>Photographed Mars; measured atmosphere</td>
</tr>
<tr>
<td></td>
<td>Zond 2</td>
<td>Contact lost after 5 months (prior to Mars orbit)</td>
</tr>
<tr>
<td>1965</td>
<td>Zond 3</td>
<td>Photographed Moon; went to Mars's orbit</td>
</tr>
<tr>
<td>1969</td>
<td>Mariner 6</td>
<td>Flyby July 31; successful mission</td>
</tr>
<tr>
<td></td>
<td>Mariner 7</td>
<td>Flyby August 5; successful mission</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>Proton booster failure</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>Proton booster failure</td>
</tr>
<tr>
<td>1971</td>
<td>Mariner 8</td>
<td>Centaur booster failure</td>
</tr>
<tr>
<td></td>
<td>Kosmos 419</td>
<td>Failed to leave Earth orbit</td>
</tr>
<tr>
<td></td>
<td>Mars 2</td>
<td>Orbited Mars; descent module crashed</td>
</tr>
<tr>
<td></td>
<td>Mars 3</td>
<td>Orbited Mars; descent module landed; transmitter failed</td>
</tr>
<tr>
<td></td>
<td>Mariner 9</td>
<td>Orbited Mars November 13; long, successful mission</td>
</tr>
<tr>
<td>1973</td>
<td>Mars 4</td>
<td>Failed to orbit Mars</td>
</tr>
<tr>
<td></td>
<td>Mars 5</td>
<td>Orbited Mars; partially successful mission</td>
</tr>
<tr>
<td></td>
<td>Mars 6</td>
<td>Flyby; descent module landed on Mars; very little data</td>
</tr>
<tr>
<td></td>
<td>Mars 7</td>
<td>Flyby; descent module missed the planet</td>
</tr>
<tr>
<td>1975</td>
<td>Viking 1</td>
<td>Orbited June 1976; landed July 20</td>
</tr>
<tr>
<td></td>
<td>Viking 2</td>
<td>Orbited August 1976; landed September 3</td>
</tr>
<tr>
<td>1988</td>
<td>Phobos 1</td>
<td>Lost telemetry August 30</td>
</tr>
<tr>
<td></td>
<td>Phobos 2</td>
<td>Orbited Mars January 1989; lost telemetry March 27</td>
</tr>
<tr>
<td>1992</td>
<td>Mars Observer</td>
<td>Launched September; loss of contact August 1993</td>
</tr>
</tbody>
</table>

### The Viking Landers and Orbiters

The Viking missions, consisting of two orbiters and two landers, provided the most complete and accurate information about Mars to date. The first Viking lander landed on the surface of Mars on July 20, 1976, initiating an overall
6.4 year mission. Building upon the foundation established through the Mars and Mariner missions, the Viking data far exceeded the variety, quantity, and quality of data which had been collected prior to 1976 (Kieffer). Following is a brief synopsis of the information which the Viking missions collected.

Each orbiter carried two cameras. Together, they transmitted 52,603 pictures which covered the entire planet during all Martian seasons. The landers carried two scanning panoramic cameras with a resolution up to 0.04°. Together, the landers transmitted 4587 pictures, many in color (Kieffer).

The Mars Atmospheric Water Detectors (MAWD) mapped the quantity of water vapor during all seasons. The Infrared Thermal Mappers (IRTM) measured the temperature, albedo, and thermal inertia over the Martian surface. The Entry Science investigation determined the composition, thermal structure, and density of the atmosphere as functions of altitude below 200 km. Meteorology sensors measured atmospheric pressure, temperature, and wind for three Mars years (six Earth years) (Kieffer).

The Biology investigation tested for and found no supportive evidence for possible life on Mars. The Molecular Analysis investigation tested for organic compounds using gas chromatograph-mass spectrometry; none were found. The Inorganic Analysis investigation used X-ray fluorescence spectrometry to measure the concentrations in the surface material of 13 elements with atomic numbers ranging from 12 to 40. The Physical Properties investigation determined the texture and cohesiveness of the surface material. The
seismometer measured for and detected no seismic activity. The Magnetic Properties investigation concluded that the Martian regolith contains several percent of a highly magnetic material, but that Mars has no indentifiable intrinsic magnetic field (Kieffer).

**Recent Discoveries**

Subsequent to the Viking mission, the most significant information discovery was of the SNC meteorites, named after Shergotty, Nakhla, and Chassigny. The SNC meteorites consist of eight stones believed to be fragments of the Martian crust. Measurements taken of the SNC fragments provide much higher quality information about trace constituent noble gases than currently available from the Viking spacecraft data (Kieffer, 124).

Beyond the above mentioned findings, our knowledge of Mars remains severely limited. Future missions must still rely on speculation regarding the surface and surface materials of Mars.

**Fundamental Characteristics of Mars (Summary)**

Fundamental characteristics of Mars are summarized in Tables 2-2, 2-3, and 2-4. Table 2-5 compares some characteristics of Earth and Mars.
Table 2-2. Mars Orbital Characteristics (Kieffer, 28)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semimajor Axis</td>
<td>1.52366 AU</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.0934</td>
</tr>
<tr>
<td>Inclination</td>
<td>1°.8504</td>
</tr>
<tr>
<td>Longitude of Ascending Node</td>
<td>49°.59</td>
</tr>
<tr>
<td>Longitude of Perihelion</td>
<td>335°.94</td>
</tr>
<tr>
<td>Mean Daily Motion</td>
<td>0°.52405 / day</td>
</tr>
<tr>
<td>Mean Longitude</td>
<td>0°.89</td>
</tr>
<tr>
<td>Mean Orbital Velocity Around Sun</td>
<td>24.13 km/sec</td>
</tr>
<tr>
<td>Ls of Perihelion</td>
<td>250°.87</td>
</tr>
</tbody>
</table>

Table 2-3. Mars Orientation of Polar Axis (Kieffer, 28)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Ascension</td>
<td>317°.61</td>
</tr>
<tr>
<td>Declination</td>
<td>52°.85</td>
</tr>
<tr>
<td>Obliquity Relative to Orbital Plane</td>
<td>25°.19</td>
</tr>
</tbody>
</table>

Table 2-4. Mars Thermal Properties (Kieffer, 32; Kaplan)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Constant (Irradiance)</td>
<td>Min: 493 W/m²</td>
</tr>
<tr>
<td></td>
<td>Max: 718 W/m²</td>
</tr>
<tr>
<td>Average Surface Temperature (Note 1)</td>
<td>210.1° K</td>
</tr>
<tr>
<td>Range of surface Temperatures</td>
<td>~140 - 300 °K</td>
</tr>
</tbody>
</table>

Note (1): Equilibrium for a perfectly conducting sphere of albedo = 0.25, emissivity = 1.0 at Mars mean heliocentric distance.
Table 2-5. Comparison of Mars and Earth Characteristics (Kieffer, Costes, et al)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mars</th>
<th>Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>3.73 m/s²</td>
<td>9.80 m/s²</td>
</tr>
<tr>
<td>Mass</td>
<td>6.42 x 10²³ kg</td>
<td>59.8 x 10²³ kg</td>
</tr>
<tr>
<td>Land Area (in millions)</td>
<td>144 km²</td>
<td>148 km²</td>
</tr>
<tr>
<td>Equatorial Diameter</td>
<td>6,786 km</td>
<td>12,756 km</td>
</tr>
<tr>
<td>Distance From Sun</td>
<td>206.6 - 249.2 km</td>
<td>147.1 - 152.1 km</td>
</tr>
<tr>
<td>Average Solar Irradiance</td>
<td>590 W/m²</td>
<td>1353 W/m²</td>
</tr>
<tr>
<td>Revolution Around Sun (Earth Days)</td>
<td>686.98</td>
<td>365.25</td>
</tr>
<tr>
<td>Rotation About Axis</td>
<td>24 hr 39 min 23 sec</td>
<td>24 hr 00 min 00 sec</td>
</tr>
<tr>
<td>Tilt of Axis</td>
<td>~ 22°</td>
<td>~ 22°</td>
</tr>
<tr>
<td>Average Density (g/cm³)</td>
<td>3.9</td>
<td>5.5</td>
</tr>
<tr>
<td>Mean Escape Velocity</td>
<td>5.027 km/s</td>
<td>11.180 km/s</td>
</tr>
<tr>
<td>Synchronous Orbit Altitude</td>
<td>17,033 km</td>
<td>35,786 km</td>
</tr>
</tbody>
</table>

Seasons on Mars are measured in terms of the areocentric longitude of the sun (L_s), which is the angular measure of the apparent revolution of the Sun about Mars measured from the vernal equinox of Mars (the intersection of Mars' equatorial plane with the plane of its orbit). At perihelion, L_s = 251°. Table 2-8 lists the dates of seasonal cycles on Mars from L_s = 0 for 1992 through 2009.
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Table 2-6. Date (Fractional Day in GMT) and Julian Day at which Mars' Seasonal Longitude (Ls) is 0 for 1992 to 2009

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Day</th>
<th>Julian Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>November</td>
<td>21.9</td>
<td>2448948.4</td>
</tr>
<tr>
<td>1994</td>
<td>October</td>
<td>9.9</td>
<td>2449635.4</td>
</tr>
<tr>
<td>1996</td>
<td>August</td>
<td>26.9</td>
<td>2450322.4</td>
</tr>
<tr>
<td>1998</td>
<td>July</td>
<td>14.8</td>
<td>2451009.3</td>
</tr>
<tr>
<td>2000</td>
<td>May</td>
<td>31.8</td>
<td>1451696.3</td>
</tr>
<tr>
<td>2002</td>
<td>April</td>
<td>18.7</td>
<td>2452383.2</td>
</tr>
<tr>
<td>2004</td>
<td>March</td>
<td>5.7</td>
<td>2453070.2</td>
</tr>
<tr>
<td>2006</td>
<td>January</td>
<td>21.7</td>
<td>2453757.2</td>
</tr>
<tr>
<td>2007</td>
<td>December</td>
<td>9.7</td>
<td>2454444.2</td>
</tr>
<tr>
<td>2009</td>
<td>October</td>
<td>26.6</td>
<td>2455131.1</td>
</tr>
</tbody>
</table>

The Atmosphere of Mars

Atmospheric Composition

The Mars atmosphere is composed predominantly of carbon dioxide with small amounts of nitrogen, argon and oxygen. The atmospheric composition of Mars is shown in table 2-7.
Table 2-7. Composition of the Atmosphere of Mars (Kaplan, 2-2)

<table>
<thead>
<tr>
<th>Gas</th>
<th>Mole Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>0.955 +/- 0.0065</td>
</tr>
<tr>
<td>N₂</td>
<td>0.028 +/- 0.003</td>
</tr>
<tr>
<td>Ar</td>
<td>0.016 +/- 0.003</td>
</tr>
<tr>
<td>O₂</td>
<td>0.0015 +/- 0.005</td>
</tr>
<tr>
<td>CO</td>
<td>0.0007</td>
</tr>
<tr>
<td>Ne</td>
<td>2.5 ppm</td>
</tr>
<tr>
<td>Kr</td>
<td>0.3 ppm</td>
</tr>
<tr>
<td>Xe</td>
<td>0.08 ppm</td>
</tr>
</tbody>
</table>

Characteristics

Although there are water-ice clouds on Mars, there is no liquid water on the surface. Large amounts of water vapor have been observed over the summer northern polar region; virtually no water vapor has been observed in the winter (Kaplan, 2-2).

The atmospheric pressure on Mars is approximately 1% of Earth's; Mars surface pressures vary between 5.4 and 15.0 mbars. Atmospheric pressure varies approximately 15% annually at the surface (Kaplan, 2-1).

The Martian atmosphere does not transfer as much heat as the Earth, and Mars cools much faster by radiation. Surface temperatures generally range from 190° to 240° Kelvin (-83° to -33° C) during the summer, and stabilize near 150° Kelvin (-123° C) during the winter (Kaplan, 2-1). The temperatures are maximum at midday near the autumn equinox, with a secondary peak near the spring equinox.
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Wind

Mars winds are generally stronger and more variable than the Earth's. Although the Viking-2 lander wind measurements averaged less than 1 m/sec, the lander also measured winds up to 20 m/sec, not including Martian dust storms (Kaplan, 2-9). It should be noted that due to the lower atmospheric pressure, the external forces from wind on Mars are much lower than the external forces from the same velocity wind on Earth.

A first-order calculation of Mars / Earth dynamic pressure ratio quantifies this difference:

The required dust/wind velocity for a test performed on Earth to achieve an equivalent dynamic pressure \((1/2\rho V^2)\) during a wind/dust storm on Mars is calculated using:

\[
P V = nRT
\]

Where \(P\) = pressure, \(V\) = volume, \(n\) = number of moles = mass/(molecular weight), \(R\) = universal gas constant, \(T\) = temperature

Rearranging, we can solve for the density by:

\[
\rho = \frac{P \text{ (mol. wt)}}{R T}
\]

Assumptions:
- Earth air is composed of 2/3 Nitrogen and 1/3 Oxygen
- Mars air is composed entirely of Carbon Dioxide
- Mars atmospheric pressure is 1% of Earth's
- Average temperature on Earth is 292° Kelvin
- Temperature on Mars ranges between 150° and 240° Kelvin

Solving for the density ratios, this gives us a range for \(\rho(\text{Earth})/\rho(\text{Mars})\) between 34.1 and 54.5, with an average of 44.3. Substituting into the
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dynamic pressure equation, we approximate the equivalent Earth/Mars wind velocity ratio to be 0.15. Thus, the dynamic pressure experienced by a spacecraft on Mars is roughly equal to the dynamic pressure experienced on Earth by a wind of only 15% of that on Mars (e.g. force from 20 m/sec wind on Mars = force from 3 m/sec wind on Earth).

Dust Storms

Dust storms are one of the more potentially hazardous environmental concerns for a rover design. Viking-1 recorded winds in excess of 25 m/sec during a local dust storm. 97 dust devils were detected from the Viking orbiters; dust devil wind speeds were not estimated (Kaplan, 2-10). Local dust storms extending at least a few hundred km (up to $10^6$ km$^2$ area) occur every year. These storms can occur during all seasons, but most commonly occur during southern spring and summer when the weather is warmest. Large storms are most commonly located around 10° to 20° N and 20° to 40° S latitudes (Kaplan, 2-14).

Dust storms of a planetary scale known as great dust storms can occur up to twice per year. These storms, covering most of one or both hemispheres of Mars, most frequently occur during southern spring and summer ($L_s \approx 250^\circ$) (Kaplan, 2-13). Table 2 cites the recorded global dust storm occurrences. It should be noted that most of these storms were observed when the Earth was close to Mars (opposition occurs every 15 years); more storms probably occurred which were not observed. There is no reliable method for predicting global dust storms (Kaplan, 2-13).
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One measure of the opacity of a Martian dust storm is optical depth ($\tau_o$). The relationship between the attenuation of solar irradiance ($I$) and optical depth is:

$$I = I_o e^{-\tau_o / \cos \theta}$$

(Kaplan, 2-11)

where $\theta$ is the zenith angle. This relationship indicates that the greater the optical depth, the greater the signal attenuation. Surface optical depth on a typical Martian day is 0.5 (Kaplan, 2-11). The dust clouds from great dust storms are very opaque, with optical depths up to 5. Optical depths greater than 1 can remain for more than 100 Martian sols (Kaplan, 2-13).

Table 2-8. Martian Great Dust Storms (Kaplan, 2-14)

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Initial Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1909</td>
<td>August</td>
<td></td>
</tr>
<tr>
<td>1911</td>
<td>November</td>
<td></td>
</tr>
<tr>
<td>1922</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1924</td>
<td>October</td>
<td></td>
</tr>
<tr>
<td>1924</td>
<td>December</td>
<td>Isidis Planitia</td>
</tr>
<tr>
<td>1939</td>
<td>November</td>
<td>Utopia</td>
</tr>
<tr>
<td>1941</td>
<td>November</td>
<td>South of Isidis</td>
</tr>
<tr>
<td>1943</td>
<td>November</td>
<td>Isidis</td>
</tr>
<tr>
<td>1956</td>
<td></td>
<td>Hellespontus</td>
</tr>
<tr>
<td>1958</td>
<td></td>
<td>Isidis</td>
</tr>
<tr>
<td>1971</td>
<td>July</td>
<td>Hellespontus</td>
</tr>
<tr>
<td>1971</td>
<td>September</td>
<td>Hellespontus</td>
</tr>
<tr>
<td>1973</td>
<td></td>
<td>Solis Planum, Hellespontus</td>
</tr>
<tr>
<td>1977</td>
<td>February</td>
<td>Thaumasia Fossae</td>
</tr>
<tr>
<td>1977</td>
<td>June</td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1982</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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Dust and Dust Deposition

The airborne particles on Mars are probably clay silicates similar to soil-derived aerosols found in the Earth's atmosphere (Kaplan, 2-11). Analysis by Toon et al. (Kaplan, 2-13) suggested Martian dust was a mixture of igneous silicates with greater than 60% SiO₂ or clay minerals. Pollack et al. (Kaplan, 2-13) modeled the Mars dust size distribution with a modified Gamma function which gives a mean particle radius of 2.5 microns. This analysis implies plate-like particles such as Montmorillonite and an average global sedimentation rate of \( \sim 2 \times 10^{-3} \) g cm\(^{-2}\) yr\(^{-1}\).

Active dust deposition occurs frequently in the northern hemisphere. It is conjectured that this occurs more as a result of atmospheric circulation than surface wind properties. Albedo features provide evidence that aeolian processes are probably the most influential in affecting change on the surface of Mars (Kieffer).

The Surface of Mars

An accurate understanding of the surface of Mars is critical for adequate rover design and testing. Unfortunately, much of the surface of Mars has not been closely observed. The Viking-1 and Viking-2 landing sites provided significant information on only two small surface locations on the planet. Also, the Viking mission priorities supported ascertaining the existence of life-forms rather than completing a physical and chemical examination of the Martian surface.
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Surface Chemical Composition

The following table is extracted from Kieffer's et al Mars:

Table 2-9. Representative Chemical Composition of Martian Soil (Kieffer, 30)

<table>
<thead>
<tr>
<th>Constituent (Note 1)</th>
<th>Concentration (%)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>43.4</td>
<td>2</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>18.2</td>
<td>2</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>7.2</td>
<td>2</td>
</tr>
<tr>
<td>SO₃</td>
<td>7.2</td>
<td>2</td>
</tr>
<tr>
<td>MgO</td>
<td>6.0</td>
<td>2</td>
</tr>
<tr>
<td>CaO</td>
<td>5.8</td>
<td>2</td>
</tr>
<tr>
<td>Na₂O</td>
<td>1.34</td>
<td>3</td>
</tr>
<tr>
<td>Cl</td>
<td>0.8</td>
<td>2</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.68</td>
<td>3</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.6</td>
<td>2</td>
</tr>
<tr>
<td>MnO</td>
<td>0.45</td>
<td>3</td>
</tr>
<tr>
<td>Cr₂O</td>
<td>0.29</td>
<td>3</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.10</td>
<td>3</td>
</tr>
<tr>
<td>CO₃</td>
<td>&lt;2</td>
<td>4</td>
</tr>
<tr>
<td>H₂O</td>
<td>0-1</td>
<td>5</td>
</tr>
</tbody>
</table>

Notes:
(1) Based on elemental composition, expressed as oxides.
(2) Based on direct soil analyses from Viking X-ray Fluorescence Spectrometer.
(3) Based on SNC meteorite analyses.
(4) Based on terrestrial simulations of Viking Labelled Release experiment.
(5) Spatially and temporally variable.

Viking Lander Site Descriptions

Viking Lander 1 (VL1) took panoramic pictures of Chryse Planitia. These pictures revealed large tracts of dune-like drifts superposed on a rocky substrate. Drift material is common. Impact craters protrude from the surface. Unlike on the Moon, craters smaller than a few tens of meters are
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not visible. It is presumed that this is a result of: 1. the Martian atmosphere disintegrating small meteors prior to impact, and, 2. the leveling effects of the aeolian processes at the surface (Golombek). Rocks varying in size from one centimeter to several meters protrude from the substrate (Kaplan, 3-1).

Viking Lander 2 (VL2) took pictures of Utopia Planitia. These views show a rock-strewn surface with a smoother horizon. The rocks are generally larger and cover more area than at the VL1 site. The rock sizes range from a few centimeters to a meter or more in diameter. Accumulations of red dust appear on most material surfaces at both sites (Kaplan, 3-1).

Descriptions of Surface Materials

The Viking Landers did not have any instruments specifically designed for measuring the physical or chemical properties of the surface materials of Mars (Kaplan, 3-3). However, scientists analyzed the interaction between the Viking landers and the surface during landing, as well as the motor-current records and estimates of exerted forces from the sampler. These provide indirect results of the characteristics of surface materials.

The surface of Mars is composed of four types of materials: drift, crusty to cloddy, blocky, and rock (Kaplan, 3-3). Table 2-10 summarizes fundamental properties of these materials.
Table 2-10. Estimates and Mechanical Properties of Mars Surface Materials in Viking Lander Sample Fields (Kaplan, 3-3)

<table>
<thead>
<tr>
<th>Viking Lander 1</th>
<th>Surface Material</th>
<th>Grain Size (mm)</th>
<th>Bulk Density (kg/m³)</th>
<th>Cohesion (kPa)</th>
<th>% of Area Covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td>0.1 - 10.0</td>
<td>1150 +/- 150</td>
<td>1.6 +/- 1.2</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Blocky</td>
<td>0.1 - 1500</td>
<td>1800 +/- 400</td>
<td>5.5 +/- 2.7</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>Rocks</td>
<td>35,000 - 240,000</td>
<td>2600</td>
<td>1000 - 10,000</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Viking Lander 2</th>
<th>Surface Material</th>
<th>Grain Size (mm)</th>
<th>Bulk Density (kg/m³)</th>
<th>Cohesion (kPa)</th>
<th>% of Area Covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crusty to Cloddy Rocks</td>
<td>0.1 - 10.0</td>
<td>1400 +/- 200</td>
<td>1.1 +/- 1.2</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>Rocks</td>
<td>35,000 - 450,000</td>
<td>2600</td>
<td>1000 - 10,000</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

Drift material is similar to extremely fine-grained, porous materials. VL1 analyzed the gas desorbed from a humidified sample of drift material and indicated a specific area of $17 \text{ m}^2/\text{g}$ (Kaplan, 3-4). Crushed Quartz and some natural clays have specific areas near $17 \text{ m}^2/\text{g}$. A close representation of drift material is loose pumice powder, crushed to pass a 44 mm sieve, and having a bulk density of $880 \text{ kg/m}^3$ (Kaplan, 3-11).

Footpad two of VL1 penetrated 16 cm through drift material when it landed at 2.3 m/s (Kaplan, 3-15), giving rise to concerns over landing or roving in drift material. An examination of dielectric constants and thermal inertias supports the presupposition that there are vast expanses of drift material in regions such as Tharsis and Arabia (Kaplan, 3-15). Drift material is resistant to aeolian erosion.
Crusty to cloddy material is similar to moderately dense soils. Individual grains of crusty to cloddy material are probably approximately the same size as drift material grains (0.1 to 10 μm) with relatively high cohesion. Scientists distinguished crusty to cloddy material from drift material by the polygonal prismatic forms of broken crusts and clods left after manipulation with a Viking Lander tool (Kaplan, 3-5). The crusts and clods could probably be broken up by finger pressure (Kaplan, 3-5), but are probably not easily eroded by Martian winds (Kieffer, 1325).

Blocky material, unlike drift and crusty to cloddy material, was never analyzed by the Gas Exchange Experiment. As a result, its grain size is unknown. Its properties, however, lead to speculation of significant amounts of silt-size or smaller grains. Blocky material has very strong, cohesive clods and fragments (Kaplan, 3-6); large amounts of sulfur and chlorine suggest cementation. Blocky material, like crusty to cloddy material, is not easily eroded by Martian winds.

The appearance of Martian rocks ranges from dense and fine-grained to vesicular. Some rocks may be breccias (Kaplan, 3-6). The Viking sampler did not chip or scratch the rocks, so it is likely the rocks do not have weak, punky rinds (Kaplan, 3-6). The rocks are gray, and are often covered by a layer of dust a few microns thick. Scientists speculate the rocks are probably mafic like basalts, basaltic andesites, or andesites (Kaplan, 3-6). Small rock fragments are absent.
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Rock Distributions

Mars rock distribution frequency equations were extrapolated from rock observations at the VL2 site. The cumulative frequency distribution of rocks down to a diameter of 0.14 m can be represented by the equation:

\[ N = 0.013D^{-2.66} \]

where \( N \) is the cumulative frequency of rocks per meter-squared with diameters of \( D \) and larger (Kaplan, 3-6). Representative values are shown in table 2-11.

Table 2-11. Representative rock diameters and their respective cumulative frequency distributions.

<table>
<thead>
<tr>
<th>Rock Diameter</th>
<th>Cumulative Frequency / m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 cm</td>
<td>2.021</td>
</tr>
<tr>
<td>25 cm</td>
<td>0.519</td>
</tr>
<tr>
<td>50 cm</td>
<td>0.082</td>
</tr>
</tbody>
</table>

Also, the cumulative fraction of area covered (A) by assumed circular rocks of diameters \( D \) and larger can be represented by:

\[ A = 0.0408D^{-0.66} \]

Representative values are shown in table 2-12.

Table 2-12. Representative rock diameters and their respective percentages of Mars surface area covered.

<table>
<thead>
<tr>
<th>Rock Diameter</th>
<th>% Area Covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 cm</td>
<td>14.27</td>
</tr>
<tr>
<td>25 cm</td>
<td>10.19</td>
</tr>
<tr>
<td>50 cm</td>
<td>6.45</td>
</tr>
</tbody>
</table>
Chapter 2: The Planet Mars

Unique Terrain

Much of the Martian terrain poses serious challenges to landers and rovers. Mountains and canyons are enormous compared to Earth's. The volcano Olympus Mons rises 27 km above the Mars datum, which is three times the height of Mount Everest. Valles Marineris is a network of canyons spanning 4000 km with depths up to 10 km. On Earth, these canyons would reach from Boston to Los Angeles, and would be three times deeper than the Grand Canyon.

Many of the slopes commonly found in Martian terrain may be composed of skree or talus, and are very close to or at the angle of repose (30° to 45° depending on the shapes and sizes of the materials) (Kaplan, 3-16). Impact-craters composed of blocky material can be very rough and have slopes as steep as 25°. The interior wall slopes of these craters may exceed 40°. Martian sand dunes would probably be near or at the angle of repose of cohesionless sand (30° to 35°) (Kaplan, 3-16). Lava flow surfaces are highly variable in strength and texture, and would have to be closely examined prior to rover exploration. It is also possible that ice and snow may occur in the northern polar region (Kaplan, 3-16).
CHAPTER 3
BACKGROUND RESEARCH

Early Rover Concepts

Rovers were extensively researched and developed during the 1960's to assist in the exploration of the moon. Prior to the use of the Lunar Roving Vehicle on the Apollo 15 mission, several studies were accomplished evaluating a spectrum of potential lunar rover concepts to accommodate scientific needs for the 1970-1980 time period. Studied rover concepts included both manned and unmanned rovers to be used for exploration, site survey, and base support operations.

The Lunar Surface Mobility Systems Comparison and Evolution Study (MOBEV) completed in 1966 examined 33 lunar rover design concepts. Following is a table extracted from the MOBEV final presentation slides showing representative design parameters for some of the primary concept proposals which were under consideration. SLRV and Runt were unmanned vehicles while Pack Mule, Go-Cart, and Mini-LSSM were designed to accommodate one driver.
Table 3-1. Summary of representative unmanned and early manned vehicles concepts (from MOBEV presentation)

<table>
<thead>
<tr>
<th></th>
<th>SLRV R0AE</th>
<th>RUNT R0CE</th>
<th>PACK MULE R0BE</th>
<th>GO-CART R1AE</th>
<th>LSSM R1A(1)E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivered Mass (kg)</td>
<td>62.1</td>
<td>148</td>
<td>66</td>
<td>107</td>
<td>133</td>
</tr>
<tr>
<td>Scientific Payload (kg)</td>
<td>4</td>
<td>50</td>
<td>75</td>
<td>10</td>
<td>75</td>
</tr>
<tr>
<td>Crew Supplied Mass (kg)</td>
<td>N/A</td>
<td>N/A</td>
<td>29</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>Total Operating Mass (kg)</td>
<td>62.1</td>
<td>148</td>
<td>170</td>
<td>288</td>
<td>379</td>
</tr>
<tr>
<td>Number of Sorties/Range (km)</td>
<td>-/72</td>
<td>-/200</td>
<td>5/15</td>
<td>20/240</td>
<td>12/144</td>
</tr>
<tr>
<td>Avg Maximum Speed (km/hr)</td>
<td>0.4</td>
<td>1.0</td>
<td>4.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Obstacle (cm)</td>
<td>30</td>
<td>27</td>
<td>27</td>
<td>20</td>
<td>33</td>
</tr>
<tr>
<td>Development Cost ($M)</td>
<td>41.3</td>
<td>51.2</td>
<td>14.8</td>
<td>24.1</td>
<td>28.4</td>
</tr>
<tr>
<td>Development Time (Mos.)</td>
<td>32</td>
<td>34</td>
<td>30</td>
<td>33</td>
<td>33</td>
</tr>
</tbody>
</table>

These rover concepts were for much larger rovers designed to travel greater distances than the micro rovers currently proposed for use on Mars. It is interesting to note that the estimated development time for each of these concepts is much less than that predicted for each major Mars micro rover design currently under consideration. This is an indication of the changes that have taken place in the space hardware development process.

The Soviet Union conducted similar studies prior to its operation of unmanned rovers on the Moon in 1970 and 1973. The final Lunokhod designs were for large (840 kg/1840 lb), slow moving, long-distance rovers. The Lunokhods traveled 10 and 37 kilometers during 11 and 4 month periods respectively. The Lunokhods required much human interaction and direct control from Earth.
The Lunar Roving Vehicle (LRV)

The Lunar Roving Vehicle was used successfully on Apollo missions 15, 16, and 17. Following is a system description of the Lunar Roving Vehicle in its final design form as taken from an Apollo 15 Report on performance of the Lunar Roving Vehicle (Costes, 2ff).

The general requirements for the Lunar Roving Vehicle were:

1. to be able to transfer astronauts and equipment from and to any two points A and B along the geological traverses.

2. to minimize travel time in traversing any section A-B without hindering the stability or controllability of the vehicle, or jeopardizing in any way the safety of the astronauts.

3. to have sufficient energy reserve in the LRV batteries to provide the power required for the traction-drive system, steering, navigation system, operation of the control and performance display console, starting and accelerating periods, etc.

Simplicity of design and operation, as well as light weight were overriding features. It was also specified that the rover should be able to transport a payload roughly twice its own weight. Repair and adjustments during the mission were considered impossible. No telemetered rover performance or operation data other than pilot-monitored and reported data was required. The rover would be transported to the Moon in a folded configuration to conserve space. The time available for design, fabrication, and flight qualification of the first unit was 17 months.
Lunar Roving Vehicle Design Specifications:

**Height:** 1.14 m

**Length:** 3.1 m. **Wheelbase:** 2.3 m

**Width:** 2.01 m. **Track:** 1.8 m

**Weight:** 2130 N (480 lbs) on Earth

**Payload:** 4800 N (1080 lbs) on Earth

**Maximum Traverse Distance:** 120 km

**Maximum Speed:** 14 km/hr

**Design Temperature Extremes:** -173°C to 117°C

**Vehicle Temperature Constraint at Liftoff:** 21 ± 3°C

**Thermal Margins From Liftoff to Touchdown:**

- **Batteries:** 4 - 52°C
- **Other Equipment:** -34 - 85°C

**Predicted Surface Conditions:** varying roughness and soft-soil consistency; wide range of crater and block distributions, 25° slopes (several vehicle lengths long)

**Design Features**

- Electric propulsion (two nonrechargeable silver-zinc batteries)
- Individually powered wheels
- Ackerman steering, both front and rear wheels (inner wheel radius smaller than outside wheel radius) Outer wheel angle: 22°, inner wheel angle: 53°; steering rate: 5.5 sec lock to lock.
- Harmonic drive gear reduction unit: 80:1, allows continuous application of power to wheels without gear shifting.
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- Wheels: zinc-coated piano wire with a spun aluminum hub and titanium bump stop. Chevron-shaped titanium treads riveted to wire mesh around outer circumference with 50% coverage.
- Chassis: 2219 aluminum alloy tubing, welded at structural joints, includes torsion bars
- Ground Clearance: 35.6 cm (14 in) loaded; 43.2 cm (17 in) unloaded
- 36 V DC brush-type drive motors with pulse-width modulation speed control
- Mobility Performance: designed to negotiate step-like obstacles 30 cm (11.8 in) high (26% of rover height), and cross crevices 70 cm (27.6 in) wide (22% of rover length). Can climb slopes of 20° to 23° in favorable circumstances. Minimum turn radius is 3.05 m (10 ft) (98% rover length)
- Navigation System: Dead-reckoning system providing direction and distance between the rover and the Lunar Module, as well as total distance traveled at any point during a traverse.
- Communication: conducted with the Lunar Module, or directly with Earth through the Lunar Communications Relay Unit
- Passive and semipassive thermal control measures (insulation, radiative surfaces, thermal mirrors, thermal straps, fusible-mass heat sinks, and special surface finishes)
- Beaded aluminum floor panels
- Fiberglass armrests and fenders

Martian Rover Concept Evolution

Foreseeing the potential capabilities of autonomous rovers, scientists began to research rovers with more automation during the 1970's. Originally these
rovers were much larger and incorporated large computers and complicated control algorithms. Overall performance was poor. The computers were not fast enough nor was the code efficient enough to adequately tackle the difficult problem of terrain navigation.

Nevertheless, research and development continued. By the mid 1980's, Mars rover plans and studies called for the development of a large (500 - 1000 kg) rover able to traverse up to a total of 1000 kilometers and return samples to Earth via a Martian lander or follow-on astronauts (Piviotto-3, E-1).

Fiscal realities did not permit these plans to come to fruition. Decisions in the late 1980's and early 1990's have led to the pursuit of smaller, simpler, and less expensive rover designs. Technology has assisted by providing significantly smaller processors, sensors, and other instruments for micro rovers.

**Additional Rover Testing and Test Considerations**

**LRV Testing**

Testing was accomplished in both direct and indirect support of the LRV design. Relevant results of this testing are included in subsequent discussions throughout this thesis.

**Mars Surface Simulant Testing and Selection**

One critical aspect of rover testing is the selection of surface simulant. Simulant selection will directly effect test results in all categories of testing.
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proposed in this research. Previous and current simulant research results are discussed below.

Lunar Simulants and Lunar Simulant Testing

Significant lunar simulant testing was accomplished during the Apollo program as part of the studies accompanying the development of the Lunar Roving Vehicle. Several different lunar simulants were considered for use during rover testing. Initially, the simulant used for testing was a uniform dune sand from Yuma Arizona (Costes, 16). However, information from the Earth-return soil samples from the Apollo 11 mission led to the use of a crushed basalt from Napa, California with a grain-size distribution matching the Apollo 11 soil samples. This was designated lunar (nominal) (Costes, 16).

One important conclusion drawn from rover testing using lunar (nominal) simulant was that the effects of lunar gravity and atmospheric conditions on dust tend to oppose each other. Combined, however, these effects tend to reduce potential hazards from dust generated by wheel-soil interactions (Costes, 29b). A first-order extrapolation of these results to the reduced gravity and reduced atmospheric pressure conditions on Mars leads to the conclusion that detrimental effects from dust ejections from rover wheel-soil interactions will be less inhibitive on Mars than they are on the Earth.

Potential Mars Surface Simulants and Simulant Testing

Five common types of simulants which have been used by scientists and engineers for modeling the various materials on the surface of Mars are: lunar (nominal), lag gravel, dune sand, loess, and rock. Lunar (nominal) was used for testing the Viking landers. Test result comparisons between penetration tests performed by the Viking landers and the same tests
accomplished on Earth using lunar (nominal) simulant indicate a close correlation in mechanical properties between the materials. Lunar (nominal) simulant is also relatively inexpensive, making it a likely candidate for use in rover testing. The following table, extracted from Viking Project Document, "Mars Engineering Model", NASA Document # M75-125-3, lists pertinent information about these common Martian surface material simulants.

Table 3-2. Martian soil models

<table>
<thead>
<tr>
<th>Grain Size Distribution</th>
<th>Lunar (nominal)</th>
<th>Lag Gravel</th>
<th>Dune Sand</th>
<th>Loess</th>
<th>Rock Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 %</td>
<td>1 µ</td>
<td>1000 µ</td>
<td>50 µ</td>
<td>3 µ</td>
<td>Rock Surface</td>
</tr>
<tr>
<td>75 %</td>
<td>15 µ</td>
<td>20,000 µ</td>
<td>150 µ</td>
<td>20 µ</td>
<td></td>
</tr>
<tr>
<td>50 %</td>
<td>40 µ</td>
<td>150,000 µ</td>
<td>190 µ</td>
<td>37 µ</td>
<td></td>
</tr>
<tr>
<td>25 %</td>
<td>300 µ</td>
<td>530,000 µ</td>
<td>230 µ</td>
<td>60 µ</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td>Large</td>
<td>1000 µ</td>
<td>1000 µ</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bulk Density (r) g/cm³</th>
<th>1.35 - 1.8</th>
<th>1.4 - 1.7</th>
<th>1.4 - 1.7</th>
<th>1.0 - 1.6</th>
<th>2.7 - 3.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity %</td>
<td>48 +/- 8</td>
<td>49 +/- 5</td>
<td>49 +/- 5</td>
<td>56 +/- 10</td>
<td>very low (~3)</td>
</tr>
<tr>
<td>Cohesion dynes/cm²</td>
<td>10³ - 10⁴</td>
<td>0</td>
<td>0 - 10³</td>
<td>0 - 10⁶</td>
<td>10⁸ to 5x10⁸</td>
</tr>
<tr>
<td>Angle of Internal Friction (°)</td>
<td>30 - 40</td>
<td>35 +/- 5</td>
<td>35 +/- 5</td>
<td>33 +/- 8</td>
<td>45 +/- 5</td>
</tr>
<tr>
<td>Dielectric Constant Farads/cm</td>
<td>2.5 - 3.8</td>
<td>3 - 4</td>
<td>3 - 4</td>
<td>2.3 - 4</td>
<td>8 - 9</td>
</tr>
<tr>
<td>Composition</td>
<td>Basaltic</td>
<td>Basaltic</td>
<td>Basaltic</td>
<td>Basaltic</td>
<td>Basaltic</td>
</tr>
</tbody>
</table>

Other potential soil simulants are palaganite and river wash sand. Palaganite is reddish in color and is chemically similar to predicted Martian
soil chemistry. Mechanically, its properties are very similar to lunar (nominal), but it is also significantly more expensive. River wash sand possesses a grain distribution which includes the extremes of the grain sizes expected on Mars. Thus, it can be sifted to match any desired grain size distribution model. River wash sand is also inexpensive.

David Carrier, whose previous experience includes Apollo program lunar soil simulations, currently is a consultant for the Jet Propulsion Laboratory on Martian rover simulant selection. Carrier recommends using a clay such as bentonite, montmorillonite, kaolinite, or saponite. These clays have roughly the same grain size and shape (and therefore similar mechanical properties) as Martian soil, but with different chemical compositions. Although Kaolinite and Saponite are the most similar to Mars surface material of the four materials mentioned above, they are difficult to obtain in sufficient quantities for testing. Montmorillonite absorbs water easily, detrimentally changing its mechanical properties (a problem for mobility testing). Bentonite is easy to obtain, and is currently a likely candidate for the Jet Propulsion Laboratory's micro rover testing simulant (Eisen).

Simulant preparation is a significant concern. It is not known how to simply and easily prepare a simulant so that it has the same bulk density as Martian soil, nor how to keep the bulk density consistent between test runs. Currently, the Jet Propulsion Laboratory is able to prepare lunar (nominal) simulant to bulk density values ranging between 1.15 and 1.6 g/cm$^3$ (Eisen). Bulk densities of 1.8 have not yet been attained. Microrover test runs accomplished over the same paths using lunar (nominal) simulant vary significantly from one run to the next due to the change in simulant bulk
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density. Lunar (nominal)'s high cohesion gives it a memory property; the same test runs accomplished in sand (a relatively incompressible material) do not show a significant deviation (Eisen).

Differences in gravity and atmospheric pressure will also affect the behavior of the soil simulants and their mechanical properties. One method of avoiding this is to bias the simulant grain size distribution toward larger grain sizes. This minimizes the effects of pore pressures and allows the mechanical properties of a simulant to more closely resemble a granular substance under reduced gravity. A second method is to perform testing in a partial vacuum (roughly 100,000 ft altitude) to reduce the effects of pore pressures, and thus more accurately simulate a soil in reduced gravity.

It is also unknown how to ensure a simulant stays as dry as Martian soil, which contains virtually no water vapor. Moisture usually increases a soil's cohesion. This is more of a problem for smaller grained, cohesive materials such as lunar (nominal) and loess.
**CHAPTER 4**

**MOBILITY**

**Introduction**

Martian terrain is known to be varied and hazardous. Current satellite image resolution is not adequate to discern terrain features on the order of a micro rover. Nevertheless, even relatively benign terrain such as that photographed by the Viking landers would challenge the mobility capabilities of a micro rover. Thus, a rover's mobility will be fundamental to its utility on Mars.

**Mobility Requirements**

Requirement #2 as described in Chapter 1 states that a rover must be able to rove across/through Mars terrain. Based upon this fundamental requirement, more specific mobility performance requirements were generated. The first of these is the simplest and most fundamental; subsequent requirements are more complex, and, consequently, more difficult for a rover to satisfy.

Following is the list of requirements developed for mobility testing:

1. Traverse unobstructed, level terrain
2. Traverse unobstructed, sloping terrain
3. Surmount small obstacles and benign terrain features
4. Surmount hazardous obstacles and traverse hazardous terrain
**Mobility Failure Modes**

For both mobility and navigation testing (discussed in Chapter 5), it is necessary to analyze and define mobility failure modes.

Hazardous obstacles are defined as obstacles that may incite one of four mobility failure modes. These are:

1. Vertical drop
2. Overturn
3. Obstacle block
4. Loss of wheel traction

A vertical drop refers to any hazard that could exact damage on a rover due to a vertical drop. Examples of a vertical drop hazard include a cliff or a crevice.

An overturn refers to a debilitating change of plane of a rover which renders propulsion mechanisms and/or other operations defunct. An overturn could be incited by steeply sloping terrain, by obstacles encountered by only one side of a rover, or a combination of both.

An obstacle block refers to any obstacle that will disallow a continuation of mobile progress, such as the base of a cliff (or large obstacle) which a rover cannot successfully negotiate.
Chapter 4: Mobility

A formation which is likely to cause an obstacle block is a spiked obstacle. This is an obstacle which fits, at least partially, between a rover's axles or subsequent lengthwise propulsion mechanisms. Due to the large amount of traction and power which are required to surmount spiked obstacles, a small obstacle in such a shape is capable of debilitating a relatively large rover. Even more challenging are combinations of spiked obstacles which fit between more than one set of wheels/propulsion mechanisms. Their effect on a rover is similar to "chocking" car tires.

Loss of wheel/leg traction is defined as a halt in a rover's forward progress due to hazardous terrain which affects a rover's traction required for propulsion. Examples of such terrain include large embankments of fine drift material, or an obstacle or series of obstacles that would cause a rover to high center.

Perhaps the most difficult failure modes to predict are those which are caused by a combination of obstacles. For example, a rover might encounter a gentle upslope, followed by a gentle downslope, which, by itself, does not pose a hazard to a rover. However, suppose at the top of the upslope there is a small obstacle or lip that overhangs the subsequent downslope. A very small such obstacle or lip would incite a "high center" loss of traction failure mode for even a large and very "mobile" rover.

All the above failure modes are tested in both mobility and navigation and control testing described in Chapter 9. The critical notion is that if a rover is incapable of traversing over or through a hazardous terrain feature, it should
Chapter 4: Mobility

decide to navigate around it. Conversely, if a terrain feature is clearly navigable, the rover should not decide to circumvent it.

Historical Background

Previous Research and Testing

Wheel-soil interactions and planetary vehicle mobility performance have been studied extensively since the start of the lunar rover program. Following is a review of some of the findings from previous research and testing which are pertinent to micro rovers on Mars.

Prior to the Lunar Roving Vehicle program, the Air Force conducted 65 wheel-soil interaction tests onboard a U.S. Air Force C-135A aircraft to test the effects of reduced gravity and reduced soil air-pore pressures on wheel-soil interactions. The aircraft flew parabolic trajectories at altitudes ranging between 25,000 and 40,000 ft to simulate a 1/6 gravity field (Costes, 28b). These tests were performed on scale prototype lunar roving vehicle wheels inside a vacuum chamber. The test wheels were able to drive themselves through dry crushed basalt lunar simulant around a 1.57 m diameter circular track.

Conclusions From Previous Research

One important conclusion drawn from these tests was that the effects of both reduced gravity and reduced pore pressures (an effect of low-atmospheric pressure) on the wheel-soil interaction tended to improve mobility performance (Costes, 29b). This same general conclusion was also supported
Chapter 4: Mobility

by astronaut observations of the Lunar Roving Vehicle performance recorded in the Apollo 15 mission report (Costes, 68b).

Further analysis has also shown that mobility performance on the Moon is likely enhanced by increased rover velocity. The effects of the lunar vacuum combined with the inertial effects of the dynamic interaction of the rover wheels with the lunar surface result in improved mobility performance (Costes, 28b). Increased momentum from greater velocity also enhances obstacle surmounting capabilities.

The above mentioned tests have not been repeated simulating surface conditions on Mars. However, first order approximations would indicate similar conclusions. Mars has 1% of Earth's atmospheric pressure (compared to the Moon's vacuum), and 1/3 of Earth's gravitational force (compared to 1/6 g on the Moon). Differences in results between the Earth and Mars and the Earth and the Moon will probably be slightly diminished. Nevertheless, the following general results are expected:

1. The combined effects of reduced gravity and reduced atmospheric pressure will probably enhance mobility performance on Mars (compared to mobility performance on Earth).

2. Increased rover velocity will probably improve overall mobility performance.
Measures of Mobility Performance

Testing in Reduced Gravity

This first expected result as stated above alleviates the need to test in simulated reduced gravity. A rover that demonstrates satisfactory mobility performance in Earth's gravity will most likely perform at least as well on Mars. This is beneficial in that reduced gravity testing methods (parabolic aircraft trajectories, balloon hangars, reduced gravity harnesses etc.) are expensive, complicated, and would likely complicate other data collection.

Traction

A thorough evaluation of various lunar rover wheel design concepts and tread covers was completed prior to the lunar rover program. (Costes, 9b). Studies included the effects of soil gradation, packing characteristics, strength, and deformability on the mobility performance of the wheels. Also accomplished were slope-climbing capability and energy-consumption rate versus wheel-slip tests (Costes, 17b).

One significant conclusion of this testing was that within the load range of 40 to 85 lbs, the pull force and torque due to the wheel-soil interaction increase linearly with increased wheel load (Costes, 28b). This load range is significantly higher than what any currently proposed micro rover will have. However, this result does support the notion that a useful measurement of traction can be obtained by normalizing a rover's tractive measurement by dividing a rover's forward (or backward) pull force by the rover's own mass.
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Traction is defined as follows:

\[ T_s = \text{Static Traction} = \text{Specific Static Pull Force} \]
\[ T_d = \text{Dynamic Traction} = \text{Specific Dynamic Pull Force} \]

\[ T_s = \frac{P_{s_{\text{max}}}}{m} \]
\[ T_d = \frac{P_{d_{\text{max}}}}{m} \]

Where: \( P_s \) = Static Pull Force
\( P_d \) = Dynamic Pull Force
\( m \) = Mass

Static pull force is the maximum pull force obtained without any wheel slip. Dynamic pull force is defined as the maximum pull force obtained with wheel slip. Obviously the selection of Mars surface simulant is critical for the measurement of these parameters.

One method of measuring the pull force of a rover is to attach a force measurement scale to the rover and command the rover to move forward (drawbar pull). If this method is used, the location of the force scale attachment point on the rover is critical. Traction changes significantly between an attachment to the top or the bottom of the rover structure. A recommendation regarding attachment location is described in the proposed test plan (Chapter 9 -- see test MOB.1 notes)

If it does become feasible to test a rover in simulated reduced gravity (not a requirement, as discussed previously), the above relations can be compensated for varying gravitational effects. This is accomplished by
dividing the rover's traction in simulated Mars gravity by its traction in Earth's gravity. Nomenclature is developed as follows:

\[
\left( \frac{T_s}{T_s} \right)_{\text{gravity}} = \text{Static Traction Ratio}
\]

and

\[
\left( \frac{T_d}{T_d} \right)_{\text{gravity}} = \text{Dynamic Traction Ratio}
\]

The ratios of specific pull forces provide a meaningful measure for comparing differences in performance that may be experienced as a result of altered gravitational fields.

As an alternate means for comparing rover tractive measurements, a normalization factor defined as the rover dimension was developed for this research. A simple dimension was sought which combined critical rover characteristics into a meaningful normalizing dimension based on current design constraint priorities. Currently, the primary rover physical design constraints are size (which is approximated for our purposes by the rover's enclosed volume in its stowed position) and weight. These are given calculation weightings of 1/3 and 2/3 respectively. Calculation weightings are selected to match mission priorities.

Applying this to the previously developed relationships gives:

\[
T_s = \frac{P_{s_{\text{max}}}}{R} \quad \text{and} \quad T_d = \frac{P_{d_{\text{max}}}}{R}
\]
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Where:

\[ R = \text{Rover Dimension} = \frac{2}{3} \sqrt[3]{\text{Volume}} \times \frac{1}{3} \text{Weight} \]

This provides an alternate means for defining traction which, depending on mission constraints, may be more applicable.

Turning Radius

A simple, yet relevant mobility performance parameter is turning radius. For some rovers, turning radius can be detrimentally affected by a rover's control algorithm due to dynamic and control restrictions in effect when a rover is moving. In such cases, it would be valuable to also measure a rover's dynamic (i.e., while moving/maneuvering) turning radius. The test plan in Chapter 9 proposes a test profile for a maneuvering turning radius test (see test MOB.2).

If it becomes feasible to test a rover for performance in simulated reduced gravity, turning radius performance can also be compensated for varying gravitational effects. This is accomplished by dividing the rover's turning radius in simulated Mars gravity by its turning radius in Earth's gravity to arrive at a useful comparative measure.

Tipping and Slipping

Another aspect relating to a rover's mobility performance is its resistance to tipping and/or slipping. This can be measured directly by determining the minimum angle at which a rover tips over (in each direction). Measurements
can also be made regarding the rover's propensity to slip down slopes of Mars simulant (minimum slip angles).

Other useful and descriptive measures are provided from hazardous obstacle/terrain testing (in conjunction with hazardous terrain navigation testing) discussed later. This testing combines a rover's mobility and navigational performance to measure the overall system hazardous terrain survival performance (which includes tip and slip resistance).

Slopes

Another important performance metric is a rover's ability to climb slopes. Increased propulsive force required to climb a slope is combined with a reduced component of gravitational force normal to the surface, which reduces rover traction. The maximum slope climb angle thus gives an indication of both propulsive pull force and traction. The maximum slope climb angle is denoted as:

$$\alpha_{\text{max}} = \text{Maximum Slope Climb Angle}$$

The degree of slip a wheel (or other propulsion mechanism) experiences while climbing a given slope provides an indication of climbing efficiency. Wheel slippage is defined as follows:

$$S = \% \text{ Slippage} = \left\{ \frac{\left[ 2\pi r (\text{rev}) - x_a \right]}{x_a} \right\} \ast 100$$
Chapter 4: Mobility

Where:

\[(S)_\alpha = \text{Slippage}(f(\alpha))\]

And:

\[\alpha = \text{Slope Angle}\]
\[\text{rev} = \text{Number of Wheel Revolutions}\]
\[r = \text{Wheel Radius}\]
\[x_a = \text{Actual Distance Traveled (Distance Tracked)}\]

Obstacles

Random obstacles are another important mobility consideration. Although an autonomous rover should be able to circumnavigate large obstacles, there are many smaller ones that it should be able to surmount. "Small" obstacles are defined to be those obstacles which a rover's nominal design would specify as being surmountable in ordinary circumstances. The larger the "small" obstacles which a rover can climb, the easier its task of navigation. This also holds true for obstacles that are on a slope.

Thus, two separate measures of obstacle mobility are the largest surmountable obstacles, and the largest surmountable obstacles on a slope (maximum obstacle size as \(f(\text{slope angle})\)). We can measure the size of a rover's largest surmountable obstacle by testing its ability to climb successively larger obstacles on both level surfaces and on varying slopes.

Obviously, the shape of the obstacles used for performance measurement will greatly influence test results. The following is suggested as a simple, but effective obstacle shape to use for measuring rover obstacle-climbing.
Chapter 4: Mobility

performance. The utility of this shape is based on preliminary results of rover model mobility testing.

Figure 4-1. Nominal Obstacle Shape for Rover Testing

In order to assist in describing and defining obstacles and hazards, an obstacle/hazard characteristic dimension, \( \lambda \), is defined. For each obstacle or hazard under consideration, a single dimension or parameter was sought which would define the fundamental challenging characteristic of that obstacle or hazard with respect to rover performance. For example, the characteristic dimension of a cliff is defined simply as the height of a cliff. All other descriptive cliff parameters (approach angle to cliff lip, approach slope to cliff lip, drop off angle at cliff bottom, etc.) are fixed at nominal values so that only a single parameter need be varied for rover performance measurement and testing.

The characteristic dimensions of obstacles and hazards are defined as follows:

\[
\begin{align*}
\lambda_{\text{obs}} & = \text{Characteristic Dimension of Obstacle} = \text{Obstacle Size} \\
\lambda_{\text{obs max}} & = \text{Size of Largest Surmountable Obstacle (Vertical Height)} \\
\lambda_{\text{obs max } \alpha} & = \text{Size of Largest Surmountable Obstacle On Slope (} f(\alpha) \text{)}
\end{align*}
\]
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Specifically:

\[ \lambda_{\text{Cliff}} = \text{Cliff Height} \]

\[ \lambda_{\text{Crevise}} = \text{Crevise Width (Assume Infinite Depth)} \]

\[ \lambda_{\text{Step}} = \text{Step Height} \]

\[ \lambda_{\text{Spike}} = \text{Spike Height} \]

\[ \lambda_{\text{Ramp}_{\text{ctr}}} = \frac{\text{Ramp Height}_{\text{ctr}}}{\text{Rover Width}} \]

\[ \lambda_{\text{Ramp}_{\text{side}}} = \frac{\text{Ramp Height}_{\text{side}}}{\text{Rover Width}} \]

In all cases, the above are defined assuming:

- the rover is positioned so as to initially negotiate each hazard/obstacle perpendicular to each hazard/obstacle
- All cliffs, crevices, and steps are 90° angles

It is recommended that all obstacles/hazards be constructed of flat rock surfaces to better simulate the friction coefficients anticipated of obstacles/hazards on Mars.

The above mentioned hazardous obstacles together will measure all the mobility failure modes discussed previously. Figure 4-2 illustrates the various hazardous obstacles/terrain features.
Energy Consumption

Increased energy consumption while climbing obstacles (and to a lesser extent, while climbing slopes) is an important consideration. Climbing over...
obstacles can impose extraordinary force and torque loadings on the wheels (or legs) of a rover, which can increase energy consumption by an order of magnitude. A rover's mobility design must not only trade off obstacle-climbing prowess with mechanical design constraints, but it must incorporate increased energy consumption considerations. For example, from the perspective of energy consumption, a rover might be much better off navigating around rather than negotiating a challenging obstacle.

Developing a meaningful measure of a rover's energy consumption performance has proved challenging. Simply measuring a rover's total energy consumption for a given task is not very relevant; such a measure does not account for rovers of varying size and mass. The next logical step would be to divide the total energy consumption by the rover's mass. This does provide a somewhat useful measure of a rover's energy consumption efficiency. However, it does not account for the large variance in available energy sources.

The measure of energy consumption that has been selected is Percent Energy Consumption, \( E \), defined as:

\[
E \equiv \% \text{ Energy Consumption} = \left( \frac{\text{Energy Expended}}{\text{Total Available Energy}} \right) \times 100
\]
Chapter 4: Mobility

Where Total Available Energy is the total energy available for the rover’s required primary mission. For example, a rover planned to conduct primary surface operations on Mars for one week may have the following energy available:

\[ \text{solar energy } f(\text{exposure time during day, time of year (probable irradiance), solar panel area, solar cell collection efficiency, etc.) x 7 days}] 

+ [total stored (non rechargeable) battery energy]

All the above parameters are readily obtainable.

Percent Energy Consumption has the benefit of a systems-level evaluation of the total energy efficiency of the rover system in relation to its fulfillment of systems-level requirements (i.e. mission requirements). It can be applied to different rover tasks to provide a comparison of energy consumption performance between rovers. The following are defined:

\[ E_{\text{Slope}_\alpha} = \text{Slope Climbing Energy Consumption } (f(\alpha)) \]

\[ E_{\text{Obs}_\lambda} = \text{Obstacle Climbing Energy Consumption } (f(\lambda)) \]

Testing for the first of these can be accomplished by establishing a fixed distance and slope angle(s) and comparing the results between rovers. Testing for the second can be accomplished by establishing a fixed number of obstacles to be climbed, obstacle size, and total traverse distance.

Similar measures of energy consumption were developed for other major performance areas (navigation, scientific support, autonomy, and environmental stress resistance) and are discussed in subsequent chapters.
Summary of Mobility Requirements and Performance Metrics

A rover must be able to traverse Martian terrain ranging from benign, level, unobstructed terrain, to complex terrain with slopes, obstacles, and hazardous features. To accomplish this, a rover must demonstrate: propulsion, traction, turning performance, climbing capability (slopes and obstacles), resistance to tipping and slipping, resistance to hazardous terrain, and energy consumption efficiency.

Following is a summary table of mobility test requirements, required capabilities, and accompanying test references.

<table>
<thead>
<tr>
<th>Requirement Description</th>
<th>Capabilities Tested</th>
<th>Test Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traverse unobstructed, level terrain</td>
<td>Forward/Backward Pull Force Traction Turning Radius Maneuvering Turning Radius (opt) Mobile Operation in Reduced g (opt)</td>
<td>MOB.1, MOB.2, MOB.1, 2</td>
</tr>
<tr>
<td>Traverse unobstructed, sloping terrain</td>
<td>Tipover Angles Slope Slip Angles Slope Climb/Descent Capab. Slope Climb. Energy Consumption</td>
<td>MOB.3, MOB.4, MOB.4</td>
</tr>
<tr>
<td>Surmount small obstacles and benign terrain features</td>
<td>Largest Surmountable Obstacle Largest Surmt. Obs. on Slope Obs. Climbing Energy Consumtion</td>
<td>MOB.5, MOB.5, MOB.5</td>
</tr>
<tr>
<td>Surmount hazardous obstacles and traverse hazardous terrain</td>
<td>Largest Survivable Hazardous Obstacles/Terrain</td>
<td>MOB.6</td>
</tr>
</tbody>
</table>
CHAPTER 5
NAVIGATION AND CONTROL

Introduction

A rover must be capable of navigating through Martian terrain. A rover's navigation and control subsystem uses sensor, tracking, and other inputs along with computational capabilities and control logic to avoid obstacles and hazards, traverse challenging terrain, and efficiently arrive at a designated location.

There are many possible strategies for achieving navigational capability. Most involve a collection of sensors and accompanying software to interpret sensor return signals and command a navigational path. Most strategies also involve navigational instruments such as gyros and accelerometers to assist the rover in navigation.

Navigation and Control Requirements

Requirement #3 as described in Chapter 1 states that a rover must be able to navigate to specified locations on Mars terrain. Based upon this fundamental requirement, more specific navigation and control requirements were generated and are presented in a build-up fashion. These are similar in nature and methodology to the mobility build-up requirements described in Chapter 4.
Chapter 5: Navigation and Control

Following is the list of fundamental navigation and control performance requirements as developed for performance measurement and testing purposes:

1. Navigate from point A to point B on level terrain with no obstacles
2. Navigate from point A to point B on level terrain with hazardous (insurmountable) obstacles
3. Navigate from point A to point B on hazardous terrain with no obstacles
4. Navigate from point A to point B on hazardous terrain with hazardous obstacles.

Measures of Navigational Performance

Central Processing Unit (CPU) Capabilities

A fundamental component of a rover's navigation and control subsystem is its CPU. A rover CPU should:

- use proven technology
- be space qualified/hardened
- have adequate computation and data storage capability for supporting science and technology experiments. Data storage estimates will probably be driven by video image storage requirements, which are on the order of 0.5 MBytes total data storage per image (including support code and compression software margin).
- be as small and as lightweight (including support circuitry) as possible.
- use minimum power
Sensor Specifications and Capabilities

Rover sensors should:

- Use proven technology
- Be space qualified and resistant to Martian environmental effects
- Be simple with the fewest components possible
- Be as small and as lightweight as possible
- Use minimum power

Obstacle Avoidance

No rover has perfect mobility. For any given design, there exists obstacles or collections of obstacles which are considered insurmountable. In these instances, a rover must be able to travel around or through these terrain features in order to arrive at a designated location. In so doing, a rover must also avoid limit cycles (infinite loops in control logic) or other debilitating or dead end situations.

Simulations of basic micro rover control logic strategies have shown that it is relatively easy to design software which will enable a rover to navigate around objects which are on the order of the rover's own size; obstacles larger than the rover, however, are more challenging. Clusters of small obstacles will often be perceived or deliberately interpreted as a single large obstacle. When the obstacle, or cluster of obstacles, extends in a direction beyond the range of the rover's navigational sensor field of view, navigational difficulty greatly increases.

In conjunction with the inherent difficulty of navigating around large obstacles is the problem of deciding whether the rover is capable of
maneuvering through a gap between two obstacles. This problem requires significant rover self-knowledge regarding its own position, turn radius, obstacle approach angle, etc.

Computer generated random obstacle fields composed of one foot diameter circular obstacles distributed throughout a 100 foot x 200 foot field at concentrations ranging from 4% to 10% were analyzed for this research. Results showed that obstacle combinations and formations generally reduce to walls, dead ends, gaps, or combinations of these. This is especially true regarding how a rover's control logic must respond to these environments.

Simulations of MITy series control logic strategies have shown that dead ends (or, alternately, large, concave obstacles) and walls with rover-sized gaps in them are two of the most difficult scenarios for a rover to negotiate (Malafeew). Both of these scenarios commonly result in a navigation failure (inability to reach the designated location) or a limit cycle.

Computer simulations are valuable for analyzing a rover's obstacle avoidance control logic. Numerous simulations can be run vs. obstacles of different sizes and shapes, providing better statistical representations and better indications of problem areas in control logic strategies. If a rover control scheme has problems in a simulation, its performance in a real-world situation can only be worse. Three dimensional simulations are instrumental in predicting and analyzing mobility and navigation performance in a three dimensional field. However, the existence of three
dimensional simulations (other than for MITy-series rovers) is not anticipated due to the inherent programming complexity involved.

The terrain slope and undulation magnitude and frequency will also effect a rover's navigation performance. The performance of most navigation sensors on current micro rovers is dependent upon rover inclination. Detection and avoidance of obstacles is inherently more difficult when the plane of a rover's sensors continually changes due to terrain undulations. Based on astronaut experience with the lunar rover, it is suspected that terrain with rover-sized undulations will probably be the most difficult type of terrain over which a rover will have to navigate (Jack Schmidt, 1).

**Hazard Avoidance**

A rover's control architecture also must be able to detect and avoid hazardous terrain which would result in any of the failure modes previously discussed in Chapter 4 (i.e., vertical drop, overturn, obstacle block, and loss of wheel traction)

If a rover is unable to surmount a hazardous obstacle or terrain feature (as determined from Mobility Testing), its control system must be able to alert it to the hazard and initiate avoidance actions. For example, if a rover is not able to successfully traverse over a cliff higher than six inches, then it must have the ability to detect its approach to a cliff which is higher than six inches. If it does not, the rover has a mobility/navigation performance gap (discontinuity) which will eventually result in mobility failures.
Chapter 5: Navigation and Control

Conversely, a rover may also have a mobility/navigation performance overlap. For example, if a rover is able to traverse safely over a one foot cliff, yet it senses and avoids all cliffs which are six inches or greater, there is a mobility/navigation performance overlap. A large overlap will detrimentally affect a rover's performance and could even result in unnecessary paralyzation. Terrain which is challenging, yet traversable, could cause a rover to continually avoid obstacles and features such that it makes no forward progress.

Thus, analysis of the results from hazardous terrain avoidance and hazardous terrain mobility testing must be made carefully. The same mobility classification system and nomenclature for hazards can be adopted for navigation and control testing:

\[ \lambda_{obs} = \text{Characteristic Dimension of Obstacle} = \text{Obstacle Size} \]
\[ \lambda_{obs\text{max}} = \text{Size of Largest Surmountable Obstacle (Vertical Height)} \]

Specifically:

- \[ \lambda_{\text{Cliff}} = \text{Cliff Height} \]
- \[ \lambda_{\text{Crevice}} = \text{Crevice Width (Assume Infinite Depth)} \]
- \[ \lambda_{\text{Step}} = \text{Step Height} \]
- \[ \lambda_{\text{Spike}} = \text{Spike Height} \]

\[ \lambda_{\text{Ramp}_{\text{Ctr}}} = \frac{\text{Ramp Height}_{\text{ctr}}}{\text{Rover Width}} \]

\[ \lambda_{\text{Ramp}_{\text{Side}}} = \frac{\text{Ramp Height}_{\text{side}}}{\text{Rover Width}} \]
It is imperative that \( \lambda_{\text{obs}_{\text{max}}} \) = Size of Largest Surmountable Obstacle obtained during mobility testing be compared with the minimum \( \lambda \) navigation detection values to determine mobility/navigation performance gaps and overlaps. Ideally, the two values should be the same, and there should be no gaps or overlaps. However, because these are unavoidable, it is better to have overlaps than gaps (overlaps only diminish performance, while gaps result in mobility failures).

**Speed (Time)**

The speed of semi-autonomous rovers is often not limited by the speed at which the motors can propel the structure; it is often more dependent upon the rover's sensing and path-planning computation speed and efficiency. The time required for a rover to traverse from point A to B is indicative of its overall intelligence and ability to process sensor data. It also gives an indication of how well design trade-offs were made between sensor sampling rates and navigation computation.

Speed also permits increased mission flexibility. The quicker a rover traverses to a given location, the more time is available for accomplishing science and technology experiments or other mission taskings. Greater overall distances can be explored. More challenging mission scenarios can be attempted. Significant speed performance also gives mission planners the flexibility to reaccomplish traverses or experiments with minimal impact on the overall mission.
Chapter 5: Navigation and Control

Location/Heading/Inclination/Tilt Knowledge

It is essential for a rover to have very accurate self-knowledge. From a navigation and control standpoint, it is better to arrive inaccurately at a destination, and be cognizant of the inaccuracy, than to stop very close to the designated destination, with no knowledge of the destination accuracy.

A rover's destination arrival accuracy is affected by two sources. By far the most significant, is the rover's own navigation errors. Most navigation schemes incorporate relatively inaccurate tracking information dependent upon the wheel-soil interactions of the rover and the terrain for navigation computation. The rover's instruments also inherently add sources of error. The second source of error derives from a rover's control logic and the physical limitations of being able to traverse to a commanded location; a rover's navigation feedback loop must have programmer-established accuracy and stability limitations.

For an example of the second source of error, consider a rover which navigates through an obstacle field, and is able to come very close to the target destination. However, assume that due to obstacle avoidance maneuvering, it arrives at the destination, but is (cognizantly) one inch to the right of where it was commanded to stop. An inefficient control logic will command the rover to expend unnecessary energy backing up and trying to arrive at the target destination exactly (which might be an impossibility). This navigation control could lock in an infinite feedback loop.
Chapter 5: Navigation and Control

However, a rover need only stop "sufficiently close" to the target to accomplish the given traverse objectives. Destination arrival precision and accuracy knowledge directly affects a rover's ability to arrive "sufficiently close". For some proposed experiments (e.g., APX-S, and visual imagery) the rover must know its pointing direction, inclination, and tilt within a few degrees.

Self-knowledge, if integrated properly into control code, can also assist the rover in detecting hazardous terrain and avoiding failure modes. Often when traversing hazardous terrain, the rover will be oriented at an unusual angle to the terrain directly in front of the rover. As a result, primary navigation sensors perceive the forward terrain at an abnormal angle. Inclinometer and tilt sensor information must be integrated into the control code to enable an accurate terrain representation when this occurs.

Inclinometer information can also be integrated to correct for small differences in required travel distance due to travel on a slope (proportional to $\sqrt{\tan(slope)}$). A rover's vertical position (z-axis) can thus be tracked.

Distance

Distance traveled while traversing from Point A to B is an indication of the intelligence and efficiency of the control logic and the capabilities of the sensor subsystems. In general, the better the range and resolution of the sensors, the better potential efficiency of the planned path. Distance traveled directly affects energy consumption. Obviously, the shortest path between two points is the desired one. However, the shortest path between
two points is not necessarily the most efficient one if obstacles are encountered.

Rovers must incorporate reactive strategies using sensors such as "bumpers", "feelers" or proximity sensors to respond immediately to hazard information which was not perceived by the primary navigation subsystem. Upon reception of the new and usually overriding information, most rovers will "react" by backing up or otherwise attempting to negotiate an obstacle or obstacle formation in a different manner. In a complex field, "reactions" can account for the majority of total distance traveled by a rover. A rover must incorporate efficient reaction strategies which will minimize the total distance traveled while traversing from point A to point B.

Performance metrics have been developed for this research which combine several of the previously mentioned navigation performance considerations into the overall performance categories of Navigation Accuracy, and Traverse Distance Efficiency. Specific metrics within these categories are:

- Heading angle error. This gives an indication of a rover's directional knowledge and control performance
- Tracking distance error (the difference between how far a rover traverses, and how far it thinks it has traversed). This measures a rover's translational knowledge and control performance
- Total distance error (total distance between stopping location and designated target). This provides a measure of overall accuracy of the rover's navigation performance.
Chapter 5: Navigation and Control

- Actual distance traveled. Provides in indication of how efficiently a rover's control logic operates when compared to the minimum path distance a rover could have traversed (minimum expected path length is defined as the minimum distance a rover would have to traverse to arrive at the target destination given perfect knowledge about all obstacles and terrain features -- see test NAV.1 notes)

Specifically, these metrics are defined as follows:

\[ A_{\text{Nav}} = \text{Navigation Accuracy} \left( f(e_\beta, e_{x_a}, e_{x_{\text{tot}}}) \right) \]

\[ \eta_{x_{\text{tot}}} = \text{Traverse Distance Efficiency} f \left( x_{\text{MEPL}}, x_a, e_{x_a} \right) \]

Where:

\[ e_\beta = \text{Heading Angle Error} = \arcsin \left( \frac{x_y}{(x_{\text{MEPL}} + x_x)} \right) \]

\[ e_{x_a} = \% \text{Tracking Distance Error} = \left( \frac{x_a - x_{\text{MEPL}}}{x_{\text{MEPL}}} \right) \times 100 \]

\[ e_{x_{\text{tot}}} = \% \text{Total Distance Error} = \left( \frac{\sqrt{(x_x)^2 + (x_y)^2}}{x_{\text{MEPL}}} \right) \times 100 \]

\[ \eta_{x_{\text{tot}}} = \text{Traverse Distance Efficiency} = \frac{x_{\text{MEPL}}}{x_a + \left( \frac{e_{x_a} \times x_{\text{MEPL}}}{100} \right)} \]
And:

\[ e_\beta = \text{Heading Angle Error} \]
\[ e_{x_a} = \% \text{Tracking Distance Error} \]
\[ e_{x_{tot}} = \% \text{Total Distance Error} \]
\[ \beta = \text{Heading Angle} \]
\[ x_x = \text{Longitudinal Distance From Target (in } x \text{ direction)} \]
\[ x_y = \text{Lateral Distance From Target (in } y \text{ direction)} \]
\[ x_a = \text{Actual Distance Traveled (Distance Tracked)} \]
\[ x_{MEPL} = \text{Minimum Expected Path Length} \]

**Energy Consumption**

Energy consumption measures how well a rover can minimize energy use while accomplishing all of the individual tasks associated with traversing from point A to point B (sensor sampling, computation, motor actuation, etc.). Energy consumption and power efficiency are very dependent upon the efficiency of the control logic. An "efficient" control logic will navigate the rover to Point B using the shortest path, requiring the fewest sensor samples and commanding the fewest and shallowest steering changes. Energy consumed during navigation is thus an important indicator of the effectiveness of systems design choices.

A metric similar to previously discussed mobility energy efficiency metrics is defined as follows:

\[ E_{NavField} = \text{Navigation Energy Consumption } f(\text{Obstacle Field}) \]
Chapter 5: Navigation and Control

Where:

\[ E = \% \text{Energy Consumption} = \left( \frac{\text{Energy Expended}}{\text{Total Available Energy}} \right) \times 100 \]

and Total Available Energy is the total energy available for the rover's required primary mission (see explanation in Chapter 4 -- Mobility).

This measures the systems-level energy efficiency performance of a rover as a function of the obstacle field chosen. This value can be compared directly between rovers for given obstacle fields and target destination locations.

Safety

Navigation safety, as discussed in this document, refers to the rover's ability to refuse negotiation of an insurmountable obstacle and thereby avoid a dangerous situation. Gentle contact with an obstacle (by either a feeler or the rover itself) should not necessarily be considered a navigation safety failure. However, trying to drive through or over an insurmountable obstacle is a failure. Control logic should incorporate allowances for safety (distance) margins when passing obstacles. Measurements include the number of safety failures as well as the closest passing distances to obstacles while navigating.

Summary of Navigation and Control Requirements and Performance Metrics

A rover must navigate from point A to point B on all combinations of level and hazardous terrain, with and without obstacles. To accomplish this, a
rover must demonstrate dead-reckoning (navigation) capability, obstacle avoidance capability, and hazardous terrain survival. It should also minimize traverse distance, travel time, and energy consumption.

The above mentioned requirements with their corresponding required capabilities are summarized in table 5-1.

**Table 5-1. Navigation and Control Requirements, Required Capabilities, and Test References**

<table>
<thead>
<tr>
<th>Requirement Description</th>
<th>Capabilities Tested/Demonstrated/Inspected</th>
<th>Test Reference</th>
</tr>
</thead>
</table>
| Navigate from point A to point B on level terrain with no obstacles | **Tested:**
|                                                            | Nav. Accuracy and Reliability            | NAV.1, 2                  |
|                                                            | Navigation Speed                         | NAV.1                     |
|                                                            | Navigation Energy Consumptn.              | NAV.1, 2                  |
|                                                            | Location & Hdg. Knowledge                | NAV.1, 2                  |
|                                                            | **Inspected:**                           |                           |
|                                                            | CPU Specs and Capabilities               | NAV.1                     |
|                                                            | Sensor Specs and Capabilities            | NAV.1                     |
| Navigate from point A to point B on level terrain with hazardous obstacles | **Tested:**
|                                                            | Traverse Distance Efficiency             | NAV.2                     |
|                                                            | Traverse Time                            | NAV.2                     |
|                                                            | **Demonstrated:**                        |                           |
|                                                            | Obstacle Avoidance Capability            | NAV.2                     |
|                                                            | Navigation Safety                        | NAV.2                     |
| Navigate from point A to point B on hazardous terrain with no obstacles | **Demonstrated:**
|                                                            | Hazardous Terrain Survival               | NAV.3                     |
| Navigate from point A to point B on hazardous terrain with hazardous obstacles | **Tested:**
|                                                            | Integrated Navigational Capability       | NAV.4                     |
CHAPTER 6
SCIENTIFIC SUPPORT

Introduction

Fundamental to a rover's planetary exploration utility is its ability to support scientific interests. Various rover science and technology experiments are planned for the MESUR Pathfinder mission. These, however, are secondary in importance to the primary objective of conducting a general performance demonstration of a micro rover on Mars. Scientific data collection and experiment support will become more important on future MESUR missions.

Scientific Support Requirements

Requirement #4 as described in Chapter 1 states that a rover must be able to conduct and support science and technology experiments. This will require the following specific capabilities:

1. Carry/store experiments
2. Deploy experiments
3. Conduct experiments
4. Monitor experiments
5. Provide power for experiments
6. Collect and store experiment data
7. Process experiment data
8. Transmit experiment data (to the lander/Earth etc.)
9. Provide TBD other required support for experiments
Chapter 6: Scientific Support

Measures of Scientific Support Performance

Measuring the performance of a rover's scientific support capability is fundamentally dependent upon the specific mission and planned scientific requirements. For the purposes of this research, the current and most probable MESUR Pathfinder missions and requirements have been assembled to provide a basis for understanding the types of tasks and activities likely to be required on Mars.

MESUR Pathfinder Planned Landed Mission Scenario

Baseline Mission (current as of July, 1993)
Nominal landing sight: 15° N, 160° W on 4/7/97 at 01:40 GMT, 03:39 Local Solar Time (LST). Viking 1 terrain is considered nominal.

Primary mission: seven days in vicinity of lander (within lander camera range)

Secondary mission: extended range rover operations (including over-the-horizon relative to the lander) until rover performance termination. The goal is a 30-day extended mission.

Current Probable Micro Rover Science Experiments

1. Alpha Proton X-Ray Spectrometry (APX-S) experiment on a rock*
2. APX-S experiment on soil
3. Image the soil/rocks tested in the APX-S experiment
4. Neutron spectrometry experiments**
5. Image the lander
Chapter 6: Scientific Support

* The APX-S experiment instruments are still under development. This test will most likely require that the instrument be placed directly on the material to be examined, roughly perpendicular to the material. Thus, an instrument deployment mechanism on the rover will probably be required.

** The neutron spectrometer instruments are still under development. Frequent neutron spectrometry data readings will probably be possible with minimal impact on the rover's operations.

Current Probable Micro Rover Technology Experiments

Technology experiments are planned which provide information regarding: Mars terrain geometry and visual appearance, soil/rover mechanical interaction, environmental effects, and the vehicle (rover) system performance. They are as follows:

1. Terrain Geometry Reconstruction/Characterization From Lander/Rover Imagery

2. Basic Soil Mechanics (from rover wheel/soil interaction)

3. Dead Reckoning Sensor Performance and Path Reconstruction/Recovery

4. Sinkage in Each Soil Type

5. Logging/Trending of Vehicle Performance Data (collection of measurable engineering parameters -- drive torques, rpm, voltages, etc.)

6. Rover Thermal Characterization (rover temperatures as a function of time and operating situation)

7. Rover Vision Sensor Performance
Chapter 6: Scientific Support

8. UHF Link Effectiveness (as a function of distance from the lander and terrain occlusion)
9. Material Abrasion (measurement of tire wear)
10. Material Adherence (measurement of dust deposition on rover)

Experiment Support

A rover's performance at supporting experiments such as those described above can be observed by commanding the rover to perform the experiment under consideration. Pass/fail measures can be used to determine whether a rover is capable of performing a given experiment according to requirements dictated by a specific experiment. Scale gradations for performance measurement are possible (and desirable) when the specific requirements and parameters of an experiment are known.

Capabilities which will be important for many of the proposed experiments include:

- Experiment storage volume
- Power production capacity
- Data storage capacity
- Data processing capability
- Transmission capabilities

In general, a rover's scientific support capability can be measured during autonomy testing by commanding a rover to accomplish experiments during extended mission scenarios. This conforms with the philosophy and methodology developed for autonomy testing (see Chapter 7).
If it is desired to conduct separate tests for specific future experiments, a proposed test format is included in the test plan of Chapter 9 (see tests SCI.1 and SCI.2).

**Summary of Scientific Support Requirements and Performance Metrics**

A rover must provide all necessary support for the effective conduction of all science and technology experiments. To accomplish this, a rover must be able to: carry, deploy, conduct, monitor, and provide power for all mission experiments. It must also collect, store, process, and transmit all experiment data.

A summary of the scientific support test requirements, capabilities, and test references is provided in table 6-1.
### Table 6-1. Scientific Support Requirements, Required Capabilities, and Test References

<table>
<thead>
<tr>
<th>Requirement Description</th>
<th>Capabilities Demonstrated/Inspected</th>
<th>Test Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carry/Store experiments</td>
<td>Exper. Carrying/Storage Capab (Demonstrated/Inspected)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Deploy experiments</td>
<td>Experiment Deployment Capab (Demonstrated)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Conduct experiments</td>
<td>TBD Exper. Conduction Capab (Demonstrated/Inspected)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Monitor experiments</td>
<td>Experiment Monitoring Capab (Demonstrated/Inspected)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Provide power for experiments</td>
<td>Power Production Capability (Demonstrated/Inspected)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Collect and store experiment data</td>
<td>Processor Data Storage Capab (Demonstrated/Inspected)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Process experiment data</td>
<td>Data Processing Capability (Demonstrated/Inspected)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Transmit experiment data to Lander</td>
<td>Experiment Data Transmission Capab (Demonstrated/Inspected)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Provide TBD other required support for experiments</td>
<td>TBD Capabilities</td>
<td>SCI.1, 2</td>
</tr>
</tbody>
</table>
CHAPTER 7
AUTONOMY

Introduction

Motivation for Micro Rover Autonomy

The rover missions currently planned as part of the MESUR program will inherently require significant rover autonomy. The time delay for round-trip transmissions between Earth and Mars during the Pathfinder mission (July 1997) will be approximately 21 minutes. The increasing distance between Mars and Earth during the mission will have a minor effect on the communication link time (on the order of two to three minutes over the duration of the mission).

Mars and the Earth are within line-of-sight for transmission for approximately 10 hours each day. In addition, current plans limit the rover to daylight operation, reducing the functional Earth-Mars communications window to approximately 7 hours each day during the July 1997 timeframe (assuming rover operations occur near the Martian equator as planned).

The lander communication capabilities will also be severely limited; lander download will be on the order of 1 Kbps, greatly hindering the ability of Earth-based ground crews to receive timely rover-transmitted information. All information which is received will be thoroughly analyzed prior to deciding which new instructions and commands to send the rover. Exhaustive and, unfortunately, often time-consuming procedures will be
Chapter 7: Autonomy

employed to ensure the safe and proper compilation of commands for transmission. For all of these reasons, command cycles from Earth will most likely be limited to only once or twice per day, driving the need for significant rover autonomy.

Level of Autonomy

A planetary rover will have to accomplish numerous taskings using minimal instructional information. By definition, a completely autonomous rover would be capable of completing all mission taskings with no required input from Earth. Current technology and micro rover development accomplishments do not appear to support this as a possibility for the MESUR missions. All current micro rovers are at most considered semi-autonomous.

It is argued that the more autonomous a rover, the less control scientists have over a rover's functions, and the less desirous for a mission to Mars. However, some degree of autonomy is necessary to accomplish any rover mission on Mars, and autonomy can generally be compromised much more easily than it can be attained. Highly autonomous rovers can be equipped with the capability for Earth-commanded overrides and interactions to enable a high level of control as desired. In any case, the level of autonomy drives the level of rover task and mission flexibility.

NASA will probably desire a high degree of control of rover operations during the MESUR Pathfinder mission, thus a very high level of autonomy will probably not be required. However, the more autonomy a rover is able
to demonstrate, the greater the overall mission planning and commanding flexibility.

To maximize a rover's potential utility on Mars, it should be as self-sufficient and self-reliant as possible. This inherently requires real-time decisions based on information it gathers on itself and its surroundings.

"Never tell people how to do things. Tell them what to do and they will surprise you with their ingenuity."

General George S. Patton, Jr.

This axiom also holds true for autonomous rovers.

**Autonomy Requirements**

Requirement #5 as described in Chapter 1 states that a rover must be able to conduct all operations on Mars semi-autonomously. Specific autonomy requirements are as follows:

1. Conduct operations with minimum transmitted data and commands from Earth
2. Prioritize and schedule tasks and activities
3. Monitor and report health and performance
4. Respond to faults
5. Demonstrate command and control efficiency
Chapter 7: Autonomy

It can be argued that no "requirements," in the truest sense of the word, are dictated for testing autonomy. "Desired attributes" is perhaps a better term. The degree to which each is demonstrated is an indication of the overall level of autonomy. These desired attributes are listed and referred to as requirements throughout this thesis.

**Measures of Autonomous Performance**

**Navigation**

Navigational capabilities incorporating obstacle and hazard avoidance are a fundamental part of autonomy. Being able to tell a rover where to go without having to dictate every portion of the traverse is an enormous advantage to Earth-based planners. Often a rover's perception and interpretation of its immediate surroundings will be more accurate and navigationally more useful than that of the mission planner's on Earth, providing an obvious advantage to rover-based navigation. A rover's navigational capabilities are thus a good indication of its level of autonomy. The same navigation performance measure parameters that were developed for navigation and control testing can be used during autonomy testing.

**Prioritization and Scheduling**

The rover must be able to organize and prioritize commanded tasks according to known restrictions and limitations.

First, a rover should be able to take into account its own limitations, such as: mobility restrictions, power budget restrictions (at different times of
Chapter 7: Autonomy

day, and during different tasks), and thermal restrictions (Martian sol
thermal cycling). Prioritization should occur on both a tactical level and a
strategic level. For example, on a tactical level, a rover must know that
retreating from a detected vertical drop-off is more important than making
progress toward a commanded destination location. On a strategic level, a
rover should not attempt to complete a 10 hour APX-S experiment when it
knows its own power supply is dangerously low.

Second, a rover should also take into account mission and lander
restrictions such as: command cycle timing restrictions, lander data
download capability restrictions, specific experiment parameter
restrictions (temperature, tilt/inclination requirements, etc.), or any other
such restrictions specific to planned missions and taskings. For example,
a rover should not initiate an APX-S experiment if it knows that the APX-S
instrument is not in contact with and at the correct contact angle to the rock
to be inspected.

To assist in assessing a rover's prioritization and scheduling performance,
a review can be accomplished of how a rover conducts operations with
regard to its own limitations and mission restrictions. Measurement of a
rover's task prioritization and scheduling performance is discussed in the
test plan of Chapter 9 (see test AUT.1).

Health Monitoring

The rover must have the ability to monitor and report on the operation and
performance of each of its subsystems. This is important for two reasons.
First, Earth-based mission planners will want to know the status and
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performance of the rover in detail; a primary objective of the MESUR Pathfinder mission is to evaluate the utility of a micro rover on Mars. Second, a highly autonomous rover will be able to use the information it collects to trouble-shoot failures or to complement its own performance.

Periodic transmissions to Earth should include the status of each rover subsystem, as well as the rover's location and position (inclination, tilt, etc.), temperature readings of components, mechanical component positions and inclinations, actuator voltage and current peaks, etc. In addition, a rover should also collect and report on its own navigation and control performance. Included in this would be information regarding the detection of navigation failures (traps and limit cycles) or any other unusual or unanticipated navigation performance. For example, a rover should detect and respond (perhaps with a warning indication) when a tachometer indicates forward progress, and the accelerometers indicate backward progress (e.g. sliding backwards down a slope).

Finally, certain information a rover collects can be integrated directly into control logic to allow for improved performance. For example, information regarding a rover's inclination to the horizon is critical for interpreting the distance measured by proximity sensors or other navigation sensors. Such integration is addressed in Chapter 5, Navigation and Control.

Measurement of a rover's health monitoring performance is discussed in the test plan of Chapter 9 (see test AUT.1)
Fault Response

A measure of a rover's autonomy includes its degree of fault tolerance or its ability to initiate contingency actions when faults or poor performance is detected. For example, most rovers have navigation feedback loops which will frequently respond to perceived tracking errors by initiating steering corrections. Thus, the crabbing effect caused by a failed motor could naturally be corrected within the rover's own navigation feedback loop. This response would indicate a rover which is fault tolerant for a drive motor failure.

An example of a rover instituting contingency plans occurs when a rover detects a mobility failure such as blockage of forward progress by a large obstacle. Most rovers will automatically respond by backing up and initiating renegotiation algorithms. The successful performance of such actions is a measure of a rover's autonomy.

No rover will be able to adequately respond to every possible (or even probable) failure. However, Earth-based operators should be able to use a rover's transmitted health data to command proper fault responses when necessary. Each rover design should be carefully examined to determine potential faults and accompanying fault contingency plans. Areas which should incorporate fault-tolerance or contingency plans include:

- Basic Mechanical Failures:
  - Motor/Actuator Failures (drive, steering, panning, deployment, etc.)
  - Mechanism Failures (structural or other moving parts)
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- Basic Electrical/Electronic Failures:
  - Navigation Sensor Failures (for each sensor)
  - Camera Failure
  - Communication Failure (both rover and lander failures)
  - Guidance/Navigation Instrument Failure (for each instrument)
  - Thermal Subsystem Failure (heaters and/or insulation failures)
  - Solar Panel Failure
  - Battery/Power Supply Failure
  - Payload Experiment Failure
  - Failure of Any Other Electrical/Electronic Component

- Software Failures (limit cycles, etc.)

- Earth Command/Instruction Failures (As discussed previously, erroneous instructions to perform improper or hazardous tasks should be taken into account in a rover's prioritization and planning algorithms).

Another important consideration for mission flexibility and rover control is the incorporation of control code which will allow rover operations to be overridden by commands from Earth. Not all hazardous, difficult, or complex circumstances can be anticipated. When a rover is not able to adequately perceive its environment and situation, and begins a response which is inappropriate or hazardous, allowance should be made for very specific Earth-based override commands. Also, recommand of a rover up to and including a complete download of control software from Earth should be made possible.

Energy Consumption

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A systems-level measure of energy efficiency performance can be obtained by measuring the percent energy consumption of a rover when it accomplishes an extended mission scenario.

\[ E_{\text{Auto}_{\text{Scenario}}} = \text{Autonomous Energy Consumption} (f(\text{Scenario})) \]

Where:

\[ E = \% \text{ Energy Consumption} = \left( \frac{\text{Energy Expended}}{\text{Total Available Energy}} \right) \times 100 \]

and Total Available Energy is the total energy available for the rover's required primary mission (see explanation in Chapter 4 -- Mobility).

This value can be compared directly between rovers for given extended mission scenarios and simulated Mars terrains.

Required Transmissions

One measure of a rover's level of autonomy is the required number of bits per transmission cycle from Earth to accomplish a given day's mission taskings. A rover will most likely need to receive traverse destination data and experiment and task commands and priorities. These can be accomplished with high level commands to minimize transmission requirements to the rover from Earth. However, the rover may likely require large amounts of other information such as hazard information, position/navigation update data, error recovery commands, communication/data transmission specifications, or other miscellaneous information as needed.
Thus, plans for transmission of such secondary mission information is as important, if not more important, than plans for primary command transmissions. Performance in this area can be facilitated by a review of plans (listing and time schedule) for transmissions.

**Required Human Interaction**

The strategy by which data from the rover is analyzed, interpreted, and used to decide future rover actions is critical. Some current rover designs incorporate the use of three-dimensional helmets for video image interpretations and way-point designations for rover traverses. Such support equipment can feasibly be more complex and expensive than the rover itself. Perhaps the best way to measure the effectiveness of the human interaction/Earth-based command strategy is simply through complete testing in simulated Martian terrain using realistic, extended-duration mission scenario taskings. The number of manhours required to command and control the rover throughout the scenarios can also be measured. Such testing would also be fundamental to highlighting inefficient or impractical rover control strategies.

A complement to information acquired through complete scenario testing is a review of the human interactions required to guide the rover. This review covers the content and estimated number of bits of required data.commands transmitted from Earth for commanding a rover for a given typical day of rover mission taskings. The required data.commands include: destination data, hazard information (as required), experiment/task commands, and instructions, position/navigation update
data (as required), and error recovery commands (if required during scenarios).

Finally, one other measure of required human interaction is the number of manhours required to command and control the rover for a typical rover day. This would include the total time to review and analyze data, decide rover taskings, translate and transmit commands, and monitor the rover.

**Summary of Autonomy Requirements and Performance Metrics**

Autonomy test requirements are based on the incorporation of complete test scenarios on simulated Martian terrain for extended periods (i.e. several days). Such testing provides an indication of a rover's level of autonomy, as well as an excellent indication of overall system performance.

A rover should be able to safely, efficiently, and reliably conduct all required operations on Mars with minimal Earth-based interaction. To accomplish this, a rover must demonstrate: minimal transmission requirements, task prioritization, self-monitoring capabilities, fault tolerance, and command and control efficiency.

A summary of desired autonomy attributes is provided in Table 7-1.
Table 7-1. Autonomy Test Requirements, Required Capabilities, and Test References

<table>
<thead>
<tr>
<th>Requirement Description</th>
<th>Capabilities Tested/Demonstrated/Inspected</th>
<th>Test Reference</th>
</tr>
</thead>
</table>
| Conduct operations with minimum transmitted data and commands from Earth | Overall Autonomous Performance  
Required Transmissions for Given Typical Rover Day (Tested/Inspected) | AUT.1 |
| Prioritize and schedule tasks and activities | Task Prioritization and Scheduling (Demonstrated/Inspected) | AUT.1 |
| Monitor and report health and performance | Health and Performance Monitoring and Reporting (Demonstrated/Inspected) | AUT.1 |
| Respond to Faults | Fault Response (Demonstrated/Inspected) | AUT.2 |
| Demonstrate Command and Control Efficiency | Efficiency of Interactions Required to Guide Rover (Tested/Inspected) | AUT.1 |
CHAPTER 8
ENVIRONMENTAL STRESS RESISTANCE

Introduction

Environmental stress testing provides a measure of design quality and flight acceptability. Qualification of rovers used for the MESUR missions will probably be accomplished with protoflight testing. In general, protoflight testing is less demanding than qualification testing, but more demanding than acceptance testing. An overall cost savings while still accomplishing adequate flight acceptability testing is the desired (though not always achieved) result.

Prior to complete systems testing, each component should be analyzed with respect to a predicted life cycle environmental exposure in accordance with a detailed mission profile. Design teams should highlight critical environmental stresses and small stress margins to ensure an adequate design. Test sequences should be in the order of environmental exposure during launch, cruise, entry, landing, and surface operations.

For the purposes of this research, a systems level environmental test plan is proposed based upon the primary environments to which a rover will be exposed: First, it must be able to survive the launch loads, vibrations, and shocks associated with launch; next it must survive 8 or 11 months (depending upon the Mars trajectory selected for the MESUR Pathfinder mission in 1996) in transit stowed in the lander; it must then survive Mars atmosphere entry and landing on the surface; finally, it must survive a 7
Environmental Stress Resistance Requirements

Requirement #1 as described in Chapter 1 states that a rover must be able to survive the environments (launch, transit, landing, and the Martian surface). Based upon this fundamental requirement, more specific environmental stress resistance requirements are generated. These requirements cover: sinusoidal vibration, random vibration, quasi-steady accelerations, pyrotechnic shock, pressure decay profile, electromagnetic interference and electromagnetic compatibility, vacuum, thermal cycles, thermal vacuum, radiation, internal charging, magnetic fields, and Mars entry and landing loads.

Specific values for these requirements as proposed by the Jet Propulsion Laboratory are listed at the end of this chapter and are not repeated here. Following are descriptions of the environments which drive the specific environmental resistance requirements.

The Launch Environment

The Delta II (7925)

The MESUR Pathfinder and MESUR Network current mission plans call for launching micro rover/lander spacecraft on Delta II 7925 launch vehicles. The Delta series of launch vehicles have been well known for their
reliability since the first Delta launched in 1960. The Delta II was developed as a medium launch vehicle class booster, and is used primarily as a geosynchronous transfer orbit or polar elliptical orbit launch vehicle. Delta II's are launched at a rate of approximately 10 per year from either Cape Canaveral or Vandenburg Air Force Base.

The three stage Delta II 7925 uses an RS-27A main engine, an extra extended long tank, 9 augmentation solid rocket motors (graphite epoxy motors), an AF10-118K second stage engine, and a PAM-D Derivative (STAR 48B) third stage engine. It is assumed the three stage version will be required to lift the payload out of orbit. Currently there is a 9.5 ft and a 10.0 ft diameter payload fairing (PLF) available on the Delta II 7925. Both PLF configurations are possibilities for a micro rover/lander combination. However, the larger PLF will reduce lifting performance by about 110 lb (50 kg) for a three stage vehicle.

The Delta II 7925 three stage launch vehicle payload accommodations are described in table 8-1.
### Table 8-1. Delta II Payload Accomodations (Isakowitz, 215, et al)

<table>
<thead>
<tr>
<th>Payload Compartment:</th>
<th></th>
</tr>
</thead>
</table>
| Maximum Payload Diameter | 100.0 in (2540 mm) for 9.5 ft PLF  
110.0 in (2794 mm) for 10 ft PLF |
| Maximum Cylinder Length | 80.0 in (2032 mm) for 9.5 ft PLF  
76.61 in (1946 mm) for 10 ft PLF |
| Maximum Cone Length | 103.8 in (2637 mm) for 9.5 ft PLF  
84.0 in (2133 mm) for 10 ft PLF |
| Payload Adapter Interface Diameter | 37.0 in (940 mm) |

<table>
<thead>
<tr>
<th>Environment:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Load Factors</td>
<td>+6.0 g axial, +/- 2.0 g lateral</td>
</tr>
<tr>
<td>Min Lateral/Longitudinal Payload Frequency</td>
<td>15 Hz / 35 Hz</td>
</tr>
</tbody>
</table>
| Max Overall Acoustic Level | 144.5 dB (1/3 octave) with 10 ft PLF  
139.6 dB (1/3 octave) with 9.5 ft PLF |
| Max Flight Shock | 4100 g at 1500 Hz |
| Max Dynamic Pressure on Fairing | 1230 lb/ft² (58,898 N/m²) |
| Max Pressure Change in Fairing | 0.5 psi/s (3.45 KPa/s) |
| Cleanliness Level in Fairing (Prior to Launch) | Class 10,000+ |

<table>
<thead>
<tr>
<th>Payload Delivery:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Payload Separation Rate</td>
<td>2-8 ft/s (0.6-2.4 m/s) for 3 stage</td>
</tr>
<tr>
<td>Deployment Rotation Rate Available</td>
<td>30 - 100 RPM for 3 stage vehicle</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Payload Integration:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Mission Schedule Begins</td>
<td>T-30 Months</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Launch Window:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Latest Countdown Hold Not Requiring Recycling</td>
<td>T-60 min</td>
</tr>
<tr>
<td>Latest Access to Payload</td>
<td>T-17 hours</td>
</tr>
</tbody>
</table>

The chief source of payload shock is separation of the payload from its attach fitting. Launch vehicle transients, staging, and fairing separation
shock are not significant (Kahre: 170, 171). The maximum level of acoustic noise and the resulting random vibration occur at liftoff and during transonic flight.

Safety Factors

Gerald Kahre, a Delta II launch vehicle specialist, recommends the following factors of safety for payload design and test for launch on a Delta II:

- Maximum flight/limit loads increased by a factor of 1.25. If a structural test is not performed, an additional 1.5 factor is required for analysis.
  - Vibration test levels 1.4 times maximum flight
  - Shock test levels 1.4 times payload separation
  - Acoustic qualification test levels 3 dB higher than maximum flight, and acoustic acceptance tests performed at maximum flight levels

With the rover stowed inside the spacecraft/lander, test values are naturally attenuated due to the protective, shock resistant, or vibration dampening effects of the lander and rover mounting structure. Applying the above safety factors to the information presented in the table, we arrive at the following test values for a spacecraft/lander structure with a rover mounted internally:

- Test load factor: + 8.4 g lateral, ± 2.8 g lateral
- Test lateral/longitudinal payload frequency: 15 Hz / 35 Hz
- Test acoustic level: 147.5 dB with 10 ft PLF, 142.6 dB with 9.5 ft PLF
Test flight shock level: 5740 g at 1500 Hz

Test pressure change rate (with 1.4 factor safety margin): 0.7 psi/s
(4.83 KPa/s)

It should be noted that the Delta II separation shock may not be the most severe shock experienced by a rover. Deploying a rover from the lander may require pyrotechnic devices which may subject the rover to larger shock loads. The most severe anticipated shock load value for a given rover/lander design can be incorporated into the test plan with a safety factor adjustment of 1.4.

Additional proposed test levels based upon past programs completed by the Jet Propulsion Laboratory are listed at the end of this chapter.

**Cruise, Entry, and Landing Environments: Earth to Mars**

Once the rover has survived launch stresses, it must also survive the stresses of transport from Earth to Mars. This includes such stresses as thermal cycling, cosmic radiation, extended exposure to a vacuum, structural (g) loads, and vibrations.

After arriving at Mars, the rover must survive atmospheric entry (protected within the lander spacecraft) and ground impact. Currently, MESUR Pathfinder plans call for the use of aeroshell braking on the lander from 78 miles to 6.6 miles above the surface with a 20° entry angle. The parachute will slow the lander to approximately 78 mph until ground impact, at
which time an airbag tetrahedron will decrease the impact shock to approximately 50 g's. Total time to touchdown is estimated to be approximately 300 seconds after entry into the Martian atmosphere.

Subsequent to cruise, entry, and landing stresses, the rover must be able to successfully deploy itself from the lander.

Following is a description of the above mentioned environmental stresses.

**Thermal Cycling**

Thermal cycling has a detrimental effect on both mechanical parts and electronics. Lubricants and bearing assemblies are especially susceptible to detrimental effects from temperature extremes. Thermal expansion adversely affects solder joints and surface mountings.

Often the rate of temperature change is also significant. Materials which are perfectly thermally matched may still have different thermal expansion rates, making them incompatible for the interplanetary cruise or Mars environment.

Throughout flight, the spacecraft will be exposed to black space, direct sunlight, and the heat produced from operating spacecraft subsystems (transmitters, etc.). Externally, the spacecraft is evenly heated as a result of spin stabilization, which helps minimize temperature extremes. However, overall heat dissipation is usually a problem. Current MESUR spacecraft plans anticipate the possible use of active means (heat pipes,
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etc.) for heat dissipation. Based on typical temperatures measured inside other interplanetary spacecraft, the cruise temperature for the rover inside a lander with active thermal control will probably be on the order of +35°C. Better temperature estimates will be available as the spacecraft/lander design evolves.

Vacuum Exposure

Extended exposure to a vacuum can cause significant harm through material out-gassing. Many plastics and adhesives, as well as materials used for potting, conformal coatings, and lubricants are susceptible to out-gassing. The planned 8 or 11 month vacuum exposure is sufficient to render serious harm to a spacecraft from this phenomenon. As a general rule, no materials used on the rover may be susceptible to out-gassing.

Another potential problem associated with prolonged vacuum exposure is the loss of hermetically sealed devices and containers. Extended over 8 or 11 months, microscopic leaks will render an otherwise sealed container or subsystem useless. This may play an important role in the selection of thermal control devices and subsystems since designs may incorporate sealed containers to protect critical subcomponents from the effects of thermal cycling.

Vibration

Although launch poses the greatest threat from vibrations to a spacecraft, other damage can be effected through prolonged low amplitude vibration experienced during cruise. Such vibrations can be caused by lander or
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other spacecraft subsystems and actuators operating regularly or irregularly during flight. Vibrations generated in this manner are not easily dampened and may affect the spacecraft for the entire cruise period. As well, the spacecraft/lander will undergo vibrations as it enters the Martian atmosphere.

Radiation

Cosmic radiation can damage integrated circuits and cause bit flips or permanent latch-ups. Most processor chips used in space applications have redundant architectures and are capable of sustaining a high dose of radiation. However, due to budget limitations, design teams are using fewer space qualified parts for their rover designs, probably detrimentally affecting a rover's radiation resistance.

Cosmic radiation is fundamentally dependent on the level of solar activity. The sun follows 11 year cycles of varying solar activity, most commonly measured by the magnitude, frequency and duration of solar flares. The sun is following a decreasing trend of sunspot activity through 1995. A four year non-active period is predicted from 1996 through mid-1999. Thus, a rover included in a MESUR Pathfinder mission will not be exposed to nearly the radiation dose expected during follow-on MESUR missions (500 Rad vs. 25,000 Rad peak for silicon assuming 0.178 cm (70 mils) aluminum shielding). This reduced radiation exposure will reduce, but not remove, the need for radiation resistance.

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Shock

The rover will experience shocks during launch separations as well as an estimated 50 g shock upon ground impact. Likely methods of deploying the rover from the lander involve the use of pyrotechnics. Shocks from deployment pyrotechnic events may be larger than any other shocks imposed on the rover.

Electromagnetic Interference/Electromagnetic Compatibility (EMI/EMC)

Although no direct mission tasks are currently required of a rover during cruise, it may have to perform periodic subsystem checks, transmit health status to Earth via the lander’s communication system, or accomplish other transient tasks while stored aboard the lander. The rover must not interfere with nor be affected by the operation of the lander/spacecraft subsystems with respect to electromagnetic signals. Circuits must be immune to magnetic effects, natural effects, electronic effects, and electric fields.

Other Environmental Stresses

Various other environmental stresses may be imposed on a rover. For example, spacecraft entry into the Martian atmosphere may result in triboelectric charging resulting in a large electrostatic discharge upon landing. This could destroy integrated circuits if not properly grounded. The rover may also be exposed to magnetic fields generated by other subsystems while on board the spacecraft/lander, adversely affecting its own components and subsystems.
The Surface of Mars

The surface of Mars is discussed in Chapter 2 -- The Planet Mars. Hazardous terrain survival is addressed in Chapters 4 (Mobility) and 5 (Navigation and Control).

Thermal cycling will be the most significant Martian environmental problem for most rover designs. Thermal cycling is discussed in the previous section, Cruise, Entry, and Landing Environments: Earth to Mars. Thermal cycling ranges and durations on the surface of Mars are included in the proposed test requirements in the following section.

Dust deposition and wind/dust exposure are considered less significant potential problems, and are also discussed in Chapter 2. The proposed test plan in Chapter 9 includes environmental testing for dust deposition and wind/dust exposure. The potential adverse effects of decreased atmospheric pressure, radiation exposure, triboelectric charging, and magnetic fields discussed earlier will most likely be less significant when the rover is on the surface of Mars than during other phases of transportation.

Summary of Environmental Design and Test Requirements For Launch, Cruise, Entry, Landing and Operations on Mars

The following proposed specific test requirements have been assembled by Marc Trummel at the Jet Propulsion Laboratory (JPL) from preliminary calculations and research of past programs. Calculations are based on the current anticipated MESUR missions and specifications.
Chapter 8: Environmental Stress Resistance

Sinusoidal Vibration

The rover is required to withstand the following sinusoidal vibrations as applied at the rover assembly mounting points or surfaces (assuming 2 octaves per minute, once up and once down in frequency, in each of three orthogonal axes):

- 5 - 20 Hz  1.27 cm (double amplitude displacement)
- 20 - 100 Hz  10.0 g (acceleration, 0-to-peak)

The rover shall have no sinusoidal resonant modes below 300 Hz.

Random Vibration

The rover is required to withstand the following random vibrations (acceleration spectral density or slope) as an average value (assuming 3 minutes per axis in each of three orthogonal axes):

- 20 - 50 Hz  +9 dB / Octave
- 50 - 800 Hz  0.1 g^2 / Hz
- 800 - 2000 Hz  -9 dB / Octave

Overall 10.5 g rms

Quasi-Steady Accelerations

The rover is required to withstand a launch-induced quasi-steady acceleration level (lasting up to two minutes) of up to 15 g in any direction
Chapter 8: Environmental Stress Resistance

Pyrotechnic Shock

The rover is required to withstand the pyrotechnic shock spectra expected during launch/cruise/entry separation events, as well as deployment pyrotechnic events. The shock spectra shall be assumed to be applied separately in each of three orthogonal axes. For design purposes, the shock pulse time history may be assumed to be an exponentially decaying sinusoid with approximately 7 mS decay time. The amplitude and frequency of the sinusoid is dependent upon the pyrotechnic shock devices selected for separation and deployment events.

Pressure Decay Profile

The rover is required to withstand a maximum rate of change in pressure of $4 \times 10^3 \pm 2 \times 10^3$ N/m$^2$/second ($30 \pm 15$ torr/second) beginning from $<2 \times 10^3$ N/m$^2$/second ($15$ torr/second) in a period of less than 10 seconds. This rate profile may occur anywhere from a one atmosphere condition (i.e., near liftoff) to a 10 % atmosphere condition depending on the launch trajectory.

Electromagnetic Interference/Electromagnetic Compatibility (EMI/EMC)

The rover shall not produce transient voltage noise in its DC power bus in excess of 50% of the line voltage, positive or negative, and not exceeding 10 microseconds in duration, for any switching or steady state condition. The rover shall operate within specification when subjected to a sinusoidal voltage of 1 volt peak-to-peak from 30 Hz to 50 MHz superimposed on its power leads. The rover shall perform within specification when subjected to the electric (E) fields defined and under the conditions given below.
Chapter 8: Environmental Stress Resistance

Above 1 MHz, the applied field shall be modulated with a 1 kHz AM square wave, 50 to 100% depth.

Operating:

<table>
<thead>
<tr>
<th>Swept Frequency Range</th>
<th>E-Field (RMS peak, Volts/Meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 KHz to 2 GHz</td>
<td>2</td>
</tr>
<tr>
<td>2 GHz to 10 GHz</td>
<td>5</td>
</tr>
<tr>
<td>5960 MHz pulse, 640 pps, 1 μS</td>
<td>60</td>
</tr>
</tbody>
</table>

Non-operating:

<table>
<thead>
<tr>
<th>Swept Frequency Range</th>
<th>E-Field (RMS peak, Volts/Meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 GHz to 3 GHz</td>
<td>10</td>
</tr>
<tr>
<td>5960 MHz pulse, 640 pps, 1 μS</td>
<td>60</td>
</tr>
</tbody>
</table>

Vacuum

A rover is required to perform properly at all pressures between Earth nominal and space vacuum, 1 x 10^5 N/m^2 (760 Torr) and 1.3 x 10^{-12} N/m^2 (10^{-14} Torr), and in the Mars atmosphere of Carbon Dioxide at a pressure of 1.3 x 10^3 N/m^2 (10 Torr).

Thermal Cycles

The rover is required to operate properly after exposure to 100 thermal cycles between -105° C to +35° C with a one hour dwell with operational
modes as required at each temperature in a carbon dioxide atmosphere at a pressure of $1.3 \times 10^3 \text{ N/m}^3$ (10 Torr). The temperature rate of change shall not exceed $30^\circ \text{C}$ per hour and shall not exceed $10^\circ \text{C}$ in any one minute.

**Thermal Vacuum**

The rover is required to meet all performance specifications when operating in a vacuum and when the mounting surface temperature is in the range of $-110^\circ \text{C}$ to $+40^\circ \text{C}$ (external temperature). The rover must be designed such that all rover device junction temperatures shall be maintained at a temperature no greater than $110^\circ \text{C}$ when the baseplate temperature is less than or equal to the highest design temperature. No conductive heat transfer from any other surfaces is allowed. The rover shall have a start-up capability from the non-operating mode at both high and low design temperature extremes. Temperature of the assembly at each start-up shall be assumed stabilized at the specified level.

**Radiation**

The rover and all of its components shall meet all performance specifications after exposure to a Total Ionizing Dose (TID) of

- $25k \text{ Rad (Si)}$ if to be a Network Mission Rover
- $500 \text{ Rad (Si)}$ if for Network Pathfinder Mission Only

assuming shielded by a spherical shell of $0.178 \text{ cm}$ (70 mils) aluminum thickness.

All rover components shall be immune to particle-induced latch-up.
Chapter 8: Environmental Stress Resistance

Other Test Requirements:

Internal Charging:
For electro-static discharge protection, all metallic elements used in association with the rover electronic design, including wires, unused conductors, connectors, and circuit board traces shall have a conductive path to the rover chassis ground with a resistance less than $10^8$ ohms when measured in air and $10^{12}$ ohms when measured in a vacuum. Non-conductive surfaces which can store more than 3 millijoules of electrostatic energy are not permitted. All conductive materials in the rover with resistances less than $10^8$ ohms and with a surface area greater than 3.0 cm$^2$ shall be electrically grounded to the rover chassis ground with a resistance less than 0.025 ohms.

Magnetic Fields
The rover shall be designed to tolerate and function within specification after exposure to magnetic fields as high as 5.0 milliTesla (50 Gauss).

Mars Entry and Landing Loads
The rover shall be designed to survive three 100 g, 30 millisecond duration, half-sine pulses in any direction.

The fundamental stress testing requirements as discussed earlier are listed in table 8-2 along with accompanying capability and test references.
### Table 8-2. Environmental Stress Test Requirements, Required Capabilities, and Test References

<table>
<thead>
<tr>
<th>Requirement Description</th>
<th>Capabilities Tested/Demonstrated/Inspected</th>
<th>Test Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survive in the launch environment</td>
<td><strong>Demonstrated:</strong> Launch Vibrations Handling, Loads Handling, Pressure Change Handling</td>
<td>ENV.1, ENV.2, ENV.4</td>
</tr>
<tr>
<td></td>
<td><strong>Inspected:</strong> Rover/Lander Interface</td>
<td>ENV.8</td>
</tr>
<tr>
<td>Survive in the transit environment (Earth to Mars)</td>
<td><strong>Demonstrated:</strong> Separation Shock Handling, Thermal Cycling Handling, Cosmic Radiation Resistance</td>
<td>ENV.3, ENV.4, ENV.6</td>
</tr>
<tr>
<td></td>
<td><strong>Inspected:</strong> Rover/Lander Interface</td>
<td>ENV.8</td>
</tr>
<tr>
<td></td>
<td>In-Transit Health Monitoring and Communications Plan</td>
<td></td>
</tr>
<tr>
<td>Survive in the landing environment</td>
<td><strong>Demonstrated:</strong> Thermal Shock Handling, Loads Handling, Pressure Change Handling, Ground Impact Shock Handling</td>
<td>ENV.4, ENV.2, ENV.4, ENV.3</td>
</tr>
<tr>
<td></td>
<td><strong>Inspected:</strong> Rover/Lander Interface</td>
<td>ENV.8</td>
</tr>
<tr>
<td>Survive in the Martian environment</td>
<td><strong>Demonstrated:</strong> Thermal Cycling Handling, Wind Resistance, Dust Resistance, Dust Storm Resistance, Low Pressure Operational Cap.</td>
<td>ENV.4, ENV.5, ENV.5, ENV.4</td>
</tr>
<tr>
<td></td>
<td><strong>Inspected:</strong> Post-Landing Health Monitoring &amp; Communications Plan</td>
<td>ENV.8</td>
</tr>
<tr>
<td></td>
<td>Deployment from Lander Plan</td>
<td>ENV.8</td>
</tr>
</tbody>
</table>
CHAPTER 9
TEST PLAN

Summary

This chapter proposes tests which measure the performance parameters described in previous chapters. Test categories follow each of the areas discussed in this thesis, namely: Mobility, Navigation and Control, Scientific Support, Autonomy, and Environmental Stress. The selection of tests exactly follows from the specific requirements proposed in previous chapters. All previously discussed requirements and required capabilities are either tested, demonstrated, or inspected.

In addition to tests which flow directly from requirements, optional demonstration tests are proposed in each category which permit the demonstration of unique capabilities. This enables a rover design team to demonstrate a useful capability or design ingenuity which the team feels is not adequately revealed by other tests.
## Micro Rover Test Listing

### Mobility

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOB.1</td>
<td>Drawbar Pull</td>
</tr>
<tr>
<td>MOB.2</td>
<td>Turning Radius</td>
</tr>
<tr>
<td>MOB.3</td>
<td>Rover Tipover and Slip</td>
</tr>
<tr>
<td>MOB.4</td>
<td>Slope Climb and descent</td>
</tr>
<tr>
<td>MOB.5</td>
<td>Small Obstacle Climbs</td>
</tr>
<tr>
<td>MOB.6</td>
<td>Hazardous Obstacles and Terrain</td>
</tr>
<tr>
<td>MOB.7</td>
<td>Unique Mobility Capability Demonstration Test</td>
</tr>
</tbody>
</table>

### Navigation and Control

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAV.1</td>
<td>Straight-Line Navigation</td>
</tr>
<tr>
<td>NAV.2</td>
<td>Obstacle Avoidance</td>
</tr>
<tr>
<td>NAV.3</td>
<td>Hazardous Terrain Navigation</td>
</tr>
<tr>
<td>NAV.4</td>
<td>Mars Scape</td>
</tr>
<tr>
<td>NAV.5</td>
<td>Unique Navigation and Control Capability Demonstration</td>
</tr>
</tbody>
</table>

### Science & Technology Experiment Support

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCI.1</td>
<td>Science Experiment Support Demonstration</td>
</tr>
<tr>
<td>SCI.2</td>
<td>Technology Experiment Support Demonstration</td>
</tr>
<tr>
<td>SCI.3</td>
<td>Unique Science &amp; Technology Experiment Support Capability Demonstration Test</td>
</tr>
</tbody>
</table>

### Autonomy

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUT.1</td>
<td>Integrated Autonomous Rover Scenarios</td>
</tr>
<tr>
<td>AUT.2</td>
<td>Fault Response</td>
</tr>
<tr>
<td>AUT.3</td>
<td>Unique Autonomy Capability Demonstration Test</td>
</tr>
</tbody>
</table>

### Environmental Stress

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENV.1</td>
<td>Vibration Test</td>
</tr>
<tr>
<td>ENV.2</td>
<td>Loads Test</td>
</tr>
<tr>
<td>ENV.3</td>
<td>Shock Test</td>
</tr>
<tr>
<td>ENV.4</td>
<td>Thermal-Vacuum Test</td>
</tr>
<tr>
<td>ENV.5</td>
<td>Wind and Dust Test</td>
</tr>
<tr>
<td>ENV.6</td>
<td>Radiation Test</td>
</tr>
<tr>
<td>ENV.7</td>
<td>Unique Environmental Stress Capability Demonstration Test</td>
</tr>
<tr>
<td>ENV.8</td>
<td>Plan Review</td>
</tr>
</tbody>
</table>
Chapter 9: Test Plan

**Mobility Tests**

All rover navigational equipment (sensors, bumpers, etc.) will be disconnected for all mobility tests.

**Drawbar Pull (MOB.1)**

**Capabilities Tested:**
- Forward and Backward Pull Force (Static and Dynamic)
- Traction
- Mobile Operation in Reduced Gravity (if possible)

**Test Description:**

The rover will be placed in a simulant sand box and tethered to a spring scale or other suitable force-measurement device (See Note 1). If possible, a "harness" will also be attached to the rover's horizontal cg (or multiple cg's for modular, flexible structure rovers) to simulate Mars 3/8 g conditions (See Note 2). The scale will measure the total forward pull force the rover is able to produce. The rover will be rotated 180° and driven backwards to test backward pull force.

**Test Variables:**
- Attachment location on rover
- Simulant (See Note 3)

**Parameters Measured:**
- Maximum Static Pull Force (immediately prior to wheel motion/slip)
- Maximum Dynamic Pull Force (subsequent to wheel motion/slip)
Chapter 9: Test Plan

Specific pull force = Traction = Static Pull Force/Mass (or Rover Dimension -- See Note 4)

More specifically:

\[ T_s = \text{Static Traction} = \text{Specific Static Pull Force} \]
\[ T_d = \text{Dynamic Traction} = \text{Specific Dynamic Pull Force} \]

\[ T_s = \frac{P_{s_{\text{max}}}}{m} \quad \text{and} \quad T_d = \frac{P_{d_{\text{max}}}}{m} \]

Where:

\[ P_s = \text{Static Pull Force} \]
\[ P_d = \text{Dynamic Pull Force} \]
\[ m = \text{Mass} \]

Traction Ratio = (Traction in 3/8 g) / (Traction in 1 g)

\[ \left( \frac{T_s}{T_s} \right)_{\text{gravity}} = \text{Static Traction Ratio} \]
\[ \left( \frac{T_d}{T_d} \right)_{\text{gravity}} = \text{Dynamic Traction Ratio} \]

Test Location: TBD

NOTE 1: The location of the spring scale attachment point on the rover is critical. A rover's performance changes significantly between an attachment to the top or the bottom of the rover structure. Recommendation: Attach the spring scale to the rover's vertical cg on the back (front) of the rover. Rover teams will determine the vertical cg location and a means by which to attach a small hook from the spring scale prior to testing.
Chapter 9: Test Plan

NOTE 2: This would be a harness system similar to a harness used by Carnegie-Mellon University Robotics Institute for testing robots in reduced gravity. One other potential method for simulating reduced gravity is to use a helium-filled balloon in a blimp hangar. Reduced gravity testing is suggested for Mobility tests MOB.1 and MOB.2. It would also be beneficial, though probably more difficult, to use for the slope and obstacle tests (MOB.4, MOB.6, and MOB.7).

It should also be noted that lunar rover testing accomplished for the Apollo program concluded that the combined effect of reduced gravity and low-atmospheric pressure (and, subsequently, lower pore pressures) generally enhances wheel mobility performance (See Chapter 4, Mobility). Thus, testing a rover under simulated reduced gravity (and reduced atmospheric pressure) is probably not critical.

NOTE 3: Selection of an appropriate Martian surface material simulant and associated baseline test parameters (depth, bulk density, grain size distribution, etc.) will significantly affect test results. Selection of suitable Mars surface simulants is discussed in Chapter 3.

NOTE 4: Rover Dimension

The rover dimension is proposed as a potentially convenient means for comparing rover test results. A simple dimension is sought which combines critical rover characteristics into a meaningful normalizing dimension based on current design constraint priorities. Currently, the primary rover physical design constraints are size (which is approximated for our purposes by the rover's enclosed volume in its stowed position) and weight. These are arbitrarily given calculation weightings of 2/3 and 1/3 respectively.
Chapter 9: Test Plan

\[ V = \text{Volume (length } \times \text{ width } \times \text{ height)} \]

\[ W = \text{Unloaded weight of rover (no experiments or extra components)} \]

\[ R = \text{Rover Dimension} \]

\[ R = \text{Rover Dimension} = \frac{2}{3} \sqrt[3]{\text{Volume}} \times \frac{1}{3} \text{Weight} \]

The rover dimension can be adapted to other situations in which rovers may need to be compared based on different criteria. The rover dimension equation need only be changed to accommodate new requirement and/or design emphases as determined by rover design evaluators. The new value of \( R \) may then be applied to the original raw data to enable comparison of test results.
Chapter 9: Test Plan

Turning Radius (MOB.2)

Capabilities Tested:

Turning Radius
Maneuvering Turning Radius (If required. See Chapter 4 -- Mobility)
Mobile Operation in Reduced Gravity (if possible)

Test Description:

The rover will be placed in a simulant sand box and attached to a harness device (if possible) to simulate 3/8 g conditions. The rover will accomplish the sharpest 360° turn possible. Turns will be accomplished to both the left and right.

The rover will then be commanded to perform an S-Turn maneuver (see diagram). While traversing straight ahead, the rover will be commanded to perform a right 90° turn, followed by an immediate left 180° turn, an immediate right 180° turn, and an immediate left 90° turn. Thus, a rover will be required to complete 90° and 180° turns in both directions.

![Maneuvering Turning Radius Test Profile](image)

Figure 9-1. Maneuvering Turning Radius Test Profile
Chapter 9: Test Plan

Test Variables:

Rover Speed
Simulant

Parameters Measured:

Minimum Turning Radius (Radius to the center of the wheel track circle)

Average Maneuvering Turning Radius = 
\[
\frac{[(\text{width of S-Turn wheel track} - \text{rover width}) + \text{length of S-Turn wheel track}]}{8}
\]

Turning Radius Ratio = (Min Turn Rad 3/8 g) / (Min Turn Rad 1 g)
Mvrg Turn Radius Ratio = (Min Mvr T.R. 3/8 g) / (Min Mvr T.R. 1 g)

Test Location: TBD
Chapter 9: Test Plan

Rover Tipover and Slip (MOB.3)

Parameters Tested:

- Tipover Angles (Lengthwise and Widthwise)
- Slope Slip Angles (Lengthwise and Widthwise)

Test Description:

The rover will be placed on a tilting simulant sand box with its front facing uphill. The simulant sand box will be tilted until the rover falls or (more probably) slides back; this angle will be recorded. This will be repeated for the rover facing all four directions on the slope.

This experiment will be repeated with the rover in a level simulant sand box. However, one side of the rover will be lifted until it reaches its "tipover" angle, which will be recorded. This will be repeated for all four rover sides.

Test Variables:

- Simulant

Parameters Measured:

- Slope Slip Angles (Facing forward, backward, left, and right)
- Tipover Angles (Facing forward, backward, left, and right)

Test Location: TBD
Chapter 9: Test Plan

Slope Climb and Descent (MOB.4)

Capabilities Tested:

- Slope Climbing/Descending Capability
- Slope Climbing Energy Consumption

(In Conjunction with MOB.5. See Note 1)

Test Description:

The rover will be configured to measure energy consumption (See Note 2) and placed in a simulant sand box capable of rotating through the simulant's angle of repose. The rover will be commanded to traverse straight ahead while the sandbox is level to obtain a baseline run for energy consumption. The sandbox will then be tilted in five degree increments, and the rover will be commanded to move up the slope. When a rover is not able to satisfactorily climb a given slope angle, the slope angle will be decreased in 1 degree increments to determine the maximum slope climb angle. The same parameters will be measured for a rover descending the slope.

Test Variables:

- Slope Tilt Angle
- Simulant

Parameters Measured:

- \( \alpha_{\text{max}} \) = Maximum Slope Climb Angle
- \( S = \frac{\left(\frac{2\pi \cdot r \cdot (\text{rev})}{x_a} - x_a\right)}{x_a} \cdot 100 \)
Chapter 9: Test Plan

where:

\[(S)_\alpha \equiv \text{Slippage (f(\alpha))}\]

and:

\[\alpha \equiv \text{Slope Angle}\]

\[\text{rev} \equiv \text{Number of Wheel Revolutions}\]

\[r \equiv \text{Wheel Radius}\]

\[x_a \equiv \text{Actual Distance Traveled (Distance Tracked)}\]

\[
\bullet \quad E_{\text{Slope}_\alpha} \equiv \text{Slope Climbing Energy Consumption (f(\alpha))}
\]

where:

\[E \equiv \% \text{ Energy Consumption} = \left( \frac{\text{Energy Expended}}{\text{Total Available Energy}} \right) \times 100\]

Test Location: TBD

NOTE 1: The total energy the rover consumes will be measured in tests MOB.4 and MOB.5 during the following activities:

1. Traverse on level terrain for a given distance (nominal = 20 feet)
2. Traverse on sloping terrain for a given distance
3. Traverse on level terrain with obstacles for a given distance
4. Traverse on sloping terrain with obstacles for a given distance

The same representative slope angles and traverse distances will be tested in both MOB.4 and MOB.5. The additional energy the rover consumes climbing slopes and the additional energy the rover consumes climbing obstacles can then be extracted to enable power efficiency comparisons between rovers (see Chapter 4 discussion of energy measurement).
NOTE 2: For measuring energy consumption, either: 1. An ammeter and volt meter will be attached to the rover power source(s) on the rover itself. or, 2. The rover's own power source(s) will be disconnected, and a standard power supply will be connected to the rover with a long (approximately 75') wire. The design team will then specify the voltage to be supplied to the rover. In both cases, measurements will be input directly to a data collection computer.
Chapter 9: Test Plan

Small Obstacle Climbs (MOB.5)

Capabilities Tested:

Largest Surmountable Obstacle
Largest Surmountable Obstacle on a Slope
Obstacle Climbing Energy Consumption (In Conjunction with MOB.4)

Test Description:

This test will measure a rover's ability to negotiate small or protruding obstacles (i.e. smaller than a rover width) which might be in the rover's planned path. Sample objects will be placed in a simulant sand box spaced apart by four feet to ensure a rover does not negotiate more than one obstacle at a time. These obstacles will be placed in increasing height and/or overall size. The rover will be commanded to move forward over the obstacles (sensors may have to be overridden). The rover will continue until it "high centers" on an obstacle or is not able to straddle/surmount the obstacle. Sliding off of an obstacle is not considered "surmounting" an obstacle. The vertical plane between all sets of wheels (legs) must cross over the obstacle.

This test will be repeated using obstacles placed in a tilting simulant sand box. The sandbox will be tilted in five degree increments.

Test Variables:

Obstacle size, height, shape, spacing, and inclination (see Chapter 4 for recommended obstacle shape)

Simulant
Chapter 9: Test Plan

Simulant sand box slope angles

Parameters Measured:

\[ \lambda_{\text{obs}} = \text{Size of Largest Surmountable Obstacle (Vertical Height)} \]

\[ \lambda_{\text{obs}}(\alpha) = \text{Size of Largest Surmountable Obstacle On Slope (f(\alpha))} \]

where:

\[ \lambda_{\text{obs}} = \text{Characteristic Dimension of Obstacle} = \text{Obstacle Size} \]

\[ E_{\text{Obs}}(\lambda) = \text{Obstacle Climbing Energy Consumption (f(\lambda))} \]

where:

\[ E = \% \text{ Energy Consumption} = \left( \frac{\text{Energy Expended}}{\text{Total Available Energy}} \right) \times 100 \]

Test Location: TBD
Hazardous Obstacles and Terrain (MOB.6)

Capabilities Tested:

Largest Survivable Hazardous Obstacles and Terrain

Test Description:

The rover will be placed in a simulant sand box with large, hazardous obstacles (See Note 1). The rover's navigation sensors will be overridden or covered. The rover will be commanded to move forward over the obstacles. After each successful negotiation of a hazardous obstacle, the obstacle size/difficulty will be increased. The test will determine the largest hazardous obstacle (of each type) the rover can surmount.

The rover will then be placed on a large obstacle, and commanded to drive to a location off of the obstacle. This will require the rover to step/slip/fall off a cliff (See Note 2), or cross a crevice. Various obstacles and obstacle approach angles can be tested.

These same tests can be repeated with approaches on tilting terrain (in a tilting simulant sand box) both ascending and descending from the obstacles.

Illustrations of hazardous obstacles are presented in Chapter 4 -- Mobility, Figure 4-2.

Test Variables:

Characteristic dimension of hazardous obstacle/terrain features
Fixed parameters of hazardous obstacles/terrain features
Simulant
Chapter 9: Test Plan

Parameters Measured:

Characteristic Dimension of Largest Surmountable Obstacle In Each Obstacle Category:

$\lambda_{\text{Cliff}} = \text{Cliff Height}$

$\lambda_{\text{Crevice}} = \text{Crevice Width (Assume Infinite Depth)}$

$\lambda_{\text{Step}} = \text{Step Height}$

$\lambda_{\text{Spike}} = \text{Spike Height}$

$\lambda_{\text{Ramp}_{\text{ctr}}} = \frac{\text{Ramp Height}_{\text{ctr}}}{\text{Rover Width}}$

$\lambda_{\text{Ramp}_{\text{side}}} = \frac{\text{Ramp Height}_{\text{side}}}{\text{Rover Width}}$

Test Location: TBD

NOTE 1: Hazardous obstacles will derive from the following four primary mobility failure modes discussed in Chapter 4:

1. Vertical drop (tested by cliffs and crevices)
2. Overturn (tested by a side ramp)
3. Obstacle block (tested by spikes (included in MOB.5) and steps)
4. Loss of wheel traction (tested by center ramp)

Design teams will be permitted to suggest other specific hazardous obstacle types which test these failure modes.

Hazardous obstacles are further described in test NAV.3 where the rover will be tested with sensors operating.
NOTE 2: Due to the precarious nature of this test, every effort should be made to ensure the safety of the rovers. This test should be accomplished after completing the other tests in case of minor damage.
Chapter 9: Test Plan

Unique Mobility Capability Demonstration Test (MOB.7)

Capabilities Tested/Demonstrated:

As determined by design teams

Test Description:

Design teams will be permitted to demonstrate any mobility capabilities and features unique to their rover.

Test Variables:

As determined by design teams

Parameters Measured:

The rover's demonstrated unique capabilities and features will be recorded. These will be included in the summary of the rover's overall performance capabilities.

Test Location:

TBD
Chapter 9: Test Plan

Navigation and Control Tests

NOTE: All rovers will be required to complete all navigation and control tests with their planned operational software and sensor configurations. No software changes or sensor adjustments will be allowed between tests.

Straight-Line Navigation (NAV.1)

Capabilities Tested/Demonstrated/Inspected:

- Navigation Accuracy and Reliability
- Navigation Speed
- Navigational Energy Consumption
- Location and Heading Knowledge

Technical Evaluation:

Processor and Sensor Specifications and Capabilities (See Note 1)

Test Description:

The rover will be placed on a flat, level, unobstructed surface. The rover will begin in a "starting box" which will perfectly align the rover with a target located a specified distance (on the order of 50 feet) directly in front of the rover. The location of the target will be given to the rover prior to the start of the run (See Note 2). The rover will be commanded to traverse to the target. The rover sensors and navigation processor must be operating during the test (See Note 3). Entrants can not allow the rover to simply traverse forward blindly for the required distance; this would give an inaccurate measure of navigation capabilities and energy consumption.
Chapter 9: Test Plan

Test Variables:
- Traverse surface/simulant
- Distance to target

Parameters Measured:
- \( A_{Nav} = \text{Navigation Accuracy} \left( f(e_\beta, e_{xa}, e_{xtot}) \right) \)

Where:
- \( e_\beta = \text{Heading Angle Error} = \arcsin \left( \frac{xy}{x_{MEPL} + x_x} \right) \)
- \( e_{xa} = \% \text{Tracking Distance Error} = \left( \frac{x_a - x_{MEPL}}{x_{MEPL}} \right) * 100 \)
- \( e_{xtot} = \% \text{Total Distance Error} = \left( \frac{\sqrt{(x_x)^2 + (xy)^2}}{x_{MEPL}} \right) * 100 \)

And:
- \( \beta = \text{Heading Angle} \)
- \( x_x = \text{Longitudinal Distance From Target (in } x - \text{ direction)} \)
- \( xy = \text{Lateral Distance From Target (in } y - \text{ direction)} \)
- \( x_a = \text{Actual Distance Traveled (Distance Tracked)} \)
- \( x_{MEPL} = \text{Minimum Expected Path Length} \)

- \( R = \text{Reliability: Target Achievement Pass/Fail (See Note 4)} \)
- \( \text{Average Speed:} \)
  \[ \frac{(\text{distance from starting box to target destination})}{(\text{time})} \]
- \( E_{NavField} = \text{Navigation Energy Consumption} \left( f(\text{Obstacle Field}) \right) \)
Chapter 9: Test Plan

Where:

\[ E = \% \text{ Energy Consumption} = \left( \frac{\text{Energy Expended}}{\text{Total Available Energy}} \right) \times 100 \]

- Rover Location Knowledge Error:
  \[ \left( \frac{\text{Distance between rover's perceived location and actual location}}{\text{minimum expected path length}} \right) \] (See Note 5)

- Rover Heading Knowledge Error:
  \[ \left( \frac{\text{Angular difference between rover's perceived final heading and actual final heading}}{\text{minimum expected path length}} \right) \]

Test Location:

A parking lot covered with a thin layer of simulant. This would provide sufficient traction and a sufficiently smooth surface to allow for comparisons of the basic navigation capabilities of rovers.

NOTE 1: Specific information collected will be as follows:

Processor Specifications and Capabilities:

1. Type (Proven technology? Space qualified/hardened?)
2. Data Storage Capacity (Bytes of memory)
3. Power Requirements (Watts, navigating; Watts, stationary)
4. Size (enclosed volume including support circuitry)
5. Weight (including support circuitry)
Chapter 9: Test Plan

Navigation Sensor Specifications and Capabilities:

1. Type(s) (Proven technology? Simple? Space qualified/hardened? Protected/resistant to Mars environment?)

2. Power Requirements (Watts, navigating; Watts stationary)

3. Size (enclosed volume including all components)

4. Weight (including all components)

NOTE 2: Potential methods for providing target destination points to the rover are:

1. Specifying X,Y coordinates relative to the rover's current position

2. Specifying X,Y coordinates relative to a beacon on the lander

3. Designating a specific object (i.e. rock)

All of these methods are acceptable. Design teams will most likely use method 1.

NOTE 3: These tests will most likely need to be conducted outside to accommodate rovers which use sun sensors for heading information.

NOTE 4: A passing grade is given when a rover stops sufficiently close to the target destination. Based upon current rover mission scenario requirements and the achievable performance predicted by control logic simulation testing, "sufficiently close" is described by a radial distance from the target destination of less than 5% of the minimum expected path length. Minimum expected path length is the minimum distance a rover would have to traverse to arrive at the target destination given perfect knowledge about all obstacles and terrain features. For the test described above, the minimum path length would simply be the distance between the starting box and the target destination.
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NOTE 5: Rover design teams would be required to provide rover-generated location and heading data at the end of the navigation runs. Where a rover stops is not necessarily where the rover thinks it is. A rover may know it is not exactly at the target destination, but it may decide it is close enough to have successfully achieved the target and stop.

Providing location and heading data should not pose a problem; teams which have accomplished control logic testing and debugging will probably have ready access to this data.
Obstacle Avoidance (NAV.2)

Parameters Tested/Demonstrated/Inspected:

- Obstacle Avoidance Capability
- Traverse Distance Efficiency
- Navigation Accuracy and Reliability
- Navigational Energy Consumption
- Traverse Time
- Navigation Safety
- Location and Heading Knowledge

Test Description:

A rover will be placed on a flat, level surface. The rover will be placed in a starting box and given a destination location at a specified distance in front of the rover. Positioned directly between the rover and the target destination will be a large, insurmountable obstacle (or collection of obstacles). The rover will be required to navigate around or through the obstacle. The proposed insurmountable obstacles are:

1. A straight wall (See Note 1), perpendicular to the direct path of the rover.
2. A concave wall (See Note 2) perpendicular to the direct path of the rover (the wall curves in around the rover).
3. A flat wall with two equal-sized gaps in it. The gaps will be offset several feet from the centerline connecting the starting box and target destination. The gaps will be two rover widths wide (a convenient distance found to be challenging in computer simulations).
Figure 9-2. Insurmountable Obstacle Formations: 1. Straight Wall; 2. Concave Wall; 3. Wall With Gaps
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Test Variables:

- Obstacle shape (type)
- Obstacle size (including gap width)
- Obstacle material
- Distance to destination. This distance must be sufficient to ensure the rover will not be required to accomplish a tight turn approaching or leaving an obstacle (i.e. at least 50 feet); obstacle avoidance measurement is the test objective, not mobility.

Parameters Measured:

- Obstacle Avoidance Capability (success or failure at navigating past each obstacle)

- $\eta_{x_{tot}} = \text{Traverse Distance Efficiency} = \frac{x_{MEPL}}{x_a + \left( \frac{e_{x_a} \times x_{MEPL}}{100} \right)}$

Where:

- $e_{x_a} = \% \text{Tracking Distance Error}$
- $x_a = \text{Actual Distance Traveled (Distance Tracked)}$
- $x_{MEPL} = \text{Minimum Expected Path Length}$

And:

- $e_{x_a} = \% \text{Tracking Distance Error} = \left( \frac{x_a - x_{MEPL}}{x_{MEPL}} \right) \times 100$

(See Note 3)
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• Navigation Accuracy and Reliability:

\[ e_{x_{tot}} = \% \text{Total Distance Error} = \left( \frac{\sqrt{(x_x)^2 + (x_y)^2}}{x_{MEPL}} \right) \times 100 \]

Where:

\( x_x \) = Longitudinal Distance From Target (in x – direction)
\( x_y \) = Lateral Distance From Target (in y – direction)

\( R \) = Reliability (Success/failure rate of target achievement within 5% Error)

• \( E_{NavField} \) = Navigation Energy Consumption (f(Obstacle Field))

Where:

\[ E = \% \text{Energy Consumption} = \left( \frac{\text{Energy Expended}}{\text{Total Available Energy}} \right) \times 100 \]

• Time required to arrive at the target destination

• Navigation Safety (See Note 4)

• Rover Location Knowledge Error:

\[ \frac{\text{Distance between rover's perceived final location and actual final location}}{\text{minimum expected path length}} \]

• Rover Heading Knowledge Error:

\[ \frac{\text{Angular difference between rover's perceived heading and actual heading}}{\text{minimum expected path length}} \]

Test Location:

A flat, level parking lot with a layer of simulant.
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NOTE 1: All insurmountable obstacles will be on the order of 15-20 feet in length (larger than the rover's navigation sensor field of view to test a rover's control logic). The walls will be composed of volcanic rocks placed together in a line to enable the rover sensors to detect realistic obstacles. The rocks need only be placed within inches of each other to ensure a realistic insurmountable obstacle scenario (rovers should not attempt to traverse between obstacles through which they cannot fit).

NOTE 2: The concave wall will be specified as 1/3 arc of a circle with radius 10 feet. This will provide sufficient curvature to challenge a rover's control logic with a wall length of ~21 feet.

NOTE 3: Measuring the distance traveled may be difficult. A stripe can be painted on a rover wheel and revolutions can be counted (both forward and backward). A better method would probably be to use the rover's own distance traveled knowledge, corrected by the error measured in the MOB.1 test.

NOTE 4: Navigation safety refers to the rover's ability to refuse negotiation of an insurmountable obstacle and thereby avoid a dangerous situation. Gentle contact with an obstacle (by either a feeler or the rover itself) is not considered a navigation safety failure. However, trying to drive through or over an insurmountable obstacle is a failure. Navigation safety failure judgments will be made during the test.
Hazardous Terrain Navigation (NAV.3)

Capabilities Demonstrated:

Hazardous Terrain Survival (Detection, Avoidance, Recovery)

Test Description:

A rover will be placed in a starting box. The rover will be given a target destination approximately 20 feet directly in front of the rover. Between the rover and the target destination will be a hazardous terrain feature which could cause a mobility failure. The test will see if the rover is able to detect and avoid the hazard, detect and successfully negotiate the hazard, or simply successfully negotiate the hazard. Attention will be given to ensuring no damage occurs to the rovers.

Hazardous terrain features which could likely cause a mobility failure include:

1. Cliff
2. Crevice
3. Side ramp
4. Spike or step
5. Center Ramp

Of the above list, hazards 1 and 2 should be detectable and avoidable/recoverable by a rover with a basic navigation and control system. Hazards 3, 4, and 5 could also be detectable, avoidable, and/or survivable, but with more difficulty. These same hazardous terrain features are also tested in MOB.6. A rover that is unable to avoid or recover from a condition
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or situation that it was not able to survive during the mobility testing will fail that specific hazard test.

Illustrations of hazardous obstacles are presented in Chapter 4 -- Mobility, Figure 4-2.

Test Variables:

Recall:

\[ \lambda_{\text{obs}} \equiv \text{Characteristic Dimension of Obstacle} \equiv \text{Obstacle Size} \]

**Hazard 1:** Cliff approach angle. Nominal: Perpendicular to the cliff;

\[ \lambda_{\text{Cliff}} = \text{Cliff Height} \]

**Hazard 2:** Crevice approach angle. Nominal: Perpendicular to the crevice

\[ \lambda_{\text{Crevice}} = \text{Crevice Width (Assume Infinite Depth)} \]

**Hazard 3:** Ramp incline angle (rate of increase in rover tilt angle).

Nominal: 5° incline

\[ \lambda_{\text{Ramp}_{\text{Side}}} = \frac{\text{Ramp Height}_{\text{side}}}{\text{Rover Width}} \]

**Hazard 4:** Size and shape of spikes/steps. Nominal: See recommended obstacle description in Chapter 4

\[ \lambda_{\text{Step}} = \text{Step Height} \]

\[ \lambda_{\text{Spike}} = \text{Spike Height} \]

**Hazard 5:** Width of ramp, Incline of ramp. Nominal: 6" width, 5° incline

\[ \lambda_{\text{Ramp}_{\text{ctr}}} = \frac{\text{Ramp Height}_{\text{ctr}}}{\text{Rover Width}} \]
Any additional types of hazardous terrain

Obstacle material (recommend using rock surfaces for obstacle construction)

**Parameters Measured:**

Pass/Fail for hazards 1 through 5 above. A passing mark consists of either a successful detection and avoidance of the hazard, or a successful negotiation and survival of the hazard. A failure includes any mobility, navigation, or other failure directly attributable to the hazard (e.g. attempting to drive off a cliff, high centering, flipping over, etc.).

**Hazardous Terrain Feature Passing Requirements:**

Hazard 1: Detection and Avoidance (e.g. reverse direction) of maximum survivable cliff height determined in test MOB.6

Hazard 2: Detection and Avoidance (e.g. reverse direction) of maximum survivable crevice width determined in test MOB.6

Hazard 3: Detection and Avoidance (e.g. reverse direction) or survival of tilt angle past tested maximum (approximately 60° is feasible)

Hazard 4: Detection and Avoidance (e.g. initiate obstacle avoidance) of maximum survivable spike/step height as determined in test MOB.6.

Hazard 5: Detection and Avoidance (e.g. reverse direction) of maximum survivable ramp height as determined in test MOB.6

**Test Location:**

TBD
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Mars Scape (NAV.4)

Capability Tested:

Integrated Navigational Capability (Navigation Accuracy and Reliability, Obstacle Avoidance Capability, Navigational Energy Consumption, Traverse Distance Efficiency, Traverse Time, Navigation Safety,)

Test Description:

The rover will be placed in a large, simulated Martian landscape. The landscape will include: Martian soil simulant (as available in large quantities) varied, undulating terrain, and both surmountable and insurmountable obstacles. The landscape will resemble Martian landscape as much as possible. The rover will be given a destination location, and placed in a starting box facing at an angle from the destination. The rover will be commanded to reach the destination.

This test will be repeated as many times as feasible using different starting angles, destination locations, and field obstacle densities. Results can be compared directly between rovers for the same starting conditions, providing a systems-level navigation performance evaluation.

Test Variables:

Simulant

Obstacle size, shape, complexity, density (See Note 1)

Terrain slope and undulation severity

Starting angle to the target

Target location
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Distance to the target

Parameters Measured:

Integrated Navigational Capability:

\[ e_{\text{tot}} = \% \text{Total Distance Error} = \left( \frac{\sqrt{(x_x)^2 + (x_y)^2}}{x_{\text{MEPL}}} \right) \times 100 \]

Where:

- \( x_x \) = Longitudinal Distance From Target (in \( x \) direction)
- \( x_y \) = Lateral Distance From Target (in \( y \) direction)
- \( x_{\text{MEPL}} \) = Minimum Expected Path Length

- \( \mathcal{R} \) = Reliability (Success/failure rate of target achievement within 5% Error)

- \( E_{\text{NavField}} \) = Navigation Energy Consumption (\( f(\text{Obstacle Field}) \))

Where:

\[ E = \% \text{Energy Consumption} = \left( \frac{\text{Energy Expended}}{\text{Total Available Energy}} \right) \times 100 \]

- \( \eta_{\text{tot}} \) = Traverse Distance Efficiency

\[ \eta_{\text{tot}} = \frac{x_{\text{MEPL}}}{x_a + \left( \frac{e_{a} \times x_{\text{MEPL}}}{100} \right)} \]

Where:

- \( x_a \) = Actual Distance Traveled (Distance Tracked)

And:

\[ e_{a} = \% \text{Tracking Distance Error} = \left( \frac{x_a - x_{\text{MEPL}}}{x_{\text{MEPL}}} \right) \times 100 \]

- Time required to arrive at the target destination
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- Success at safely navigating past insurmountable obstacles
  (Obstacle Avoidance Capability and Navigation Safety)

Test Location:

A location similar in concept to the Martin-Marietta rover test facility in Denver, CO

NOTE 1: Rocks and obstacles in the simulated Martian landscape will be distributed according to the following relations derived from rock observations at the Viking Lander - 2 site:

\[ N = 0.013D^{-2.66} \]

where \( N \) is the cumulative frequency of rocks per meter-squared with diameters of \( D \) and larger. And

\[ A = 0.0408D^{-0.66} \]

where \( A \) is the cumulative fraction of area covered by assumed circular rocks of diameters \( D \) and larger (rocks will not be circular in the simulated landscape).
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Unique Navigation and Control Capability Demonstration Test (NAV.5)

Capabilities Tested/Demonstrated/Inspected:

As determined by design teams

Test Description:

Design teams will be permitted to demonstrate any navigation and control capabilities and features unique to their rover.

Test Variables:

As determined by design teams

Parameters Measured:

The rover's demonstrated unique capabilities and features will be recorded. These will be included in the summary of the rover's overall performance capabilities.

Test Location:

TBD
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Scientific Support Tests

NOTE: Scientific support testing can be incorporated into autonomy testing by including science and technology experiment demonstrations in extended autonomous scenarios (AUT.1). Tests SCI.1 and SCI.2 provide the opportunity for specific science/technology experiment testing.

Science Experiment Support Demonstration (SCL.1)

Capabilities Demonstrated/Inspected:
Experiment Capabilities (as required): Carrying/Storage, Deployment, Conduction, Monitoring, Power Provision, Data Storage, Data Processing, Data Transmission

Technical Design Review:

For each specific scientific experiment, the applicable rover experiment support capabilities will be documented. For example, for a seismometer deployment experiment, the rover's available seismometer storage space, robotic arm capability, etc. will be examined and documented. An overall review and assessment of a rover's support capability for each experiment will be accomplished.

Test Description:

A rover will be placed in simulated Martian terrain and commanded to accomplish science experiments. Specific test scenarios will depend on selected science experiments and their requirements.
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Typical scenarios are:

Image a rock; transmit the image data.

Deploy a dummy seismometer; transmit deployment verification data.

Approach a specified rock; place dummy APX-S against rock; accomplish APX-S experiment.

Test Variables:

Type and number of science experiments

Science experiment specifications (e.g. image toward specific heading, APX-S of specific rock, etc.)

Terrain severity/complexity

Parameters Measured:

Successful accomplishment of science experiments according to experiment/mission requirements

Test Location: TBD
Technology Experiment Support Demonstration (SCL2)

Capabilities Demonstrated/Inspected:
Experiment Capabilities (as required): Carrying/Storage, Deployment, Conduction, Monitoring, Power Provision, Data Storage, Data Processing, Data Transmission

Test Description:
A rover will be placed in simulated Martian terrain and commanded to accomplish technology experiments. Specific test scenarios will depend on selected technology experiments and their requirements.

Typical scenarios are:
Perform a soil mechanics test; transmit the test data.
Transmit technology experiment data (sensor performance data, location data, vehicle performance data, thermal data etc.)

Test Variables:
Type and number of technology experiments in scenarios
Technology experiment specifications
Terrain severity/complexity

Parameters Measured:
Successful accomplishment of technology experiments (pass/fail)

Test Location: TBD
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Unique Scientific Support Capability Demonstration (SCL3)

Capabilities Tested/Demonstrated:

As determined by design teams

Test Description:

Design teams will be permitted to demonstrate any science and technology experiment support capabilities and features unique to their rover.

Test Variables:

As determined by design teams

Parameters Measured:

The rover's demonstrated unique capabilities and features will be recorded. These will be included in the summary of the rover's overall performance capabilities.

Test Location:

TBD
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**Autonomy Tests**

**Integrated Autonomous Rover Scenarios (AUT.1)**

**Capabilities Tested/Demonstrated/Inspected:**

- Overall Autonomous Performance
- Required Transmissions for Given Typical Rover Day
- Task Prioritization and Scheduling
- Health and Performance Monitoring and Reporting
- Efficiency of Interactions Required to Guide Rover

**Technical Design Review:**

Information will be collected from each design team which will help indicate the general level of the rover's autonomy, as well as some of its specific autonomous capabilities. Analysis of the information collected will weigh heavily on the judgment of the level of rover autonomy in this test. Following is a list of the desired information.

1. A description of human interactions required to guide the rover.
2. A flow diagram of the rover's prioritization and scheduling of activities and tasks.
3. A listing of and collection/transmission time schedule for all collected and transmitted health information.

Each of these categories of collected information is further described below.
1. A description of human interactions required to guide the rover.

Design teams must provide the content and estimated number of bits of required data/commands transmitted from Earth for commanding their rover for a given typical day of rover mission taskings. Required data/commands include: destination data, hazard information (as required), experiment/task commands and instructions (TBD), position/navigation update data (as required), and error recovery commands (if required during test scenarios).

Design teams must also provide a description of the human actions required to collect and send the above information. This includes any necessary processing of rover or lander information, or the use of additional equipment (e.g. 3-D image "helmets" etc.)

2. A flow diagram of the rover's prioritization and scheduling of activities and tasks.

Design teams will show how their rover will "wisely" carry out its given day's tasks and activities according to the following considerations:

A. Rover Limitations:
   Mobility Restrictions (hazards and obstacles)
   Power Budget Restrictions (to include solar collection requirements)
   Thermal Restrictions (cycling changes during sol)
   Any Other Rover Restrictions Specific to Rover Design
B. Mission Restrictions:

Command Cycle Timing Restrictions

Lander Capability Restrictions (Data download and any restrictions imposed from any other rover interactions with the lander required by rover design)

Restrictions Imposed by TBD Experiments (Temperature requirements, Tilt/Inclination restrictions, etc.)

3. A listing of and collection/transmission time schedule for all collected and transmitted health information.

Design teams will list all of the health data which their rover collects on itself (rover locations, temperatures, mechanical part positions, motor currents, etc.) and explanations (as necessary) of what useful information the data provides. Teams will also list which of these values will be transmitted to the lander as rover health/status information, and the planned schedule of transmissions of each. Health information includes the rover's own detection and/or analysis of degraded performance or inoperation. Any special "flags" the rover transmits based on its own analysis of health information should be included in the description.

Areas a rover should monitor and report include:

A. Subsystem Performance and Status

   Power
   Drive Motors
   Steering Motors
   Other Actuators
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Sensors
Processor
Thermal Subsystem
Communication Subsystem
Other Subsystems Unique to Rover Design

B. Navigation Performance

Current Location/Heading/Inclination/Tilt
Detection of Limit Cycles
Detection of "Traps"
Detection of Unusual/Unanticipated Performance
Detection of Location/Heading/Tracking/Errors (From Irregular Feedback)

Test Description:

A rover will be placed in simulated Martian terrain. Design teams will be given a typical rover day scenario. Design teams will transmit to the rover in a single command cycle all the required information for the rover to accomplish the scenario. The rover will demonstrate its ability to accomplish the given scenario. Testing can be repeated using different typical day scenarios, and may extend several days to ensure a complete system performance evaluation (See Note 1).

Test Variables:

Given typical day scenarios
Type/complexity of Martian terrain
Parameters Measured (See Note 2):

Overall Autonomous Performance (Successful accomplishment of typical rover day taskings and activities). A point scale can be established for all the day's specific tasks and activities. Points will be subtracted from a perfect score for deviations, incomplete task accomplishments, or general rover problems/failures. Point values for tasks and activities will be assigned based on requirements of chosen typical rover day scenarios.

- Number of instructions transmitted
- Number of bits transmitted
- Successful accomplishment of: communication, health and performance monitoring and reporting, and each scenario task
- Manhours required to command and control rover for typical rover day (total time to review and analyze data, decide rover taskings, translate and transmit commands, and monitor rover)
- Simplicity/Ease of commanding rover (subjective assessment)

Test Location:

TBD

NOTE 1: The rover must supply all of its own power for the duration of autonomy scenario testing from internally stored power and/or solar panels. Solar panels will be partially shielded to simulate the decreased solar irradiance on Mars (as low as 36% of Earth's, with an average of approximately 44%). Shielding for testing will ensure a reduction between 40% and 50% of Earth's solar irradiance.
NOTE 2: Autonomy testing will indirectly measure virtually all of the performance parameters described in Mobility, Navigation and Control, and Science and Technology Experiment Support tests. For this reason, autonomy performance should weigh heavily in the overall evaluation of the rover's system performance evaluation.
Fault Response (AUT.2)

Capabilities Demonstrated/Inspected:

Fault Response

Technical Design Review:

Description of Rover Contingency Plans for Possible Faults

A rover should be able to respond appropriately to problems detected in its health information. This response can be either self-initiated or commanded from Earth. Design teams will describe how their rover has fault tolerances or contingency plans for:

Basic Mechanical Failures:

Drive Motor Failure
Steering Motor Failure
Panning, Deployment, or Any Other Motor/Actuator Failure
Suspension Failure
Failure of Any Other Moving Part

Basic Electrical/Electronic Failures:

Navigation Sensor Failure (for each sensor)
Camera Failure
Communication Failure (Both Rover and Lander Failures)
Guidance/Navigation Instrument Failure (for each instrument)
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Thermal Subsystem Failure (heaters and/or insulation failures)

Solar Panel Failure
Battery Failure
Payload Experiment Failure
Failure of Any Other Electrical/Electronic Component

Software Failures ("Watchdog" timer?)

Earth Command/Instruction Failures (e.g. an instruction which would require the rover to drive off of a cliff to accomplish it. This should be addressed by design teams in Task and Activity Prioritization and Scheduling). This capability is partially demonstrated during hazardous terrain survival testing (NAV.3).

Design teams should also describe any capabilities their rover may have for accepting override commands from the Earth which would provide additional flexibility in handling difficult, complex, or otherwise unanticipated situations. This would include the capability of sending a new software download to the rover.

Test Description:

The rover will be commanded to accomplish basic rover tasks and activities. During these tasks and activities, standardized faults will be imposed on the rover as possible. The rover's response and subsequent performance will be monitored.
Possible standardized faults include:

- Failed motor/actuator (Simulated by disconnected wiring -- See Note 1)
- Failed navigation sensor (Simulated by disconnected wiring, or simply placing a covering over the sensor)
- Incorrect command/navigation error (See Note 2)
- Other predicted common potential failures (highly dependent on individual rover design. MTBF information for components will probably not be available for most rover designs to aid in selecting common potential failures for each rover)

**Test Variables:**

- Type of fault
- Severity of fault
- Overall task/mission commanded

**Parameters Measured:**

- Successful discovery and reporting of failure (30 %)
- Successful implementation of response actions (40 %)
- Successful task/activity accomplishment with failure (30 %)

**Test Location:**

TBD
NOTE 1: The motor chosen for failure should probably be one of the front wheels. Three-dimensional simulations of the MITy micro rover mobility performance have shown that a front wheel motor failure on a six-wheeled rover degrades mobility and navigation performance much more than a middle or rear wheel failure.

NOTE 2: Some rovers may specify target destinations as specific objects for the rover to find. The navigation instruction fault response of these rovers can be tested by providing them a traverse command with a known error. The actual destination object may be displaced by a known amount, and the ability of the rover to arrive at the object (by adapting and responding to the error) can be measured.
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Unique Autonomy Capability Demonstration Test (AUT.3)

Capabilities Tested/Demonstrated:

As determined by design teams

Test Description:

Design teams will be permitted to demonstrate any autonomy capabilities and features unique to their rover.

Test Variables:

As determined by design teams

Parameters Measured:

The rover's demonstrated unique capabilities and features will be recorded. These will be included in the summary of the rover's overall performance capabilities.

Test Location:

TBD
Environmental Stress Tests

Vibration Test (ENV.1)

Capability Tested:

Launch Vibrations Handling Capability

Test Description:

Design teams will configure the rover as planned for launch to include attaching the rover to vibration isolators (if included in rover/lander interface plan). The rover and vibration isolators will be mounted to a shake table. The rover will be subjected to the sinusoidal and random vibration amplitudes and frequencies as presented in Chapter 8 -- Environmental Stress Resistance.

After the shake table test, the rover will be examined for damage or loosened components. The rover will be reconfigured for roving on Mars, and commanded to accomplish basic operations (See Note 1).

Test Variables:

- Vibration Frequency
- Vibration Magnitude
- Vibration Duration
- Basic operations required

Parameters Measured:

- Degree of damage (if any)
- Successful accomplishment of all basic rover operations after vibration testing
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Test Location: TBD

NOTE 1: Frequently during environmental stress testing, the rover will be required to demonstrate basic operational capabilities. "Basic operations" refers to a standard set of commanded instructions such as:

Rove straight ahead
Turn left, turn right
Move all actuators specific to rover
Activate sensors
Activate thermal subsystem (if applicable)
Activate other subsystems specific to rover
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**Loads Test (ENV.2)**

**Capability Tested:**

Loads Handling Capability

**Test Description:**

The rover will be configured as planned for launch. The rover will be subjected to loads 1.5 times what will be expected during launch on a Delta launch vehicle as discussed in Chapter 8 -- Environmental Stress Resistance.

After the loads test, the rover will be examined for damage or loosened components. The rover will be reconfigured for roving on Mars, and commanded to accomplish basic operations.

**Test Variables:**

Simulated launch load magnitude

Simulated launch load duration

Basic operations required

**Parameters Measured:**

Degree of damage (if any)

Successful accomplishment of all basic rover operations after loads testing

**Test Location:**

TBD
Shock Test (ENV.3)

Capabilities Tested:

Separation Shock Handling Capability
Ground Impact Shock Handling Capability

Test Description:

The rover will be configured as planned for landing, mounted as planned to the lander (probably inside a container), and mounted to a shock table. The rover container will be subjected to 1.4 times the shock anticipated from Delta launch vehicle separation. The rover will be reconfigured (if required) for landing, and subjected to 1.4 times the shock anticipated from ground impact on Mars (anticipated impact load is approximately 50 g's). In addition, the rover will be subjected to 1.4 times the shock anticipated from the use of deployment pyrotechnic devices, as discussed in Chapter 8 -- Environmental Stress Resistance.

After the shock test, the rover will be examined for damage or loosened components. The rover will be reconfigured for roving on Mars, and commanded to accomplish basic operations.

Test Variables:

Shock magnitude
Basic operations required
Parameters Measured:

- Degree of damage (if any)
- Successful accomplishment of all basic rover operations after shock testing

Test Location:

- TBD
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Thermal-Vacuum Test (ENV.4)

Capabilities Tested:
- Thermal Shock Handling Capability
- Thermal Cycling Handling Capability
- Pressure Change Handling Capability
- Low Pressure Operational Capability

Test Description:
Design teams will configure the rover as planned for launch. The rover will be placed in a thermal-vacuum test chamber (deep space simulator) on a test stand which will allow it to configure itself for deployment and operation on Mars. The rover will be instrumented to monitor and record the performance of all functions. The chamber will be evacuated, and the rover will be subjected to temperatures and temperature changes expected inside the lander-transit vehicle during Earth to Mars transit and Martian atmosphere entry (as discussed in Chapter 8 -- Environmental Stress Resistance). Energy expended to activate a thermal control subsystem (if required) will be measured.

The rover will then be commanded to configure itself for roving operations on Mars. The chamber pressure will be increased to .01 Earth atmospheric pressure. The rover will be subjected to temperatures and thermal cycling in accordance with anticipated Martian thermal extremes (as discussed in Chapter 8 -- Environmental Stress Resistance). Energy expended to activate a thermal control subsystem (if required) will be measured. The rover will be required to simulate basic operations during testing.
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Test Variables:

Initial temperature
Magnitude of temperature change (simulated Mars atmosphere entry)
Thermal cycle temperature range
Thermal cycle duration
Basic operations required

Parameters Measured:

Rover survival and subsequent deployment reconfiguration after simulated entry temperature change (demonstrated)
Accomplishment of basic operations during thermal cycling
Degradation of actuator performance during thermal cycling (voltage required vs. RPM)
Pressure change handling capability (Demonstration of successful rover reconfiguration after pressure change)
Low Pressure Operational Capacity (Demonstrated)
Percent Energy Consumed During Thermal Cycle (if required -- measurement similar to % energy consumption for mobility and navigation testing)

Test Location:

TBD
Wind and Dust Test (ENV.5)

Capabilities Tested:
- Wind Resistance
- Dust Resistance
- Dust Storm Resistance

Test Description:

The rover (or an appropriate mock up) will be placed in an enclosed room with a floor covered with Martian drift simulant. A ducted fan will blow the drift simulant against the rover so that the dynamic pressure will be equivalent to twice the dynamic pressure expected during wind and dust storms on Mars (Approximately 6 m/s -- See Note 1). The rover will be instructed to accomplish basic operations. The rover will be rotated 45° and the test will be repeated. This will continue until the rover has rotated 360°. The rover will then be examined to assess the impact of a simulated dust storm.

Test Variables:
- Wind velocity
- Simulant (type, depth, preparation)
- Duration of test wind/dust storm
- Basic operations required

Parameters Measured:
- Operation of rover during dust storm
- Operation of rover after simulated dust storm
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Amount of dust collection inside rover cavities
Degree of dust penetration within sealed rover compartments

Test Location:
TBD

NOTE 1: The required dust/wind velocity for a test performed on Earth to achieve an equivalent dynamic pressure \( \frac{1}{2} \rho V^2 \) during a wind/dust storm on Mars is calculated using:

\[ PV = nRT \]

Where \( P \) = pressure, \( V \) = volume, \( n \) = number of moles = mass/(molecular weight),
\( R \) = universal gas constant, \( T \) = temperature
Rearranging, we can solve for the density by:

\[ \rho = \frac{P \text{ (mol. wt)}}{RT} \]

Assumptions:

- Earth air is composed of 2/3 Nitrogen and 1/3 Oxygen
- Mars air is composed entirely of Carbon Dioxide
- Mars atmospheric pressure is 1% of Earth's
- Average temperature on Earth during testing is 292° Kelvin
- Temperature on Mars ranges between 150° and 240° Kelvin

Solving for the density ratios, this gives us a range for \( \frac{\rho \text{(Earth)}}{\rho \text{(Mars)}} \) between 34.1 and 54.5. The average density ratio value is 44.3. Substituting into the dynamic pressure equation, we approximate the equivalent Earth/Mars wind velocity ratio to be 0.15. Thus, to simulate an equivalent dynamic pressure for a Martian dust storm with winds at 20 m/s, the equivalent Earth test wind velocity must be 3 m/s.
Chapter 9: Test Plan

Radiation Test (ENV.6)

Capability Tested:

Cosmic Radiation Resistance

Test Description:

The rover will be placed in a radiation simulation chamber. The rover will be subjected to twice the level of cosmic radiation expected during space travel and operations on Mars. The rover will be commanded to accomplish basic operations.

Test Variables:

Type of radiation
Level and exposure time of radiation
Basic operations required

Parameters Measured:

Degree of damage to processor and/or components (number of single event phenomena (SEP's) and single event upsets (SEU's))

Successful accomplishment of all basic rover operations after cosmic radiation test

Test Location:

TBD
Chapter 9: Test Plan

Unique Environmental Stress Capability Demonstration Test (ENV.7)

Capabilities Tested/Demonstrated:
  As determined by design teams

Test Description:
  Design teams will be permitted to demonstrate any environmental stress resistance capabilities and features unique to their rover.

Test Variables:
  As determined by design teams

Parameters Measured:
  The rover's demonstrated unique capabilities and features will be recorded. These will be included in the summary of the rover's overall performance capabilities.

Test Location:
  TBD
Plan Review (ENV.8)

Plan Review Description:

The following plans will be collected from design teams and reviewed for feasibility and effectiveness, simplicity, and completeness:

1. Rover/Lander Interface Plans (Launch, In-Transit, and Landing)
2. Health Monitoring and Communications Plans (In-Transit and Post-Landing)
3. Deployment from Lander Plan

A summary of the results of the plan reviews will be included in the overall evaluation of each rover.
CHAPTER 10
MICRO ROVER PERFORMANCE MEASUREMENT AND TESTING SUMMARY

Development of Requirements, Metrics, and Tests

One of the inherent difficulties associated with developing requirements, performance measurements and tests arises from the fact that: 1) effective methods for accomplishing specific design goals and objectives vary widely, and 2) as a result, rover designs and design approaches also vary radically. Each of the rover designs currently under consideration for inclusion in the MESUR missions contain unique mobility, navigation, and functional strategies. Future rovers will undoubtedly explore and challenge the performance limitations of current rovers.

Counter to this innate diversity, there is also a degree of intrinsic commonality between rover designs. Even a rover which was not designed for space flight or any planetary type mission must still have some means of propulsion, some degree of mobility, a sensing capability (even if all of the sensing is performed by humans), some ability to respond to the sensed information (even if all response is accomplished by humans), and a higher purpose for existence (there must be some specific purpose for designing a mobile robot, even if it is only for human interest or research experience). This research has attempted to extract that which is common and fundamental to enable valid measurements and comparisons.
Chapter 10: Performance Measurement and Testing Summary

What a rover must do is dictated by its stated (or unstated) requirements. The ability of the rover to meet those requirements is a direct indicator of the success of its design.

This thesis develops micro rover requirements and proposes metrics and tests to quantify the fulfillment of those requirements. Specifically, this research includes: 1) development of fundamental requirements based upon probable Mars missions planned for the next 10 - 15 years, 2) performance metrics to quantify the accomplishment of each of those requirements, and 3) proposed tests which, collectively, measure all of the proposed performance metrics.

The most important foundation upon which a rover assessment methodology can be built is a firm set of requirements. All capabilities are measured relative to a standard, and without one, comparisons and performance measurements are invalid.

In lieu of this, strong emphasis is placed on the development of relevant, nonexclusive, and exhaustive rover requirements. Specifically, requirements were sought which related to the most probable scenarios in which a micro rover flown to Mars would be expected and required to operate. The measures themselves follow directly from specific requirements, thus ensuring that all relevant (and only relevant) capabilities are measured and tested.
Summary of Requirements and Performance Metrics

Following are summaries of the requirements and performance metrics proposed and discussed in this research.
Fundamental Micro Rover Requirement #1:

Survive the Environments (Launch, Transit, Landing, and Martian Surface)

Table 10-1. Specific Environmental Stress Resistance Requirements, Tested/Demonstrated/Inspected Capabilities, and Test References

<table>
<thead>
<tr>
<th>Specific Requirement Description</th>
<th>Capabilities Tested/ Demonstrated/Inspected</th>
<th>Test Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survive in the launch environment</td>
<td><strong>Demonstrated:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Launch Vibrations Handling</td>
<td>ENV.1</td>
</tr>
<tr>
<td></td>
<td>Loads Handling</td>
<td>ENV.2</td>
</tr>
<tr>
<td></td>
<td>Pressure Change Handling</td>
<td>ENV.4</td>
</tr>
<tr>
<td></td>
<td><strong>Inspected:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rover/Lander Interface</td>
<td>ENV.8</td>
</tr>
<tr>
<td>Survive in the transit environment (Earth to Mars)</td>
<td><strong>Demonstrated:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Separation Shock Handling</td>
<td>ENV.3</td>
</tr>
<tr>
<td></td>
<td>Thermal Cycling Handling</td>
<td>ENV.4</td>
</tr>
<tr>
<td></td>
<td>Cosmic Radiation Resistance</td>
<td>ENV.6</td>
</tr>
<tr>
<td></td>
<td><strong>Inspected:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rover/Lander Interface</td>
<td>ENV.8</td>
</tr>
<tr>
<td></td>
<td>In-Transit Health Monitoring and Communications Plan</td>
<td>ENV.8</td>
</tr>
<tr>
<td>Survive in the landing environment</td>
<td><strong>Demonstrated:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermal Shock Handling</td>
<td>ENV.4</td>
</tr>
<tr>
<td></td>
<td>Loads Handling</td>
<td>ENV.2</td>
</tr>
<tr>
<td></td>
<td>Pressure Change Handling</td>
<td>ENV.4</td>
</tr>
<tr>
<td></td>
<td>Ground Impact Shock Handling</td>
<td>ENV.3</td>
</tr>
<tr>
<td></td>
<td><strong>Inspected:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rover/Lander Interface</td>
<td>ENV.8</td>
</tr>
<tr>
<td>Survive in the Martian environment</td>
<td><strong>Demonstrated:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermal Cycling Handling</td>
<td>ENV.4</td>
</tr>
<tr>
<td></td>
<td>Wind Resistance</td>
<td>ENV.5</td>
</tr>
<tr>
<td></td>
<td>Dust Resistance</td>
<td>ENV.5</td>
</tr>
<tr>
<td></td>
<td>Dust Storm Resistance</td>
<td>ENV.5</td>
</tr>
<tr>
<td></td>
<td>Low Pressure Operational Cap.</td>
<td>ENV.4</td>
</tr>
<tr>
<td></td>
<td><strong>Inspected:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Post-Landing Health Monitoring &amp; Communications Plan</td>
<td>ENV.8</td>
</tr>
<tr>
<td></td>
<td>Deployment from Lander Plan</td>
<td>ENV.8</td>
</tr>
</tbody>
</table>
Fundamental Micro Rover Requirement #2:
Rove Across/Through Mars Terrain

Table 10-2. Specific Mobility Requirements, Tested/Demonstrated/Inspected Capabilities, and Test References

<table>
<thead>
<tr>
<th>Specific Requirement Description</th>
<th>Capabilities Tested</th>
<th>Test Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traverse unobstructed, level terrain</td>
<td>Forward/Backward Pull Force Traction Turning Radius Maneuvering Turning Radius (opt) Mobile Operation in Reduced g (opt)</td>
<td>MOB.1 MOB.1 MOB.2 MOB.2 MOB.1, 2</td>
</tr>
<tr>
<td>Traverse unobstructed, sloping terrain</td>
<td>Tipover Angles Slope Slip Angles Slope Climb/Descent Capab. Slope Climb. Energy Consumption</td>
<td>MOB.3 MOB.3 MOB.4 MOB.4</td>
</tr>
<tr>
<td>Surmount small obstacles and benign terrain features</td>
<td>Largest Surmountable Obstacle Largest Surmt. Obs. on Slope Obs. Climbing Energy Consumption</td>
<td>MOB.5 MOB.5 MOB.5</td>
</tr>
<tr>
<td>Surmount hazardous obstacles and traverse hazardous terrain</td>
<td>Largest Survivable Hazardous Obstacles/Terrain</td>
<td>MOB.6</td>
</tr>
</tbody>
</table>
**Table 10-3. Specific Navigation and Control Requirements, Tested/Demonstrated/Inspected Capabilities, and Test References**

<table>
<thead>
<tr>
<th>Specific Requirement Description</th>
<th>Capabilities Tested/Demonstrated/Inspected</th>
<th>Test Reference</th>
</tr>
</thead>
</table>
| Navigate from point A to point B on level terrain with no obstacles | **Tested:**  
Nav. Accuracy and Reliability  
Navigation Speed  
Navigation Energy Consumptn.  
Location & Hdg. Knowledge  
**Inspected:**  
CPU Specs and Capabilities  
Sensor Specs and Capabilities | NAV.1, 2  
NAV.1  
NAV.1,2,4  
NAV.1, 2 |
| Navigate from point A to point B on level terrain with hazardous obstacles | **Tested:**  
Traverse Distance Efficiency  
Traverse Time  
**Demonstrated:**  
Obstacle Avoidance Capability  
Navigation Safety | NAV.2  
NAV.2  
NAV.2 |
| Navigate from point A to point B on hazardous terrain with no obstacles | **Demonstrated:**  
Hazardous Terrain Survival | NAV.3 |
| Navigate from point A to point B on hazardous terrain with hazardous obstacles | **Tested:**  
Integrated Navigational Capability | NAV.4 |
### Table 10-4. Specific Scientific Support Requirements, Tested/Demonstrated/Inspected Capabilities, and Test References

<table>
<thead>
<tr>
<th>Specific Requirement Description</th>
<th>Capabilities Demonstrated/Inspected</th>
<th>Test Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carry/Store experiments</td>
<td>Exper. Carrying/Storage Capab (Demonstrated/Inspected)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Deploy experiments</td>
<td>Experiment Deployment Capab (Demonstrated)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Conduct experiments</td>
<td>TBD Exper. Conduction Capab (Demonstrated/Inspected)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Monitor experiments</td>
<td>Experiment Monitoring Capab (Demonstrated/Inspected)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Provide power for experiments</td>
<td>Power Production Capability (Demonstrated/Inspected)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Collect and store experiment data</td>
<td>Processor Data Storage Capab (Demonstrated/Inspected)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Process experiment data</td>
<td>Data Processing Capability (Demonstrated/Inspected)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Transmit experiment data to Lander</td>
<td>Experiment Data Transmission Capability (Demonstrated/Inspected)</td>
<td>SCI.1, 2</td>
</tr>
<tr>
<td>Provide TBD other required support for experiments</td>
<td>TBD Capabilities</td>
<td>SCI.1, 2</td>
</tr>
</tbody>
</table>
Fundamental Micro Rover Requirement #5:

Conduct All Operations on Mars Semi-Automously

Table 10-5. Specific Autonomy Requirements, Tested/Demonstrated/Inspected Capabilities, and Test References

<table>
<thead>
<tr>
<th>Specific Requirement Description</th>
<th>Capabilities Tested/Demonstrated/Inspected</th>
<th>Test Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conduct operations with minimum transmitted data and commands from Earth</td>
<td>Overall Autonomous Performance&lt;br&gt;Required Transmissions for Given Typical Rover Day (Tested/Inspected)</td>
<td>AUT.1&lt;br&gt;AUT.1</td>
</tr>
<tr>
<td>Prioritize and schedule tasks and activities</td>
<td>Task Prioritization and Scheduling (Demonstrated/Inspected)</td>
<td>AUT.1</td>
</tr>
<tr>
<td>Monitor and report health and performance</td>
<td>Health and Performance Monitoring and Reporting (Demonstrated/Inspected)</td>
<td>AUT.1</td>
</tr>
<tr>
<td>Respond to Faults</td>
<td>Fault Response (Demonstrated/Inspected)</td>
<td>AUT.2</td>
</tr>
<tr>
<td>Demonstrate Command and Control Efficiency</td>
<td>Efficiency of Interactions Required to Guide Rover (Tested/Inspected)</td>
<td>AUT.1</td>
</tr>
</tbody>
</table>

All requirements and necessary capabilities are directly measured in a series of proposed tests (referenced in the preceding tables) which are described in Chapter 9. Following is a summary listing of proposed tests.
Summary of Micro Rover Tests

Mobility Tests

MOB.1 Drawbar Pull
MOB.2 Turning Radius
MOB.3 Rover Tipover and Slip
MOB.4 Slope Climb and Descent
MOB.5 Small Obstacle Climbs
MOB.6 Hazardous Obstacles and Terrain
MOB.7 Unique Mobility Capability Demonstration Test

Navigation and Control Tests

NAV.1 Straight-Line Navigation
NAV.2 Obstacle Avoidance
NAV.3 Hazardous Terrain Navigation
NAV.4 Mars Scape
NAV.5 Unique Navigation and Control Capability Demonstration

Science & Technology Experiment Support Tests

SCI.1 Science Experiment Support Demonstration
SCI.2 Technology Experiment Support Demonstration
SCI.3 Unique Science & Technology Experiment Support Capability Demonstration Test
Chapter 10: Performance Measurement and Testing Summary

Autonomy Tests

AUT.1 Integrated Autonomous Rover Scenarios
AUT.2 Fault Response
AUT.3 Unique Autonomy Capability Demonstration Test

Environmental Stress Tests

ENV.1 Vibration Test
ENV.2 Loads Test
ENV.3 Shock Test
ENV.4 Thermal-Vacuum Test
ENV.5 Wind and Dust Test
ENV.6 Radiation Test
ENV.7 Unique Environmental Stress Capability Demonstration Test
ENV.8 Plan Review

Using This Research: Some Practical Hints

Prioritizing Rover Requirements

To determine the relevance of the proposed performance metrics and tests for a given rover, one must first determine the suitability of the established requirements. If the requirements are relevant, nonexclusive, and exhaustive to the rover and mission scenario under consideration, the proposed performance metrics will be entirely applicable.
Chapter 10: Performance Measurement and Testing Summary

It is incumbent upon the individual intending to use some or all of the proposed tests to determine beforehand the priority of the required capabilities for the rover and mission under consideration. For example, a mission which will require a rover to explore and image hazardous terrain will have very different priorities than a mission requiring a rover to collect scientific data at non-threatening locations. Each rover may have (and probably will have) the same or close to the same list of general requirements (mobility, navigation, etc.). However, the priority and degree of specification of each of those requirements will necessarily be different based on the mission requirements and priorities.

Thus, from a performance metric and test methodology perspective, the most important foundation is the establishment and prioritization of relevant, nonexclusive, and exhaustive requirements. An engineer desiring to test a rover must know clearly the purpose and goal of his testing. This understanding will influence the selection of performance metrics and the interpretation of test results.

It is also critical to note that a test is not as important as the rover capabilities it is designed to measure. A natural tendency is to categorize a specific test as an end product; it is not. Tests are only a byproduct of the development and prioritization of requirements. Thus, prospective rover test administrators are warned not to administer a test without carefully examining the ultimate purposes of the test with respect to the established requirements and priorities.
Chapter 10: Performance Measurement and Testing Summary

Collecting and Interpreting Results

One important area for future study is an evaluation of techniques and methodologies for combining and interpreting test data. For example, how important is the fact that one rover arrives at a target destination 50% more accurately than another rover? How significant is one rover's ability to climb a 30° slope in comparison to another rover's ability to only climb a 20° slope?

The answers to such questions must be extracted from specific mission requirements and priorities. Navigation accuracy would be critical to a mission requiring precise placement of an experiment (e.g., an APX-S experiment). Slope climbing capability would be more important for a rover destined to explore hazardous terrain. It is imperative that mission designers work closely with test administrators to ensure pertinent testing and data evaluation.

One proposed method of summarizing and examining collected test information is provided in an example based on the currently planned MESUR Pathfinder mission. Specific steps to collect and analyze data are described as follows:

1. Each required rover capability is separately listed and weighted according to priorities required for a specific mission. The weightings provided in this example are arbitrarily determined based upon the current mission proposal for the MESUR Pathfinder mission.
2. Rover performance of each required capability is measured (i.e., all tests are accomplished).

3. Raw performance data is scaled. Test measurements must be scaled according to relative measures (other rovers' performance), or according to absolute measures depending on mission priorities and the nature of the measurement.

4. The previously determined weightings are applied to the scaled results, allowing a summed overall performance rating for each category (note that some categories use pass/fail criteria).

This method provides a measurement of performance in each of the major categories, as well as an overall evaluation of a rover's suitability to perform a specific mission.
### Example Test Data Collection Methodology

**Example Case: MESUR Pathfinder Mission**

#### Mobility Capabilities

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>TEST REF.</th>
<th>WEIGHTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobility Capabilities</td>
<td></td>
<td>Total: 20 %</td>
</tr>
<tr>
<td>Largest Survivable Hazardous Obstacle/Terrain</td>
<td>MOB.6</td>
<td>20 %</td>
</tr>
<tr>
<td>Largest Surmountable Obstacle</td>
<td>MOB.5</td>
<td>10 %</td>
</tr>
<tr>
<td>Largest Surmountable Obstacle on a Slope</td>
<td>MOB.5</td>
<td>10 %</td>
</tr>
<tr>
<td>Slope Climbing Energy Consumption</td>
<td>MOB.4</td>
<td>10 %</td>
</tr>
<tr>
<td>Obstacle Climbing Energy Consumption</td>
<td>MOB.5</td>
<td>10 %</td>
</tr>
<tr>
<td>Forward/Backward Pull Force</td>
<td>MOB.1</td>
<td>5 %</td>
</tr>
<tr>
<td>Traction</td>
<td>MOB.1</td>
<td>5 %</td>
</tr>
<tr>
<td>Turning Radius</td>
<td>MOB.2</td>
<td>5 %</td>
</tr>
<tr>
<td>Maneuvering Turning Radius</td>
<td>MOB.2</td>
<td>5 %</td>
</tr>
<tr>
<td>Mobile Operation in Reduced Gravity</td>
<td>MOB.1, 2</td>
<td>5 %</td>
</tr>
<tr>
<td>Tipover Angles</td>
<td>MOB.3, 6</td>
<td>5 %</td>
</tr>
<tr>
<td>Slope Slip Angles</td>
<td>MOB.3</td>
<td>5 %</td>
</tr>
<tr>
<td>Slope Climb and Descent Capability</td>
<td>MOB.4</td>
<td>5 %</td>
</tr>
</tbody>
</table>

#### Navigation and Control Capabilities

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>TEST REF.</th>
<th>WEIGHTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navigation and Control Capabilities</td>
<td></td>
<td>Total: 20 %</td>
</tr>
<tr>
<td>Integrated Navigational Capability</td>
<td>NAV. 4</td>
<td>20 %</td>
</tr>
<tr>
<td>Navigation Accuracy and Reliability</td>
<td>NAV. 1, 2</td>
<td>10 %</td>
</tr>
<tr>
<td>Traverse Distance Efficiency</td>
<td>NAV. 2</td>
<td>10 %</td>
</tr>
<tr>
<td>Obstacle Avoidance Capability</td>
<td>NAV. 2</td>
<td>10 %</td>
</tr>
<tr>
<td>Navigation Energy Consumption</td>
<td>NAV.1, 2, 4</td>
<td>10 %</td>
</tr>
<tr>
<td>Navigation Speed</td>
<td>NAV. 1</td>
<td>10 %</td>
</tr>
<tr>
<td>Location and Heading Knowledge</td>
<td>NAV. 1, 2</td>
<td>5 %</td>
</tr>
<tr>
<td>Processor Specifications and Capabilities</td>
<td>NAV. 1</td>
<td>5 %</td>
</tr>
<tr>
<td>Navigation Sensor Specifications and Capabilities</td>
<td>NAV. 1</td>
<td>5 %</td>
</tr>
<tr>
<td>Traverse Time</td>
<td>NAV. 2</td>
<td>5 %</td>
</tr>
<tr>
<td>Navigation Safety</td>
<td>NAV. 2</td>
<td>5 %</td>
</tr>
<tr>
<td>Hazardous Terrain Survival</td>
<td>NAV. 3</td>
<td>5 %</td>
</tr>
</tbody>
</table>
## Chapter 10: Performance Measurement and Testing Summary

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>TEST REF.</th>
<th>WEIGHTING</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Science and Technology Exper. Support Capabs.</strong></td>
<td></td>
<td><strong>Total: 20 %</strong></td>
</tr>
<tr>
<td>Experiment Carrying/Storage Capability</td>
<td>SCI.1, 2</td>
<td>P/F</td>
</tr>
<tr>
<td>Experiment Deployment Capability</td>
<td>SCI.1, 2</td>
<td>P/F</td>
</tr>
<tr>
<td>TBD Experiment Conduction Capability</td>
<td>SCI.1, 2</td>
<td>P/F</td>
</tr>
<tr>
<td>Experiment Monitoring Capability</td>
<td>SCI.1, 2</td>
<td>P/F</td>
</tr>
<tr>
<td>Power Production Capability</td>
<td>SCI.1, 2</td>
<td>P/F</td>
</tr>
<tr>
<td>Processor Data Storage Capability</td>
<td>SCI.1, 2</td>
<td>P/F</td>
</tr>
<tr>
<td>Data Processing Capability</td>
<td>SCI.1, 2</td>
<td>P/F</td>
</tr>
<tr>
<td>Experiment Data Transmission Capability</td>
<td>SCI.1, 2</td>
<td>P/F</td>
</tr>
<tr>
<td>TBD Capabilities</td>
<td>SCI.1, 2</td>
<td>P/F</td>
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<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>TEST REF.</th>
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</thead>
<tbody>
<tr>
<td><strong>Autonomy Capabilities</strong></td>
<td></td>
<td><strong>Total: 40 %</strong></td>
</tr>
<tr>
<td>Overall Autonomous Performance</td>
<td>AUT.1</td>
<td>30 %</td>
</tr>
<tr>
<td>Req'd Transmissions for Given Typical Rover Day</td>
<td>AUT.1</td>
<td>20 %</td>
</tr>
<tr>
<td>Health and Performance Monitoring and Reporting</td>
<td>AUT.1</td>
<td>20 %</td>
</tr>
<tr>
<td>Task Prioritization and Scheduling</td>
<td>AUT.1</td>
<td>10 %</td>
</tr>
<tr>
<td>Fault Response</td>
<td>AUT.2</td>
<td>10 %</td>
</tr>
<tr>
<td>Command and Control Efficiency</td>
<td>AUT.1</td>
<td>10 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>TEST REF.</th>
<th>WEIGHTING</th>
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<td><strong>Environmental Stress Capabilities</strong></td>
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<td><strong>Total: Pass/Fail</strong></td>
</tr>
<tr>
<td>Launch Vibrations Handling</td>
<td>ENV.1</td>
<td>P/F</td>
</tr>
<tr>
<td>Loads Handling</td>
<td>ENV.2</td>
<td>P/F</td>
</tr>
<tr>
<td>Pressure Change Handling</td>
<td>ENV.4</td>
<td>P/F</td>
</tr>
<tr>
<td>Rover/Lander Interface</td>
<td>ENV.8</td>
<td>P/F</td>
</tr>
<tr>
<td>Separation Shock Handling</td>
<td>ENV.3</td>
<td>P/F</td>
</tr>
<tr>
<td>Thermal Cycling Handling</td>
<td>ENV.4</td>
<td>P/F</td>
</tr>
<tr>
<td>Cosmic Radiation Resistance</td>
<td>ENV.6</td>
<td>P/F</td>
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<td>Launch, In-Transit, and Post-Landing Health Monitoring and Communications</td>
<td>ENV.8</td>
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<td>Thermal Shock Handling</td>
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<td>P/F</td>
</tr>
<tr>
<td>Ground Impact Shock Handling</td>
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<td>P/F</td>
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<tr>
<td>Wind Resistance</td>
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<td>P/F</td>
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<td>Dust Resistance</td>
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<td>Dust Storm Resistance</td>
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<td>Low Pressure Operational Capability</td>
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<tr>
<td>Deployment from Lander</td>
<td>ENV.8</td>
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Chapter 10: Performance Measurement and Testing Summary

The Future

The performance measurement methods developed in this research will be tested by the Draper Laboratory rover design team and also possibly by the Jet Propulsion Laboratory's rover design team. Test results will hopefully indicate where revisions and additions to these methods may be beneficial. The Draper design team intends to modify this test plan and performance methodology as necessary to ensure it is up-to-date, meaningful and effective.

Many teams and organizations are in pursuit of the most practical, least expensive, and best performing rover design. The myriad design choices available to a systems engineer, many of which lead to effective rover design options, have served to broaden the spectrum of unique rover capabilities and design ingenuities. The future will no doubt support an even greater diversity of designs.

The variety of possibilities is matched by an equivalent diversity in the application of performance measurement techniques. How does one measure the performance of a unique and uncategorizable instrument such as a planetary rover? With great difficulty!

The methods and ideas presented herein are the compilation of many minds and much experience. This research has provided a background of information, ideas, and applicable tools intended to capacitate the sound assessment and comparison of rovers. It is the author's hope that this
work will benefit future engineers and positively influence the design of future rovers flown to Mars.
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