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SYSTEMS ENGINEERING FOR A MARS MICRO-ROVER

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ABSTRACT

A student-run project was initiated to design, build, and launch hardware on a future mission to Mars. A five kilogram, imaging micro-rover was chosen as the project most likely to be launched in support of NASA's Space Exploration Initiative. This thesis focused on the systems engineering aspects of the project.

The mass constraint severely constrained the available power. The mass and power constraints drove the rest of the design. The rover's mission was defined to be 30 days long. The rover was required to traverse 100 meters per day based on commands transmitted from Earth. The rover was also required to transmit 2 pictures per day from the surface of Mars back to Earth. The system was partitioned into 8 subsystems. The mass and power budgets were allocated among the subsystems based on the design of a phase one prototype. Tradeoff studies led to the selection of primary batteries for the power system, and an orbiting link for the communications system. The other subsystems were specified to the greatest detail possible.

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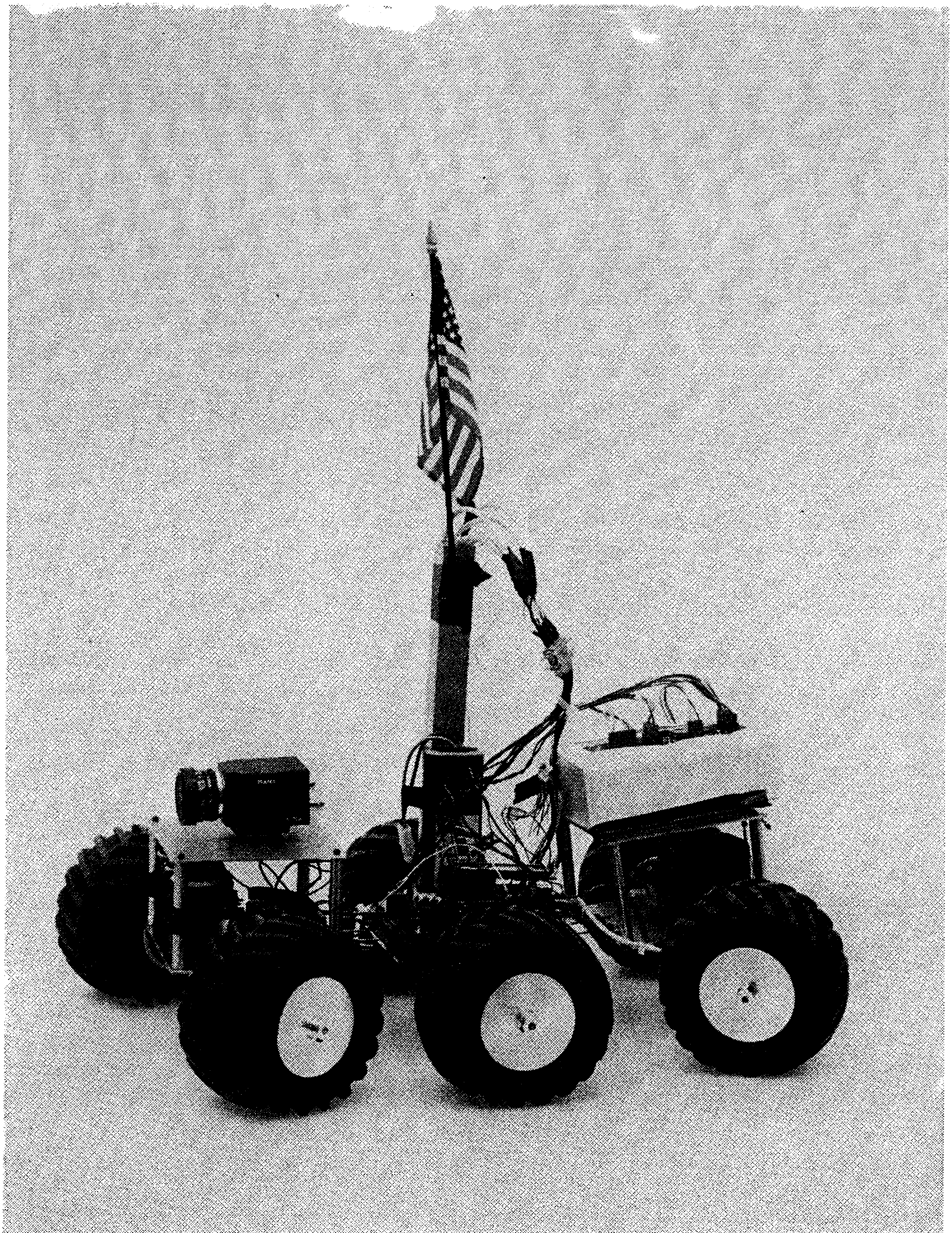

"We shall not cease from exploration,
and the end of all our exploring will be
to arrive where we started and know the
place for the first time."

T. S. Eliot

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

Some day humans will explore Mars. Be it decades or centuries hence, people will explore the Red Planet's surface, and possibly colonize it. Until then, however, robots will be our hands, eyes, ears, and brains. Economic, political, and safety considerations dictate that humans will play a minor role in Martian exploration until technical hurdles in propulsion, life support, and access to low earth orbit are overcome. Robots are less expensive and more expendable than humans. Although they are less able to deal with unknown situations, they can perform some tasks much better.

A large part of any Mars exploration program will be a series of unmanned precursor missions to enlarge the knowledge base of science and engineering data. Surface imaging, atmospheric analysis, meteorology, spectroscopy, and soil sampling are just some of the activities that can be performed well with semi- or fully-autonomous robots. In today's economic environment large sums of money are not readily available for scientific exploration. Unless concrete returns are expected, the space exploration community will have to rely on low-budget missions to accomplish their goals. Consequently, small robots with significant capabilities are high on the list of critical technologies.

1.2 OBJECTIVE

The objective of the Mars micro-rover project was to develop a small, lightweight, roving camera for planetary exploration. It was a student-run project to demonstrate the key role students can play in a results-oriented, low-budget space program. The project's overriding goal was to build a space-qualified micro-rover to be launched on a real mission.

1.3 SCOPE

This thesis focused on the systems engineering aspects of the Mars micro-rover project. It began with the vague concept of designing a small mission to Mars, and concluded with the complete system requirements for a space-qualified micro-rover. Policy questions surrounding space exploration were addressed, including constraints imposed by the United States' national space policy.

1.4 PROJECT GOALS

The key to a successful system design is the definition of goals. Goals lead to system requirements, which flow down to subsystem and lower-level requirements. A successful design is one which allocates resources into an optimal design that fulfills the requirements and accomplishes the goals.

The Mars micro-rover project began with a simple idea. Draper Laboratory wanted to sponsor a student project to demonstrate the contributions students can make to the space program. The criteria for the undefined project were that it have a high probability of being launched, take advantage of the expertise available at Draper Laboratory, and support the Space Exploration Initiative (SEI). Project managers decided that engineering design data was more important to the Space Exploration Initiative than scientific data. Therefore, in order to maximize the chance of launch, they decided the project should generate engineering data to support future SEI missions.

1.5 SYSTEMS ENGINEERING

Systems engineering keeps complex development efforts focused on meeting system requirements. Without good systems engineering, projects are more likely to run over budget, fall behind schedule, require numerous design changes, encounter conflicting interfaces, fail to meet performance requirements, or experience organizational headaches. Systems engineering disciplines engineers to design from the top down. It demands that the highest level objectives and goals be clearly stated before development begins. Designs must be based on system requirements derived from the program goals. Subsystem specifications must logically flow down from the system requirements. The process continues until a complete set of specifications exists for all of the components in the design.

Systems engineering also focuses on subsystem interfaces. The clarity of the lines drawn between interfaces is critical to the success of a design effort. There must be a logical separation of hardware into functional subsystems. The inputs to and outputs from each subsystem must be defined. The means of communication between subsystems must be specified. In summary, systems engineering is a disciplined, common sense engineering approach to developing complex projects so that they meet the design goals.

1.6 THESIS OVERVIEW

This thesis has six chapters. Chapter 1 serves as an introduction and provides background information. Chapter 2 discusses the decision process that led to choosing a Mars micro-rover for the project's focus. Chapter 3 describes the origin of the system requirements, some of the high-level subsystem requirements, and the mission profile. Chapter 4 presents an overview of the rover's design including a system breakdown, subsystem interfaces, resource allocations, and subsystem tradeoff studies. Chapter 5 details the subsystem specifications, interfaces, and required telemetry. Chapter 6 concludes the thesis with a summary of what has been done, and some recommendations for the future.

CHAPTER 2
DEFINING THE MISSION

The Mars Micro-rover project began in January, 1991. It grew out of Draper Laboratory's desire to sponsor a student design project that would result in real flight hardware for the Space Exploration Initiative. The project was to follow the tenets of systems engineering as closely as possible. Design efforts often address problems without adequately understanding what those problems involve. In this case, the problem definition was clear, but there was not adequate knowledge to immediately determine which project would have the best chance of being launched. Five months were spent studying the options before a decision was made. A micro-rover for Mars was determined to have the highest possibility of satisfying the objectives.

This chapter focuses on the project selection process and the analysis that led to the baseline design mission. It outlines the decision process and discusses the history of the Space Exploration Initiative. It presents the project concepts that were considered and explains how the possibilities were evaluated. The chapter concludes with a recommendation for the baseline mission.

2.1. DECISION PROCESS

The process used to determine what hardware was most likely to be launched on a planetary mission is shown in Figure 2.1a. It began with a thorough investigation of the state of the Space Exploration Initiative -- the goals of the effort, the problems it faced, and the persons and institutions involved. The investigation led to a preliminary set of possible topics. Decision criteria were then defined for evaluating the topics on the list. Based on a quick evaluation and a study of current work in planetary exploration, the initial list was narrowed down to five choices. Those concepts were fully evaluated against the criteria, and the micro-rover project was chosen.

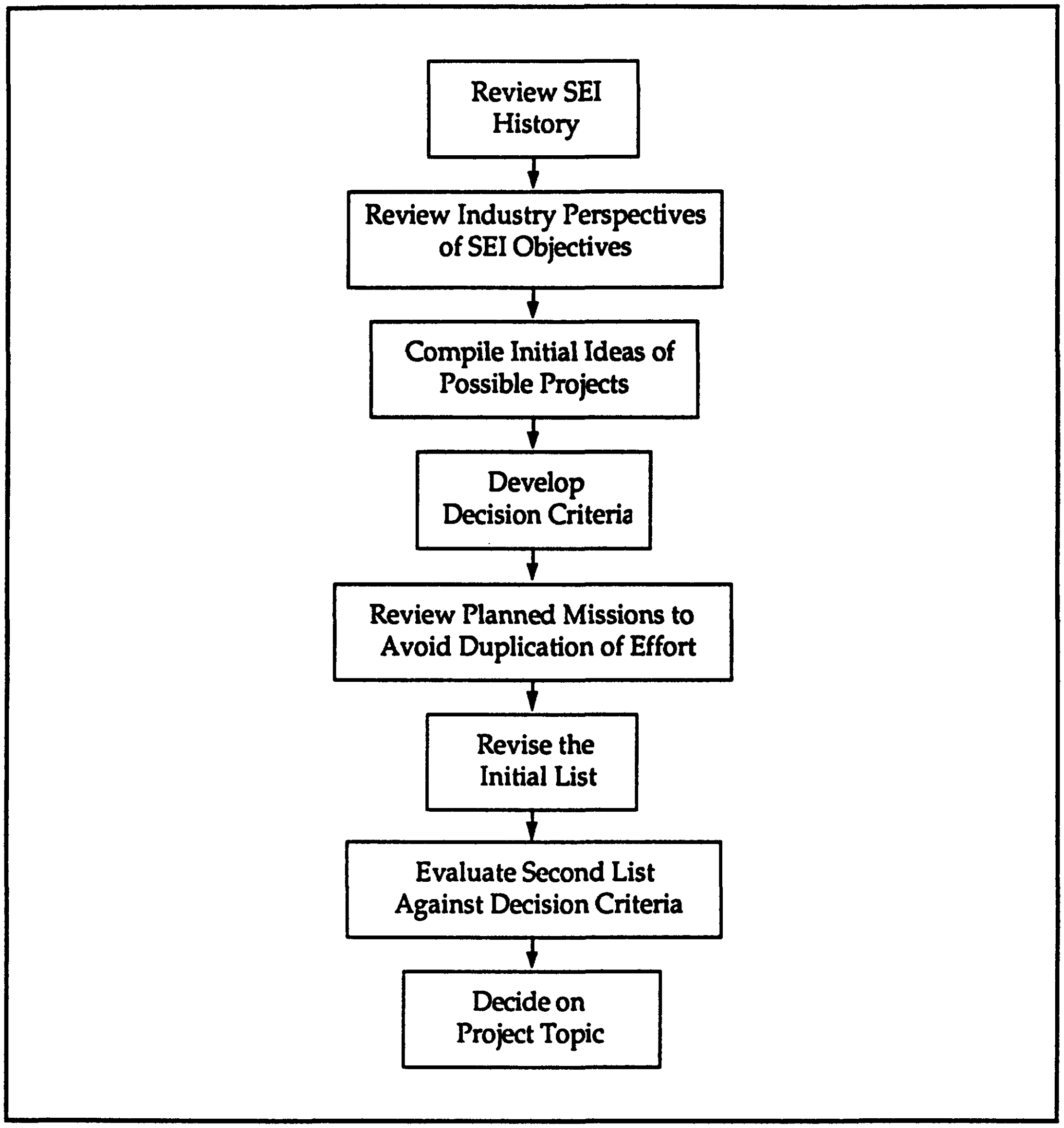

Figure 2.1a - Process for determining project topic

2.2. SPACE EXPLORATION INITIATIVE HISTORY

On the twentieth anniversary of the Apollo Lunar landing, President George Bush announced his interest in pursuing space exploration. He said: "... back to the moon, back to the future. And this time back to stay. And then a journey into tomorrow...a manned mission to Mars." The President's reasons for the Space Exploration Initiative (SEI) were very unclear. Even today there is little justification given for exploring the solar system. The simple answer has been because it is there. But why America? Why now?

After the President's announcement, NASA instituted a 90 day study to develop an implementation plan for SEI. They convened a task team with many of the experts who had been working on Lunar and Mars exploration since 1960. The output of the 90 day study was a $400 billion plan for the next thirty years.

Vice-President Dan Quayle led the response to the 90 day study. He claimed that the report lacked creativity and freshness. He decided that NASA should call on the vast resources of the American public to seek new concepts that would make SEI less expensive, and more successful. NASA Administrator Richard Truly did just that. He assembled three teams to collate the 5000 ideas that were submitted. Then he assembled the Stafford committee to examine the best ideas. The committee's purpose was to suggest several potential architectures upon which a space exploration program could be based.

The Stafford committee struggled with their task for almost a year. It included some of America's most renowned experts in the aerospace industry. Their main difficulty was not identifying the architectures, but defining the goals that would optimize those architectures. During their struggle, they called on many sources for help. One of those sources were the students of a systems engineering seminar at MIT. The class spent half of a semester developing a strategy for the committee to follow. Some of the seminar's ideas were incorporated into the committee's final report. The experience taught the valuable lesson that concrete goals are fundamental to successful endeavors.

The Stafford committee eventually defined six objectives for the Space Exploration Initiative. They are listed in Figure 2.2a. The committee did not prioritize the goals or determine how to achieve them. Instead the committee presented four architectures, each of which would satisfy some of the objectives to varying degrees.

- Expand human presence and activity beyond Earth orbit into the solar system
- Strengthen U.S. security
- Promote science, technology and economic benefits
- Encourage private sector investment
- Promote international cooperative activities
- Maintain freedom of space for all activities

Figure 2.2a - The SEI goals defined by the Stafford Committee

Another advisory committee, led by Norman Augustine, suggested a more concrete focus for America's space program. They said that it was inappropriate to justify space expenditures based on economic returns or short-term benefits to society. Although NASA claimed that previous programs generated benefits in weather forecasting, satellite communications, and technology spin-offs, it is likely that these things would have been developed anyway. The Augustine committee advocated a purely philosophical basis for America's leadership in space exploration. The country must decide to invest a certain amount of money in space activities, and hope there is a worthwhile return at some point in the future. The committee believed that returns will generally be intangible, manifesting themselves because society is pursuing worthy goals [Augustine, 1990].

2.3. INITIAL PROJECT LIST

Since no clear direction had been set by the activities mentioned above, a list of potential projects was developed by reviewing documents published by various organizations involved in the Space Exploration Initiative. Publications from the Jet Propulsion Laboratory, Ames Research Center, and the NASA Exploration office provided a good overview of the major areas of interest to planetary exploration scientists and engineers.

Fourth Mars Science Working Group Minutes

The minutes of the fourth Mars science working group meeting suggested six objectives being considered for the Mars Environmental Survey (MESUR) mission [McKay, 1990]. The first suggestion was to "characterize global atmospheric circulation." It involved an orbiter and a descent craft to measure wind speeds, atmospheric thermal gradients, and atmospheric currents over daily and seasonal periods. Its goal was to improve the database of the Martian atmosphere.

The second suggestion was to "characterize the chemistry and mineralogy of major surface units." It involved several fixed or roving landers to sample and analyze rocks and regolith at various sites on the Martian surface. The third idea was to "characterize the morphology of major surface units at a scale of one meter." It was similar to the second suggestion, although concerned with organic rather than inorganic data.

The fourth suggestion was to characterize the internal structure and seismicity of Mars. Such a mission might involve at least several surface probes, fixed or roving, to measure seismic activity on the surface of Mars, thus improving scientists' understanding of the Martian interior.

The fifth was to analyze the low temperature mineralogy and volatile chemistry of the soil. This suggestion was a variation on the second and third themes with a focus on the low temperature regions of Mars. For example, such a mission might be targeted on the north and south poles to determine water concentrations.

The final suggestion was to analyze the structure of the middle and lower atmosphere. This suggestion was much like the first, although it would require more spectrometry than thermal or wind current profiling. Like the first idea, it would require an orbiter and at least one descent craft.

NASA Ames MESUR Presentation

The NASA Ames MESUR presentation added some information to the fourth Mars science working group minutes, presenting the objectives in a different way [MESUR, 1990]. The first objective was to generate "descent imaging and surface imaging for SEI site selection." The second was to analyze "atmospheric structure for aerocapture application." The third was to "investigate Martian atmospheric characteristics and processes (e.g. atmospheric structure, temperature, pressure, wind, circulation, dust, and water vapor transport)." The fourth objective was to conduct a broad chemical analysis, including an analysis of soil toxicity and a search for volatiles.

The Ames presentation also mentioned that any meteorology or seismology studies required missions longer than one Martian year, and approximately ten to twenty dispersed sampling stations. A final note in the presentation was that impact acceleration studies could be included in any mission using a hard surface landing. Such studies would improve understanding of the surface, and aid development of future hard landing protection schemes.

United States Planetary Rover Status -- 1989

The United States Planetary Rover Status -- 1989 offered a comprehensive overview of exploratory rovers, describing two types of rover missions [Pivirotto and Dias, 1990]. The first was a science mission that might focus on sample collection and characterization. Rovers covering distances up to 1000 km would collect diverse sets of Martian samples for return to Earth. Such a mission might also place seismic or meteorological sensors on the surface.

The second mission would provide engineering support data for later manned missions. One useful function would be the characterization of the surface and subsurface features for landing site selection. Another would be chemical analysis of resources for human use. Unmanned rovers could be used on such a mission as test beds for future construction techniques or resource collection.

Strategy Options for Robotic Missions

The short presentation by NASA Code RZ listed engineering data sets in three categories: critical need, very important need, and important need [NASA Code RZ, 1990]. The listing appears in Figure 2.3a.

Critical Need

- Soil Toxicity
- Dust and Particles
- Radiation
- Micro-meteoroids flux

Very Important Need

- Wind Storms
- Atmospheric Profile
  - Components
  - Temperature
  - Pressure
- Site Specific Topography
  - Rubble Size
  - Rutting/Washboard of Soil
- Engineering Soil Mechanics
  - Angle of Repose
  - Density
- Geochemical Mapping of Mineralogy and Chemistry
- Location of Water Ice or Permafrost
- Electromagnetic Transmission

Important Need

- Subsurface Site
  - Voids
  - Temperature Profile
- Seismic
  - Activity Magnitude
  - Wave Transmission
- Magnetic Field Strength
- Solar Flux at Surface
  - Gamma
  - Ultraviolet
  - X-ray
- Thermal Data
- Global Topographic Imaging

Figure 2.3a - Code RZ list of mission criticality

A Planetary Science Strategy for the Moon

A Planetary Science Strategy for the Moon addressed the question of the distribution of tasks between men and machines [NASA, 1990a]. It specifically assigned certain tasks to unmanned rovers. The first task was *in situ* analysis of the lunar surface. Such measurements are needed for measuring time-dependent phenomena as well as analyzing undisturbed rocks and soils. The second task was geophysical analysis of the rocks, regolith, and bedrock beneath the landing site. The third task was sample analysis to broaden the range of samples returned to Earth. The report suggested that rovers could be used as test beds for telepresence technology. Telepresence can enhance the operational capabilities of an outpost in a hostile environment.

Mars Aeronomy Orbiter Precursor Workshop Minutes

The minutes from the Mars Aeronomy Orbiter Workshop contained interesting information concerning atmospheric studies of Mars [Mars Aeronomy, 1989]. It revealed that little is known about how the solar wind interacts with the Martian atmosphere, how dust storms interact with the upper regions of the atmosphere, or how the air density varies with altitude. Any mission that uses an aerobrake to enter Mars orbit will require that type of detailed data about the Martian upper atmosphere.

Summary

The possible topics that appeared in the presentations discussed above are listed in Figure 2.3b.

- Sample collection and analysis
- Seismology
- Surface and subsurface characterization
    - chemistry
    - mineralogy
    - morphology
    - toxicology
    - volatile inventory
- Landing site analysis
    - imaging
    - soil composition
- Inventory of resources for manned missions
- Atmospheric characterization
    - structure
    - composition
    - meteorology
- Global mapping/descent imaging
- Radiation environment
    - cosmic activity
    - solar activity
- Test bed for telepresence
- Impact acceleration analysis

Figure 2.3b - Preliminary list of potential projects

2.4. DECISION CRITERIA

After the initial list in Figure 2.3b was developed, it became clear that specific criteria were needed to evaluate each topic. The criteria would depend on the goals each of the project participants hoped to achieve and on the outside constraints that impacted the project.

The consensus among the initial participants -- Joseph Shea, Malcolm Johnson, David Kang, and Steven Schondorf -- was that the primary goal of the project should be to maximize the probability of launch. All agreed that launching any project was more important than working on a particular project. Choosing a project based on this criterion would be difficult since the focus of the Space Exploration Initiative was undefined, and it was not at all clear what missions would be most useful to the program. Therefore, the first criterion focused on the number of possible missions that a project could benefit, as well as the significance of those benefits.

The second criterion was related to the first. Although some of the projects seemed worth pursuing based solely on their excitement value, it would not have been effective to choose a project that focused on an interesting area if that area was not valuable to SEI. Therefore the second criterion evaluated the criticality of the data that each project would produce. The second criterion was evaluated based primarily on the Code RZ list shown in Figure 2.3a.

The project selection was also constrained by the limited resources available to it. The abilities of the student participants, the thesis-quality of the graduate students' work, and the cost of the project would all impact the project's success. Since these constraints were difficult to quantify, the third criterion measured how many of the available resources a project used relative to the other projects.

The final criterion was the degree to which the project could be tested on Earth. Although the project's major goal was to build something to visit Mars, it was clear that there was a measurable probability that it would not be launched. It was essential, from the perspective of completing the project despite the ups and downs of SEI's fortunes, that the hardware be tested on Earth and potentially modified for alternative purposes.

Although the four criteria were difficult to evaluate, they provided a framework within which each project could be considered. One of the lessons learned from interacting with the Stafford committee was that broad criteria like these must be applied qualitatively rather than quantitatively. No matter how criteria are quantified, the result will depend primarily on the method used to combine them. Virtually any answer can be justified by weighting the criteria differently. The robustness of a solution can be tested by varying the weights used, but there is no way to determine whether the chosen weights are appropriate.

Based on that lesson, ratings of good, neutral, and bad were used to evaluate potential topics. The projects were rated relative to one another rather than absolutely. Once all of the projects were considered, the ratings were assessed qualitatively to determine which project best satisfied the combined criteria.

2.5. MARS MISSIONS

For applying the first two criteria, *A Strategy for the Scientific Exploration of Mars* was particularly helpful [NASA, 1990b]. It detailed the precursor missions as they were then currently envisioned. The presentation suggested that precursor missions should sharpen scientists' perception of a planet. They should resolve the basic issues which affect the strategy for human exploration. The following paragraphs outline the mission-specific information obtained from the report.

Mars Observer

The Mars Observer mission will analyze surface mineralogy, surface composition, surface altimetry, Mars' gravity field, Mars' magnetic field, atmospheric temperature, pressure, dust, and aerosol profiles, and imaging at 1.4 meters per pixel. The laser altimeter on the Mars Observer should adequately characterize Martian topography. If it does not, it is critical to obtain this information by alternative means. In any case, the Mars Observer mission will be deficient in surface imaging and high resolution imaging of landing sites; i.e. resolutions in the range of 0.25 to 0.5 meters per pixel.

Mars-94

The Mars-94 mission[1] will include surface reflectivity analyses, imaging at 10 meters per pixel resolution, balloon imaging at less than one meter per pixel resolution, and measurement of atmospheric composition, meteorology, and magnetic fields. The Mars-94 mission will also include four instrumented penetrators which might include cameras, magnetometers, seismometers, or meteorological instruments.

---

[1] This Mars-94 mission should not be confused with other missions of the same name. This American mission is no longer planned for launch.

Mars Network

The Mars Network mission has two main goals: to establish a long term network of simultaneously operating scientific stations on Mars, and to obtain ground truth at those stations. The mission will examine Mars' upper atmosphere and its interaction with the solar wind. The scientific stations will study global seismicity and internal structure, surface meteorology, chemistry of near-surface rocks, water content of near-surface materials, and surface topography.

Mars Aeronomy Orbiter

The Mars Aeronomy Orbiter will examine Mars' upper atmosphere and plasma-planet interactions. This mission was not well-defined, but could be executed as part of a variety of other missions by using any orbiting hardware to perform the experiments.

Mars Sample Return

The Mars Sample Return mission will be the logical follow-up to the Mars Observer and Mars Network missions. It uses the imaging data collected on previous missions as a starting point, but in addition, has the ability to collect samples within one kilometer of a landing site. The combination should result in a good collection of Mars' soil samples. The mission does not require rovers, but it is expected that some type of rover will be used.

Rovers

The report also discussed ideas that were independent of specific Mars missions. It stated emphatically that rovers are uniquely important for performing certain tasks on unmanned precursor missions. They can make *in situ* measurements of geophysical properties. They can explore their surroundings, adding an element of flexibility to any mission plans.

Summary

The three well-defined precursor missions: Mars Observer, Mars Network, and Mars Sample Return offered a realistic perspective on which activities were already underway and which would be worth pursuing. Many of the ideas listed in Figure 2.3b were already incorporated into these precursor missions. A student project could add little value to what was already being done. Figure 2.5a summarizes the missions which were adequately addressed by the missions discussed above.

- Surface composition
- Atmospheric characterization
- Large scale imaging
- Magnetic analysis
- Sample collection

Figure 2.5a - Topics already addressed by official precursor missions

Fran Sturms, Study Leader for Small Mars Surface Missions at the Jet Propulsion Laboratory agreed with the previous analysis and offered a few observations. Fran thought that atmospheric studies would be the least useful addition to SEI. He believed roving capability within 10 to 100 meters of a landing site was the key ingredient missing from the existing precursor missions. The local roving capability is necessary to look behind rocks, provide close-up views in awkward places, place scientific instruments up against rocks or regolith, and make measurements outside the reach of fixed robotics. Fran suggested that, although seismology and meteorology missions would require less mass, power, and design effort, surface composition and small scale imaging missions would be much more useful to SEI.

Revised Project List

Based on these mission-specific details, the initial list was narrowed down to the five options shown in Figure 2.5b. It should be noted that the first three topics require maneuverability beyond the reach of the landing craft. Because of this requirement, the first three missions were assumed to require small rovers.

- Small scale surface imaging; looking behind rocks and into crevices that are outside the reach of fixed robotics
- Martian soil spectroscopy and sampling of rocks or soil outside the reach of fixed landers
- Local seismology, particularly listening to rocks and soil in the local area of the lander, but outside the lander's reach
- Surface meteorology and dust storm analysis
- Local toxicology and radiation analysis

Figure 2.5b - The revised list of potential topics

2.6. EVALUATING THE TOPICS

The five potential topics shown in Figure 2.5b were evaluated against the four decision criteria described earlier. The criteria were: satisfies numerous missions, SEI-enabling, within available resources, and Earth-testable. The evaluations are explained below and summarized in Figure 2.6a.

Small-scale surface imaging

The small scale surface imaging mission will be an integral part of virtually any precursor mission. It was mentioned in four of the references, and has value both for science and engineering. The Mars Observer discussion specifically noted it as a deficiency . "A Strategy for the Scientific Exploration of Mars" stated that surface imaging was an excellent function to be performed from a micro-rover. Because an imaging system will be the eyes of any rover, additional goals can easily be achieved if resources allow scientific payloads to be added. For all these reasons, small-scale surface imaging received the highest rating for mission satisfaction.

The Code RZ study cited "site specific topography" as a "very important need," but most major imaging will be returned by large vehicles. Range and scale will drive the bulk of imaging to designers who are better known than students. Consequently, imaging was rated neutrally in terms of SEI-enabling.

The last two categories required more subjective judgment than the first two. Student projects in universities across the country are designing robots. Although a Mars imaging rover requires a higher level of sophistication than one which performs in a laboratory, designing one seemed well within the capabilities of students. Since the rover's capabilities could be tailored to any budget, it was rated highest on the question of using available resources.

All five missions could be readily tested on Earth. Two sites for such testing are the Mojave desert in California, and the Kamchatka Peninsula in the Soviet Union. All five projects received the highest rating for being capable of testing on Earth.

Soil spectroscopy and rock sampling

The spectroscopy mission was also mentioned in four of the references. In addition to imaging, it is one of the most basic sciences for planetary understanding. There are few unknowns more fundamental than planetary composition. Spectroscopy was rated highest in mission satisfaction. On the other hand, spectroscopy is not required to support future missions. It is primarily a scientific objective, not an engineering one. The Code RZ presentation listed it as a "very important need." As such, it received a neutral rating for enabling.

It was difficult to evaluate the available resources criterion for spectroscopy and the remaining three topics. Although the platform for any of the three could easily be built by students, the instruments themselves could be very difficult. It would be desirable to purchase the most sensitive instruments available for space applications. It was unclear whether these primarily scientific missions could be performed within the project's resources. The educational value would be less for a project whose primary component was purchased rather than designed and built by students. Taking these concerns into account, all four scientific missions received a neutral rating for resource use.

Local seismology

The seismology mission was mentioned in five of the references. Like spectroscopy, it is a basic planetary science that is not required as input data to the SEI engineering effort. Since it will be an integral part of many missions, it was rated highest in for mission satisfaction. Since the Code RZ study rated seismology as an "important need," even less important than spectroscopy, it was rated lowest for SEI-enabling. As stated above, it was rated as neutral for resource use and highest for Earth-testability.

Surface meteorology

The meteorology mission was mentioned in only three of the references. It is of interest for both science and engineering, but it is not critical to either. Since it will not be a major part of any existing mission, it was rated lower than the first three options. Although the Code RZ study lists windstorms and atmospheric profiles as "very important needs," it does not mention surface meteorology. Therefore, meteorology was rated lowest for SEI-enabling.

Toxicology and radiation

The toxicology mission was mentioned in only two of the references. Like meteorology, it is not currently included on an existing mission. For this reason, it received the same neutral rating as meteorology. On the other hand, it is a critical need for engineering a human mission to Mars. Therefore, it was rated higher than any other mission for SEI-enabling.

	Satisfies many missions	SEI-enabling	Within resources	Earth-testability
Imaging	+	0	+	+
Spectroscopy	+	0	0	+
Seismology	+	-	0	+
Meteorology	0	-	0	+
Toxicology	0	+	0	+

Legend: + is best, 0 is neutral, - is worst

Figure 2.6a - Summary of ratings for final five topics

2.7. RECOMMENDATION

The evaluation above showed that the first three projects satisfied more potential missions than did the other two, the first two projects were more important to the SEI engineering effort than the third, and the first project best fit within the available resources. The first three topics offered the greatest potential to be launched on a precursor mission to Mars. All were good choices for the following reasons:

- They incorporated micro-rovers; a capability that NASA lacked.
- They were within the design capability of graduate students.
- They were complex enough to warrant a meaningful systems engineering effort.
- The data was tangible enough to excite a broad spectrum of potential students.

Of the three, the small scale imaging mission was most appropriate for this project. All of the decision makers agreed. It was the simplest of the three best topics, and could be used as a platform for the other two. An imaging micro-rover will be the building block of any mission requiring mobility. It is a flexible system that can be adapted for a variety of uses if there is no need for simple visual imaging. It also has significant growth potential. If resources become available, instruments can be added or the rover made larger and more advanced. Eventually it can become a fully-autonomous unmanned explorer.

Endnote

After the decision was made to proceed with an imaging rover, a planning meeting was held for Rover Expo '92. The Expo is sponsored the Planetary Society and the Smithsonian museum. It will display planetary rover technology to the aerospace community and the general public. All of the major organizations involved in space exploration attended the planning meeting. They agreed that a student-run project involving micro-rovers would be very exciting to the community at large.

CHAPTER 3
REQUIREMENTS DEFINITION

As discussed in Chapter 2, the project goal was to design and launch a real piece of useful space hardware. The reasons for doing so were to get students excited about aerospace engineering, to remind NASA and the aerospace industry that students and universities have a lot to offer the civilian space program, and to demonstrate that meaningful scientific data can be generated with significantly less expensive missions than are currently planned. The project chosen was a Mars micro-rover that responds to Earth commands and transmits video images from the planet's surface back to Earth.

Before designers began developing an optimal rover design, they needed more information about the project constraints. The project cost, development schedule, system performance, and system mass had to be defined before design began in order to fully impact the final result. In addition, it was important to define the program philosophy. The program philosophy determined how the four types of constraints were weighted relative to one another.

The purpose of the effort was to design a simple, semiautonomous rover that could be included on virtually any planetary mission to transmit imaging data from a landing site. Mass constraints had the highest priority since most missions lack surplus mass for additional payloads. Cost constraints had second priority because the design team's development resources were severely limited. The development schedule was the third most important because planetary missions are rare, and potential opportunities could not be missed. Performance requirements had the lowest priority, although they were still very important in determining the rover's success.

This chapter focuses on how the top level requirements lead to constraints in each of the four areas. It illustrates how the mass, cost, and schedule requirements were derived from the project goals. It shows the minimum set of subsystems required to perform the mission goals, and describes how the mass constraint drove the system design. It also shows how the performance requirements developed from the top down.

3.1. MASS, COST, AND SCHEDULE REQUIREMENTS

This section describes how the project goals led to mass, cost, and schedule requirements. Figure 3.1a illustrates the flow from the project goals down to the programmatic requirements.

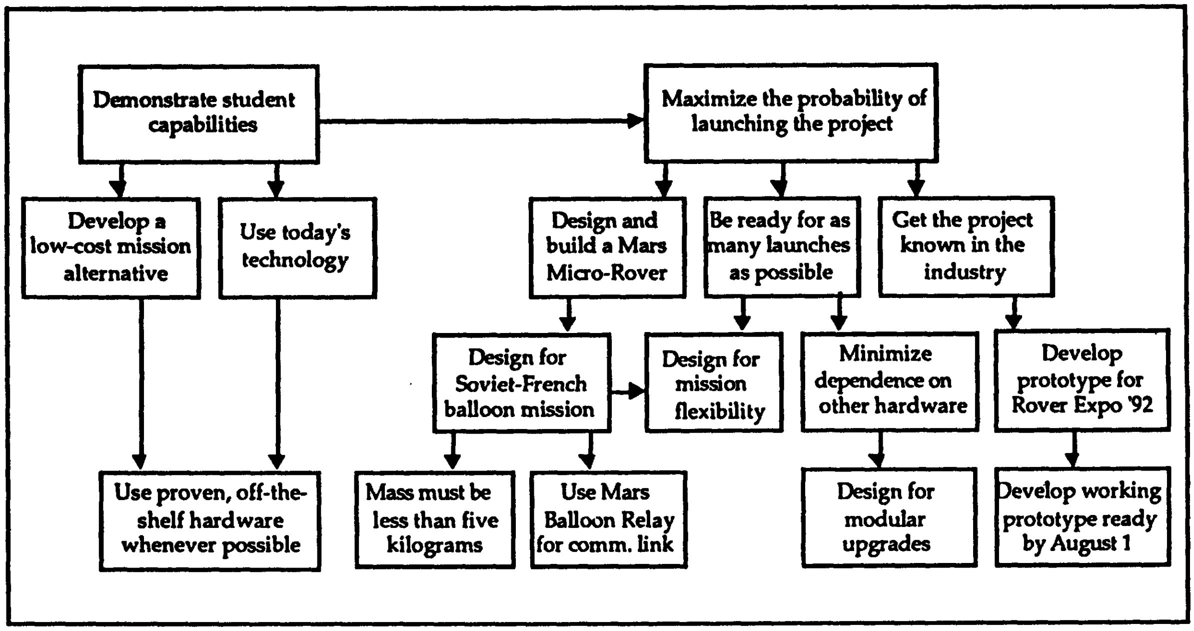

Figure 3.1a - Flow of mass, cost, and schedule requirements

The two highest requirements summarize the project goals. The goals were to demonstrate student capabilities and maximize the probability that hardware would be launched. Demonstrating student capabilities put two constraints on the design. The project had to be inexpensive because there were limited resources available to buy materials. The financial constraint worked to the project's advantage by forcing it to demonstrate a low-cost mission for the Space Exploration Initiative. Similarly, the project had to focus on current technology. Since students would each be involved for only a few years, there would be neither time nor money available to push technologies beyond the state of the art. The technology constraint was a selling point because it allowed the project to show what was possible without complicated technology development.

Summarizing these two constraints, there was a requirement to use proven, off-the-shelf hardware whenever possible. The simplest, most reliable components should be chosen. Unique hardware would only be developed when there was no viable alternative. Positive results of this effort might convince industry that small, low-technology projects are feasible and that they can deliver results as well as large programs can.

Maximizing the probability of launch suggested three ideas. As discussed in Chapter 2, the launch criterion led directly to the choice of a rover. During phase zero of the project, Draper and Planetary Society personnel pursued launch opportunities for small missions to Mars. Thomas Heinsheimer found an opportunity to include five kilograms on a French-Soviet mission to Mars in 1994.[2] The Mars '94 mission was one of the few planned launches to Mars this decade and could not be overlooked. Additionally, five kilograms is a small enough package to fit on almost any interplanetary mission in the near future. The Mars '94 mission provided a good deadline for completing the project. Three years was adequate for finishing the design, yet short enough to ensure a high level of interest among the students. As a result, the French-Soviet Mars '94 mission and a firm mass constraint of five kilograms became the baseline to which the rover was designed.

Designing for the Mars '94 mission also offered the possibility of communicating with Earth via the Mars Balloon Relay. The relay is a communication link built into the NASA Mars Observer spacecraft. The Mars Observer is scheduled to be launched in the fall of 1992 and will remain operational through 1996. This opportunity will be discussed further in the Section 4.4.

To maximize the probability of launching a micro-rover, the second requirement was to be compatible with as many missions and launches as possible. At the same time, the rover could not be so generic as to be useless. The rover needed a basic set of functions to complement the baseline mission, while maintaining independence from mission-specific hardware. By accepting modular upgrades, it can easily enhance its functionality when a mission planner needs added capability.

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[2] The Mars '94 mission has recently been postponed until 1996 due to program delays. Throughout this thesis it will be referred to as the Mars '94 mission or the French-Soviet balloon mission. It should not be confused with another French-Soviet Mars mission originally scheduled for 1992 but recently rescheduled for 1994 and renamed Mars '94!

The third result of the launch objective was that the project develop a high profile within the industry. If the project is to be launched, the managers who define launch manifests must be aware of its existence. If it is to be selected over other designs, it must have a constituency in the aerospace industry that supports its launch. Therefore, it is important to present the project in public or industry-wide forums. Conveniently, the Planetary Society and the National Air and Space Museum established Rover Expo '92, a public demonstration of planetary rovers. They invited the Draper team to demonstrate the rover in Washington, DC on September 1, 1992. The invitation led to two development milestones. A working, semiautonomous vehicle had to be ready for final testing by August 1, 1992. It had to be ready for public demonstration and industry criticism by September 1, 1992.

3.2. SUBSYSTEMS REQUIRED

This section discusses the minimum set of subsystems that the rover design required. Figure 3.2a illustrates how the project goal led to this minimum set. The first three subsystems were defined as a result of the project choice. By definition, a rover must have a means of roving. It must move forward and backward, and it should maneuver off the straight and narrow. This capability was defined as the maneuvering system. Similarly, there must be a power system to provide the maneuvering system with energy. In addition, there must be a structure to hold the first two subsystems together. Beyond this initial setup, it was not obvious what else was required. Past experience and other design studies suggested a set of standard subsystems, but it was important to fully define the system from the top down.

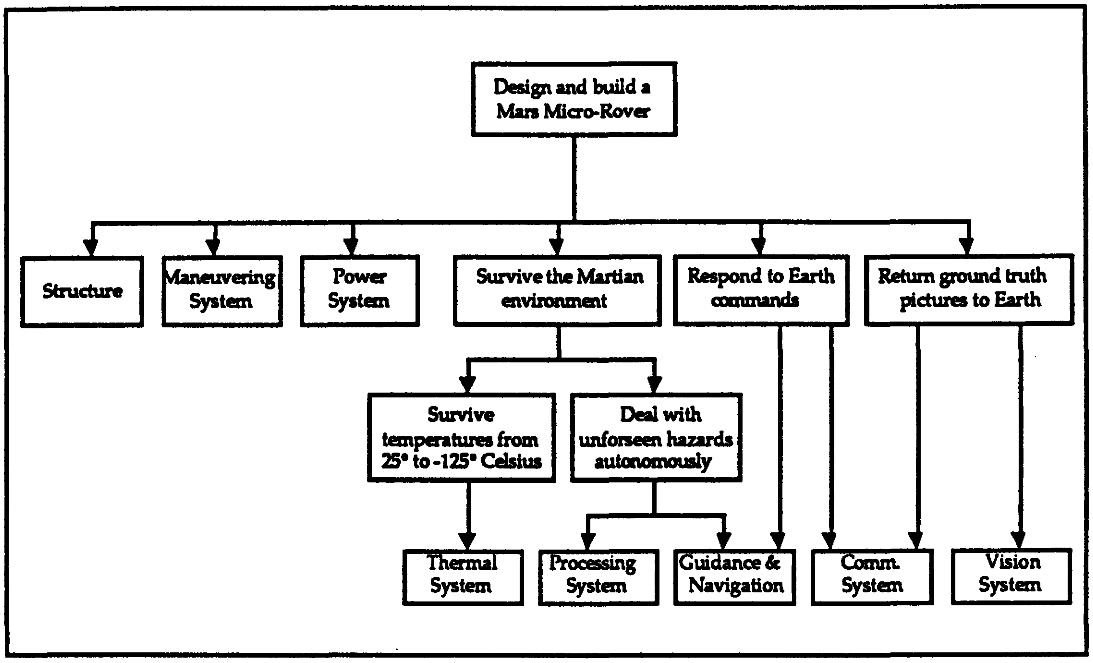

Figure 3.2a - Origin of required subsystems

What were the real goals of the micro-rover? Figure 3.2a shows three basic requirements. First and foremost, the rover must survive the Martian environment. If it does not survive environmental conditions, its other capabilities are worthless. Second, the rover must respond to Earth commands. Although it may have been possible to build a rover that was fully autonomous and preprogrammed, doing so was completely beyond the scope of this project. Therefore the rover must be able to receive and act on Earth commands that tell it where to go. Finally, the rover must transmit video images of the surrounding landscape back to Earth.

The three requirements just mentioned were enough to identify the rest of the subsystems that were needed. Surviving the Mars environment entails adapting to wide variations in ambient temperature, functioning in a low pressure, low gravity, dusty atmosphere, and autonomously dealing with hazards not foreseen by Earth operators. Only the first and last items required additional subsystems to accomplish them. The differences in pressure, gravity, and weather were design constraints only -- they did not require new capabilities. The temperature variations required a thermal subsystem to keep sensitive hardware within an acceptable temperature range, neither overheating or freezing. Dealing with unknown hazards required two subsystems, a set of sensors to detect hazards, and a processor to interpret and negotiate them. Thus the rover required a processing capability and a sensing capability that was included in the guidance and navigation subsystem.

Responding to Earth commands required a communication subsystem capable of receiving commands from Earth and transmitting the rover's position and telemetry to Earth. It also required a navigation capability to direct the rover to its commanded destination. The navigation capability was included in the guidance and navigation subsystem. Transmitting images of the rover's surroundings back to Earth required a vision subsystem to collect the images, and a communication subsystem to transmit them.

3.3. HOW MASS CONSTRAINS THE DESIGN

One of the more interesting aspects of this project was to understand how the five kilogram constraint impacted the system design. The allocation of mass to the various subsystems was very complex. Mass allocated to the power system to obtain more power for operations, left less mass available for the hardware to perform those operations. If the maneuvering system was made more robust to allow the rover to survive in hazardous terrain, less mass was available for processors that enabled the rover to negotiate simpler terrain. A balance had to be found between all of these considerations. It was possible to design a system and accept whatever came out of the effort, but the premise of systems engineering is that better designs result from considering all of the issues before hardware is designed. The decisions are then reevaluated throughout the development process. By doing so, it is possible to develop a rover design that optimizes its use of mass, rather than cutting mass in a few places just to meet the constraint.

Figure 3.3a illustrates that the mass constraint, to a certain extent, defined the remainder of the system. The mass constraint immediately placed an upper bound on both the size of the vehicle's structure and on the total power available. The size was restricted because the rover's overall density must be reasonable if it is to support itself under the force of gravity. The available power was constrained because only a fraction of the mass could be allocated for power generation.

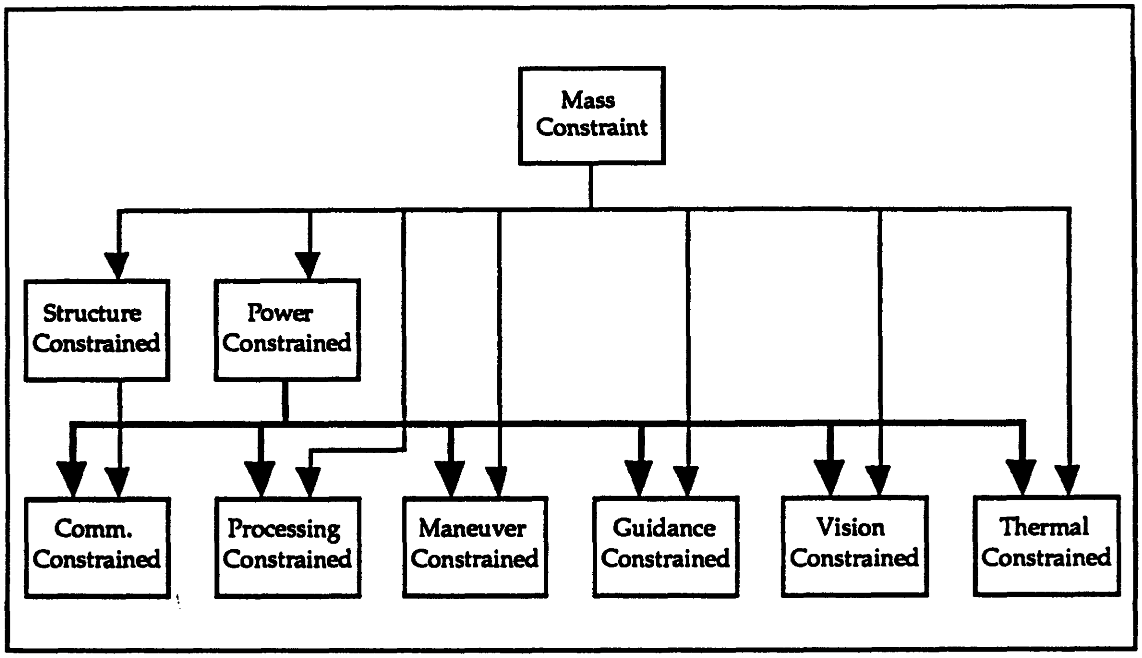

Figure 3.3a - How mass constrained the design

Thereafter, all of the other parameters were constrained by some combination of mass, size, and power. The communication system was primarily constrained by size and power since there is a direct tradeoff between the power required for transmission and the size of the antenna. The antenna's effective aperture was roughly bounded by the overall size of the rover. The system was constrained by power since some types of communication links require excessive amounts. For example, direct communications between the rover and Earth required an unreasonable amount of the available power budget. This question will be addressed in detail in Section 4.4.

The processing system was primarily constrained by power because silicon technology provides virtually mass-free computer chips. The processor must draw power continuously to maintain the integrity of its data. Therefore the processor's power requirements will have a huge impact on the total energy required for the mission.

The maneuvering system was equally constrained by mass and power. Motors and suspension systems were some of the heaviest components on the vehicle. The speed, steering, and flexibility of the rover were all constrained by mass allocations. The maneuvering system's ability to climb over and around obstacles was also constrained by the amount of power available to the motors.

The mass and power constraints affected the guidance system by limiting the number of sensors included on the rover, and by limiting the sampling frequency at which the sensors collect information. Similarly, the vision system was constrained in terms of the number of cameras and the size of the lenses.

The thermal system was severely constrained by power, and only slightly by mass. Thermal conditioning during the cold Martian night could require significant amounts of energy. Thermal conditioning does not add capability to the rover, it merely allows the hardware already there to perform its mission. Energy burned for heat had to be minimized in order to save the available power for other functions. Alternatives include insulation and temperature-resistant components.

3.4. PERFORMANCE REQUIREMENTS

System Performance Requirements

Once the subsystems were defined, the rover's capabilities had to be refined so that performance requirements could be developed for the system as a whole, and for each subsystem. Figure 3.4a shows the system performance requirements that resulted from the same high level constraints that identified the minimum set of subsystems.

Many of the performance requirements were arbitrary, or a balance of what was desirable with what was possible. As previously stressed, it is very important to define what is acceptable and design to it, rather than designing something as good as it can be and accepting the result. Arbitrary requirements give designers targets at which they can shoot. They can fall short of or exceed the targets. The targets can be moved as necessary, but designers must be informed of what is acceptable before they begin to work.

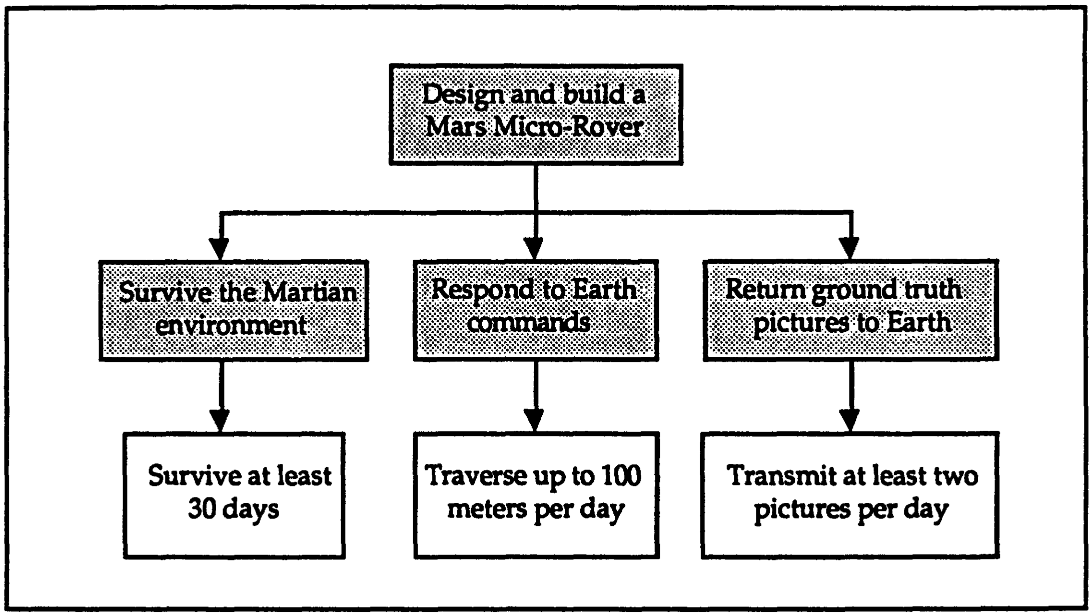

Figure 3.4a - Flow chart of system performance requirements

Three system performance requirements had a large impact on the design effort, and offered a lot of guidance regarding the required performance of different subsystems. The three requirements were the length of the mission, the daily traverse distance, and the number of images transmitted each day.

Mission Length

The mission length was important for several reasons. First, it impacted the choice of a power system. A year-long mission might justify the costs of a radio-isotope thermal generator -- large structural mass, high cost, and excessive heat -- whereas a mission lasting only a few days can not make use of the benefits -- long life, high reliability, and limited performance degradation. Similarly, single-use batteries that might be adequate for a mission of a few days can not possibly power a year-long mission.

Second, mission length defined the reliability required of the rover's components. If the power system was designed to last three months but two other critical subsystems only lasted two weeks, resources were wasted on the power system that could have been better spent making the rest of the vehicle more robust. It was important to balance the expected lifetime of the whole system so that the available resources were optimized.

Finally, the mission length determined the amount of time available to Earth operators to master using the rover's capabilities. Although operator training will begin before the rover is launched, it is unlikely that simulations will reveal all of the scenarios that might occur in the Martian environment. If the mission lasts two days, the operator interface and mission expectations must be very different than if the mission is designed for two weeks. A longer mission provides operators with a few days to work out the bugs before using the rover to its fullest potential.

What was known about mission length?

- If the rover dies on the first day before returning any data, the mission will not be considered successful.
- If the rover returns data for several months, it will definitely be considered successful.
- Since the use of the Mars Balloon Relay was decided upon in Section 3.1, there will only be two communication windows per day, one at two o'clock in the afternoon and one at two o'clock in the morning. This requirement drove the decision towards a longer mission since only one or two traverses were possible each day.

Appropriate durations lay between one day and several months. The choice impacted the method of operation, the data returned, and the overall power requirements. The operation of a mission lasting several days will be more hectic and stressful than a longer one. There will be no time to break in the rover and its operators; everything must be perfect from the first traverse. As a consequence, a short mission will be more sensitive to unexpected circumstances since there will be less time for operators to deal with them. Decisions that are made for the first few traverses will have a huge impact on the value of the data returned. If the rover sets out in a direction that proves unfruitful, there will be little chance of correcting the mistake.

On the other hand, a mission lasting several weeks will have a different tone. The first few days can be spent putting the rover through its paces. Earth operators can develop a good sense of how operations differ from Earth-based simulations and tests. They can make better decisions about optimizing the use of the rover as they gain experience using it.

There was the additional question of power requirements. Long missions require more overhead power than short missions because hardware such as the processor must draw power even when not being used. If the rover maneuvers for a short time each day, the overhead requirements are a greater percentage of the total power used. This wasted power had to be traded against the operational benefits of the longer mission. The power system was also impacted because the design of the system may depend on the mission length. Solar arrays or nuclear power would not limit the mission length like batteries do. This impact will be discussed further in Section 4.3.

At this stage, the choice was arbitrary. The mission length had to be bounded, coming reasonably close to the final answer, so that design could begin with a notion of the overall power and reliability requirements. Thirty days was decided upon as a reasonable compromise between a few days and several months. A 30 day mission provides at least two days to learn how the system works and four weeks of real operations. It allows for a significant number of images to be returned, and it will not drive the power system design to an undesirable extreme. This decision must be revisited frequently to ensure that it is possible as the design progresses. If it is changed, the impact on the entire system and on each of the subsystems must be considered.

Daily traverse

The second system performance requirement concerned the distance the rover will travel each day. The daily traverse influenced the power required for maneuvering because more power is needed to traverse greater distances. It impacted the capability of the guidance and navigation system because navigation errors increase with the distance traveled between calibrations. If maneuvers must be completed in a fixed time period, the distance traveled would also drive the average speed required. Finally, the daily traverse impacted the marketability of the rover. Clearly, the more capable the rover was, the more attractive it would be to mission planners.

What was known about the daily traverse?

- Based on the 30 day mission defined above, the rover's total range was 30 times the daily traverse. Since there were 30 days to work with, daily distance was less critical than it would be on a several day mission.

- If the rover can only travel a few meters per day and 100 meters overall, it may not be useful to a wide range of missions.
- The daily traverse depended on the ability of the Earth operators to command a destination based on the images returned by the rover. Alternatively, the traverse distance determines the sensitivity of the camera, but there is a practical limit to the camera's resolution.

Reasonable traverse distances depend on the landing site. If the terrain in the immediate vicinity of the landing site is interesting, the rover may not need to go far to generate useful images. If the terrain is undistinguished, short traverses will not be effective. Some missions may require the ability to see around a rock in the immediate vicinity of the landing site, but more are likely to need the capability to look over the next ridge, travel down into a crater, or other tasks that are on the order of kilometers.

There was also the question of what was possible. The camera requires sunlight to generate images. Since it can only communicate with Earth at 2 pm and 2 am, there will only be two chances per day for Earth operators to send a new destination to the rover. It might be counterproductive for the operators to command the rover to a position they cannot discern. Then again, that might be the whole point.

The daily traverse was strongly constrained by the feasibility of negotiating obstacles. Earth operators will command the rover based on the pictures received. Their information will be limited, so the rover will have to be capable of handling some obstacle avoidance and terrain negotiation on its own. There was clearly a limit on how far the rover could travel in one day without requiring advice from Earth. The distance was directly dependent on the quality of the sensors and the control scheme used.

As before, the problem was bounded with reasonable estimates. Remembering that the mission was 30 days, a daily traverse of five meters would provide a maximum range of 150 meters. It is unlikely that many mission planners would be willing to sacrifice five kilograms of payload to gain the ability to explore only 150 meters from the landing site. On the other hand, a daily traverse of 100 meters would allow the rover to range up to three kilometers from the landing site. It seems far more likely that a mission planner would buy the ability to explore up to three kilometers for a mere five kilograms.

In balancing the different concerns, 100 meter traverses seemed a reasonable compromise. In flat terrain, 100 meters is easily attainable. In rocky terrain, 100 meters may be difficult. On the other hand, it may not be possible for operators to see 100 meters in rocky terrain, thus the commanded destination would probably be closer to the starting point than it would be in flat terrain. As in the case of mission length, it is easier to relax requirements later in the design than it is to tighten them. The daily traverse distance should be reevaluated when more is known about the rover's autonomous capabilities.

Daily images transmitted

The third system performance requirement was the number of images returned to Earth -- the mission's scientific return. The number of images transmitted influenced the overall power requirements, although not as much as the mission length and the daily traverse did. It impacted the data rate required of the communication system since the communication windows were predetermined and short -- each one will be only ten minutes long. It impacted the processing system because images must be stored in memory. It also affected the overall attractiveness of the rover to mission planners.

What was known about the number of images returned each day?

- At least one image must be returned every time the rover completes a maneuver so that Earth operators can update their database and issue a new command.
- Only twenty minutes of communication link time is available with the Mars Balloon Relay.
- The Mars Balloon Relay can receive data at a rate of 128 kilobits/sec.
- A video image contains on the order of one megabit of data.
- Some fraction of the twenty minutes must be used to send commands to the rover.
- Pictures transmitted in the middle of the night will have to be stored in memory since there is no light to generate images at night.

One image per traverse is an absolute minimum. Without a new image after each traverse, Earth operators will have to guess what terrain the rover is facing, and where they might like it to go. Transmitting many images is difficult because, as will be discussed in Section 4.4, the transmission data rate must be very low to minimize the amount of power required for the communication system. As such, it will be difficult to transmit more than one image during a pass of the Mars Balloon Relay unless significant data compression is possible. Without data compression, it is only possible to transmit two images per day, one during each communication window.

The decision came down to whether there should be one or two images per day. The second image would have to be stored in memory and transmitted during the 2 am window. The first image might need to be stored in memory also. Early on, it made sense to push the design to return at least two images per day. Since the images are the major scientific return, the rover should transmit as many as possible.

Subsystem Performance Requirements

Figure 3.4b depicts some of the subsystem performance requirements that resulted from the project goals and system performance specifications.

Power Requirements

The power budget is detailed in Section 4.2. This section discusses how the power budget was affected by the system performance requirements defined above.

The maneuvering and processing subsystems required the most energy. The maneuvering system because it is power intensive, and the processing system because it will be used most of the time. A recent Jet Propulsion Laboratory (JPL) design study for a Mars micro-rover discussed three different power levels for maneuvering [JPL, 1991]. On hard ground, their rover needed 0.1 watts. On a loose sandy surface, it required 3 watts. To climb obstacles, it required up to 8 watts. Although the terrain a Mars rover will encounter is unknown, 3 watts seemed like a reasonable estimate for the Draper rover. Assuming it will maneuver for 90 minutes a day, the maneuvering subsystem will need 4.5 watt-hours per day.

The same JPL study indicated that the processing subsystem required 0.3 watts. The Draper rover's processor would operate continuously to monitor the rover's status. Assuming the processor would be working for four hours per day at 0.3 watts and 20 hours per day at 0.2 watts, the processor required almost 5 watt-hours of energy per day. The other systems would be used for only short periods of time or require very little power to operate. For an initial estimate, an additional 5 watt-hours was allotted for them. Thus, the rover required on the order of 15 watt-hours of electrical energy per day, or 450 watt-hours over 30 days. The implementation of the power system is discussed in Section 4.4.

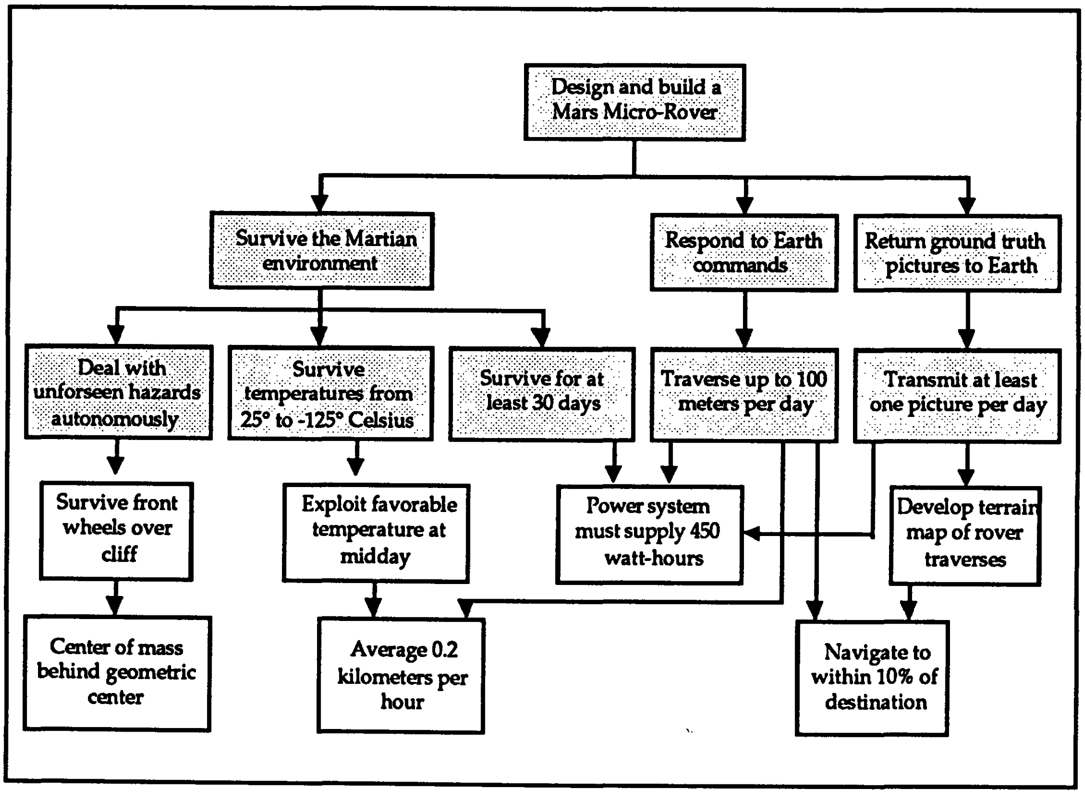

Figure 3.4b - Flow chart of lower level performance requirements

Average Speed

The next question was how fast the rover would travel. The warmest temperatures on Mars, between 0° and 25° Celsius occur around one o'clock in the afternoon [Kaplan, 1988, page 3-11]. The Martian day is almost the same length as Earth's, about 24 hours and 39 minutes. Since the baseline mission depends on the Mars Balloon Relay for communications, the rover must complete all maneuvers before the 2:00 pm fly-by. Although daily temperatures and sunlight hours vary with season and latitude, assuming that the temperature will be high enough sometime in the mid-morning defines a two to four hour period for maneuvering. Traveling 100 meters in two hours required an average speed of 0.05 kilometers per hour (kph). There may be periods of no motion that drastically lower the average. At this point it seemed wise to complete maneuvers in one hour in case the rover required the most benign thermal environment possible. Therefore, the average speed had to be 0.1 kph. It was assumed that the rover would not be moving during 30 of the 60 minutes, so the average speed had to be 0.2 kph. Based on the JPL study, cruising speeds less than 1.5 kph and climbing speeds around 0.1 kph should not be a problem.

Other Requirements

Figure 3.4b illustrates the origin of several other less significant requirements. The most important was to navigate the rover within a ten percent error circle of a commanded destination. If the rover is commanded to traverse 100 meters to a certain location, it will have made a successful traverse when it is within ten meters of that location. The requirement was necessary to provide direction to the designers of the guidance and navigation subsystem and the processing subsystem. It was based upon a desire to understand the terrain the rover traverses based on the images it transmits. If the rover deviates more than ten percent from the commanded location, 6° in either direction, at some point its path would not be traceable from image to image. As a result, Earth operators would be confused.

3.5. MISSION PROFILE

This section summarizes all of the mission requirements discussed previously. It then examines all stages of the rover's mission starting on the launch pad. The mission profile defines each of the environments the rover will encounter, before and after it is turned on. Finally, a day in the rover's life is detailed with a timetable and a power profile.

Assumptions

- The goal of the project is to build a five kilogram micro-rover that will piggyback on a future mission to Mars. The five kilograms includes all aspects of the functional rover. It does not include launch protection, landing protection, or interfaces with the launch vehicle.
- The rover design should be flexible enough to perform on a Lunar mission, in case such a mission is scheduled before a Mars mission.
- The rover's purpose is to supplement the host mission by exploring the area surrounding the landing site.
- The rover's design lifetime is 30 days. It should travel up to 100 meters per day subject to commands from Earth, and transmit at least two images of its new surroundings back to Earth.
- The rover's design should maximize the number of missions on which it can piggyback. It can do so by minimizing dependence on external hardware such as landers, power sources, and Earth-based processors.
- The rover will use the Mars Balloon Relay as a baseline communications link from Mars to Earth. There will be ten minute communication periods each day at 2:00 pm and 2:00 am. The rover can transmit video images and telemetry data, and receive commands from Earth during both periods. In general, commands will be transmitted from Earth to the rover during the early morning window. Those commands will be implemented before the next afternoon window.
- The rover should be semiautonomous. It will receive daily commands from Earth specifying a destination and a suggested route. The rover will execute the commands to the best of its ability, stop, take pictures, send them to Earth, and await further commands.
- The rover must be designed to withstand Mars' harsh environment. A Martian day is 24 hours 39 minutes. The temperature ranges from 25° Celsius in the daytime to -125° at night. The rover will maneuver during the relatively warm Martian day to exploit the natural heating at that time. It will sleep or plan the next days activities during the cold Martian night.

Mission Environments

Launch

For launch, the rover will be integrated into the payload package of the host mission. Power, communications, and telemetry will depend on the host vehicle until the rover emerges onto the planetary surface. The launch loads are the worst case accelerations the rover will encounter. Since the launch vehicle is not yet known, acceleration envelopes are provided in figures 3.5a and 3.5b.

- The rover will potentially have to survive axial launch loads on the order of ±5.5 g's and lateral launch loads between ±5.0 g's.
- Vibrations could be as high as 0.1 g^2/Hertz as shown in Figure 3.5b

	Lift-Off		Max Airloads		Stage 1 Shutdown (Booster)		Stage 2 Shutdown (Booster)	
Vehicle	**Axial**	**Lateral**	**Axial**	**Lateral**	**Axial**	**Lateral**	**Axial**	**Lateral**
T34D/IUS								
Steady State	+1.5	-	+2.0	-	0 to +4.5	-	0 to +2.5	-
Dynamic	±1.5	±5.0	±1.0	±5.0	±4.0	±2.0	±4.0	±2.0
Atlas-II								
Steady State	+1.3	-	+2.2	-	+5.5	-	+4.0	-
Dynamic	±1.5	±1.0	±0.3	±1.0	±0.5	±0.5	±2.0	±0.5
Delta								
Steady State	+2.4	-	-	-	-	-	+7.7	-
Dynamic	±1.0	+2.0 to +3.0	-	-	-	-	+4.0	-
H-II								
Steady State-		-	-	-	-	-	-	-
Dynamic	±3.2	±2.0	-	-	-	-	±5.0	±1.0
Shuttle								
Steady State	+3.2	+2.5	+1.1 to +3.2	+0.25 to -0.6		-	+3.2	+0.6
Dynamic	+3.2	+3.4	-	-	-	-	-	-

Figure 3.5a - Launch loads for a variety of launch vehicles
[Wertz and Larson, 1991, page 627]

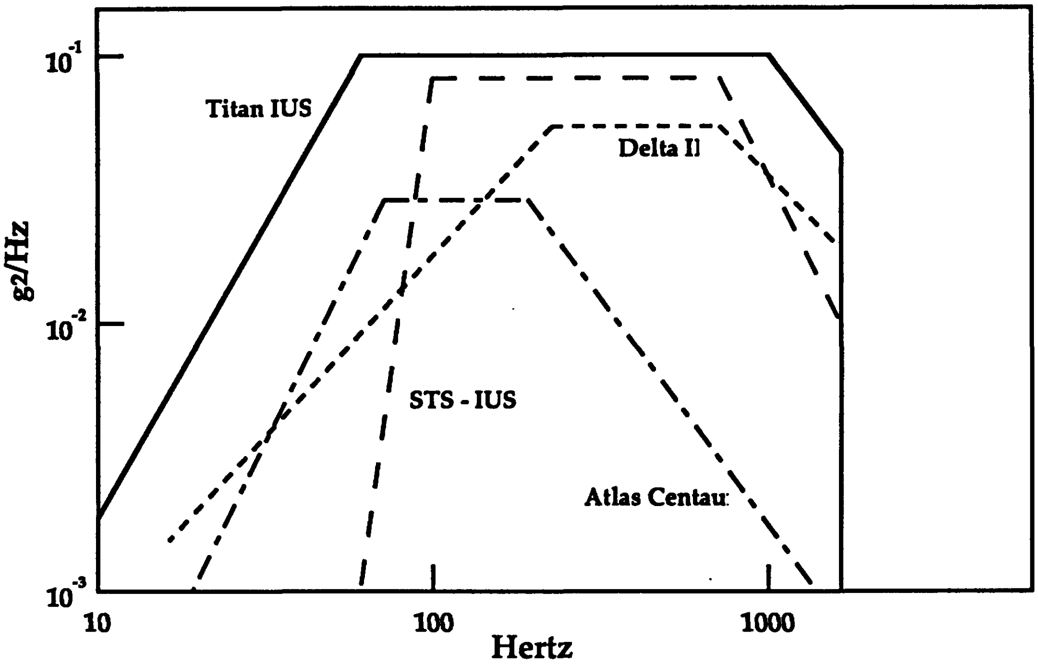

Figure 3.5b - Vibration loads for a variety of launch vehicles
[Wertz and Larson, 1991, page 627]

Trans-Mars Injection

Once the launch vehicle is gone, the rover will remain integrated with the host vehicle for the trip to Mars. Depending on the trajectory chosen the journey to Mars might take anywhere from three months to two years.

Landing

The rover will depend on the host vehicle for primary landing protection, although it may need some additional protection for sensitive components.

Excursion

Once the host vehicle has established itself on the surface of Mars, the rover will check its status one last time and prepare to leave the host vehicle.

- Rover power switched on
- System checkout
- Rover receives final commands from host vehicle
- All links to host vehicle severed
- Rover leaves haven of lander

- Rover begins its new life

A Day in the Life of the Rover

This section provides an outline of what a typical day for the rover will entail. Figure 3.5c shows the schedule for subsystem usage.

Morning

11:00 Wake up processor
System Checkout
- Check health status of all systems
- Check batteries
- Check temperatures

Plan maneuvers based on Earth commands
When ambient temperature reaches acceptable level begin activities
- Shut down thermal subsystem
- Turn on maneuvering subsystem
- Turn on guidance and navigation system
- Take and store telemetry readings for afternoon transmission

Maneuver to destination or implement other Earth commands
- Calculate best path based on Earth commands
- Begin maneuver
- Calculate the error from the desired path
- Adjust maneuvers to minimize errors
- Repeat last two steps until the destination is achieved

Afternoon

1:50 Shut down maneuvering subsystems
Shut down guidance and navigation subsystem
Turn on vision subsystem
Scan horizon for interesting features and lock onto best scene
1:55 Turn on communication subsystem
2:00 Establish contact with the Mars Balloon Relay
Transmit video and telemetry data to the orbiter
Receive commands from Earth through the orbiter
2:10 Shut down communication subsystem when orbiter contact is lost

Find second image and store for morning transmission
Shut down vision subsystem
Interpret received commands
Implement commands as appropriate
3:00 System Checkout
Store telemetry data for morning transmission
Reconfigure for night, i.e. sleeping
- Turn on heaters
- Put processor in sleep mode until 1:45 am

After Mid-Night

1:45 Wake up processor
System Checkout
1:55 Turn on communication subsystem
2:00 Establish contact with the Mars Balloon Relay
Transmit video and telemetry data to the orbiter
Receive commands from Earth through the orbiter
2:10 Shut down communication subsystem when orbiter contact is lost
Interpret received commands
Implement commands as appropriate
2:45 Put processor into sleep mode until 11:00 am

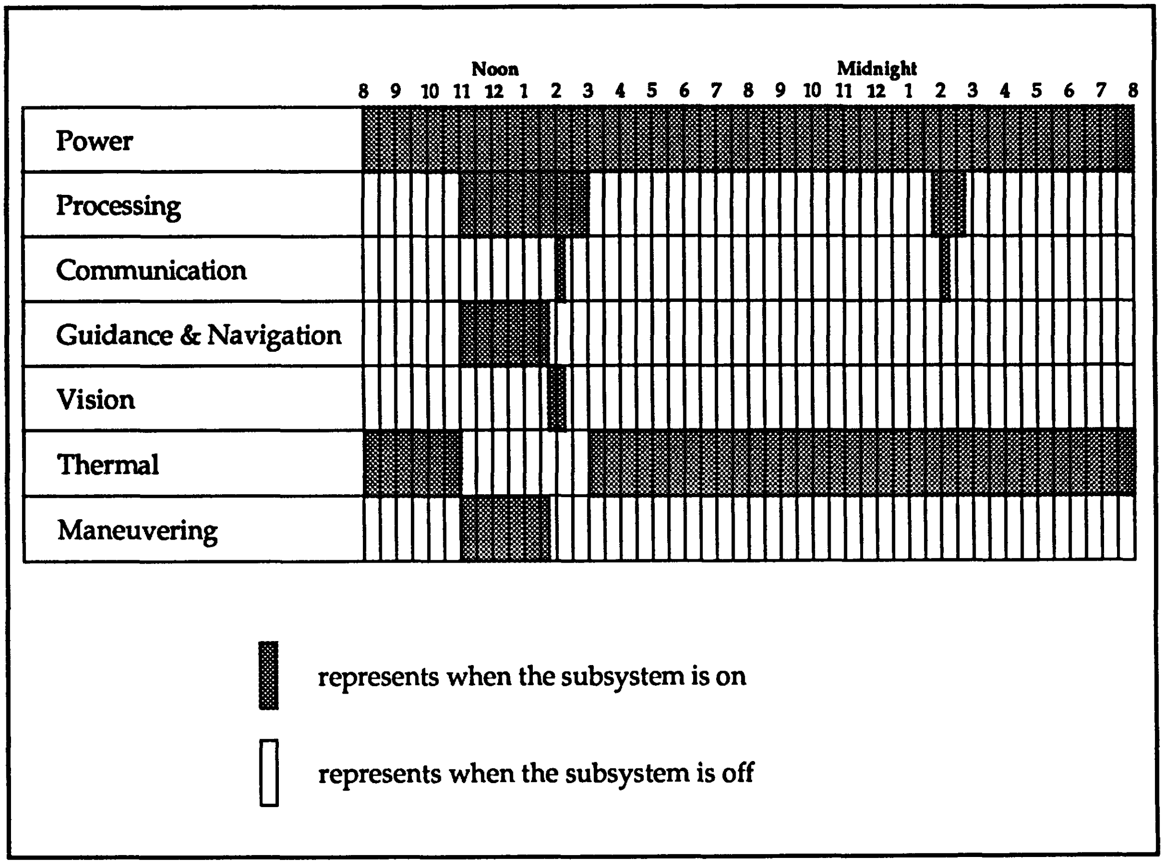

Figure 3.5c - Schedule of subsystem usage

CHAPTER 4
SYSTEM OVERVIEW

Chapter 4 presents a high level view of the rover's design, and two of the important tradeoffs that led to the design. It begins by describing the rover as a system, outlining the subsystems, and defining the interfaces between them. It discusses the budget allocations for mass and power, the two most constrained resources. Finally, it analyzes the power system and the communication system tradeoffs.

4.1. SYSTEM DESCRIPTION

System Breakdown

As illustrated in Figure 4.1a, the rover system is parsed into eight subsystems. The subsystems are power, processing, communication, guidance and navigation, vision, thermal, structure, and maneuvering. The subsystem functions and their components are briefly described below, and in more detail in Chapter 5.

Power

The power system uses primary batteries for reasons detailed in Section 4.3. It consists of two battery packs, a twelve volt pack and a six volt pack. There is also power distribution and surge protection hardware. The system provides 450 watt-hours of electricity over the rover's lifetime.

Processing

The processing system issues on/off commands, controls complex subsystem behaviors, formats video and telemetry data for transmission, implements commands received by the communication subsystem, maintains knowledge of the rover's position and destination vectors, and coordinates the rover's activities throughout the mission.

The processing system currently consists of a microprocessor board built around a Motorola 6811 chip. The design is based on a board with which several of the team members have worked previously. It is inexpensive, readily available, and easy to modify. The board will include additional chips if they can enhance speed or performance with reduced power. The board includes a clock.

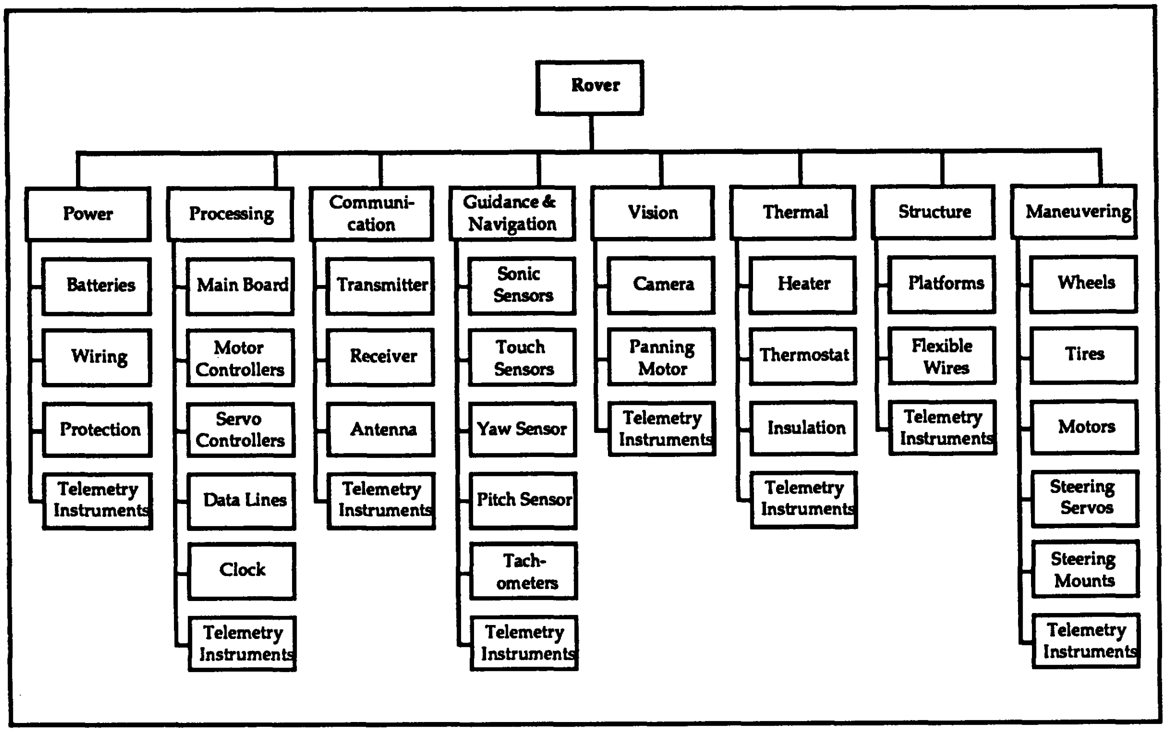

Figure 4.1a - System Breakdown Diagram

Communication

The communications system provides the rover's link with Earth. It sends data to Earth and receives commands from Earth. It consists of a transmitter, a receiver, and an antenna. It uses the Mars Balloon Relay as a link for reasons detailed in Sections 3.1 and 4.4.

The transmitter sends video images and telemetry when the Mars Balloon Relay is overhead. The orbiter passes by for ten minutes at 2:00 in the morning and 2:00 in the afternoon. The video and telemetry data will be multiplexed into a single data stream.

The receiver will receive signals from Earth via the Mars Balloon Relay twice a day during the same windows mentioned above. Most commands will be received during the morning window to provide Earth operators with adequate time to examine the most recent video images and determine a new destination for the rover.

Guidance/Navigation

The guidance and navigation system provides sensor data to the processor concerning the rover's environment and operations. It consists of five proximity sensors, two touch sensors, a pitch and yaw sensor, and two tachometers.

Vision

The vision system generates images for transmission back to Earth. It consists of a camera mounted on a panning motor. If necessary, it can provide continuous video to the processor as an input to navigation.

Thermal

The thermal system maintains the rover's temperature within acceptable bounds. The Martian surface temperature varies between 25° and -125° Celsius. The thermal system consists of one or more heaters, thermostats, and insulation, but it will not be defined until the rest of the design is better established. Mass and power allocations have been made to account for a reasonably sized system.

Maneuvering

The maneuvering system moves the rover from one destination to another. It implements the control commands issued by the processor. It consists of six individually powered wheels and the motors that power them. The front and rear wheels are steered independently by two steering servo motors. The maneuvering system includes the servo motors and the blocks that connect them to the wheels.

Structure

The structure physically supports all other subsystems. It consists of the flexible frame with three platforms and two sets of steel wire connectors. It includes all other hardware that holds the system together.

System Interfaces

Figure 4.1b illustrates the system interfaces. These interfaces are described briefly below. The detailed subsystem interfaces are described in Chapter 5.

Power

The power system provides power to all the other subsystems.

Processing

The processing system has data interfaces with all of the other subsystems.

Communication

The communications system interfaces with:

- the 12 volt power bus
- the processing system
- the thermal system

Guidance/Navigation

The guidance and navigation system interfaces with:

- the 6 volt power bus
- the processing system

Vision

The vision system interfaces with:

- the 12 volt power bus
- the processing system

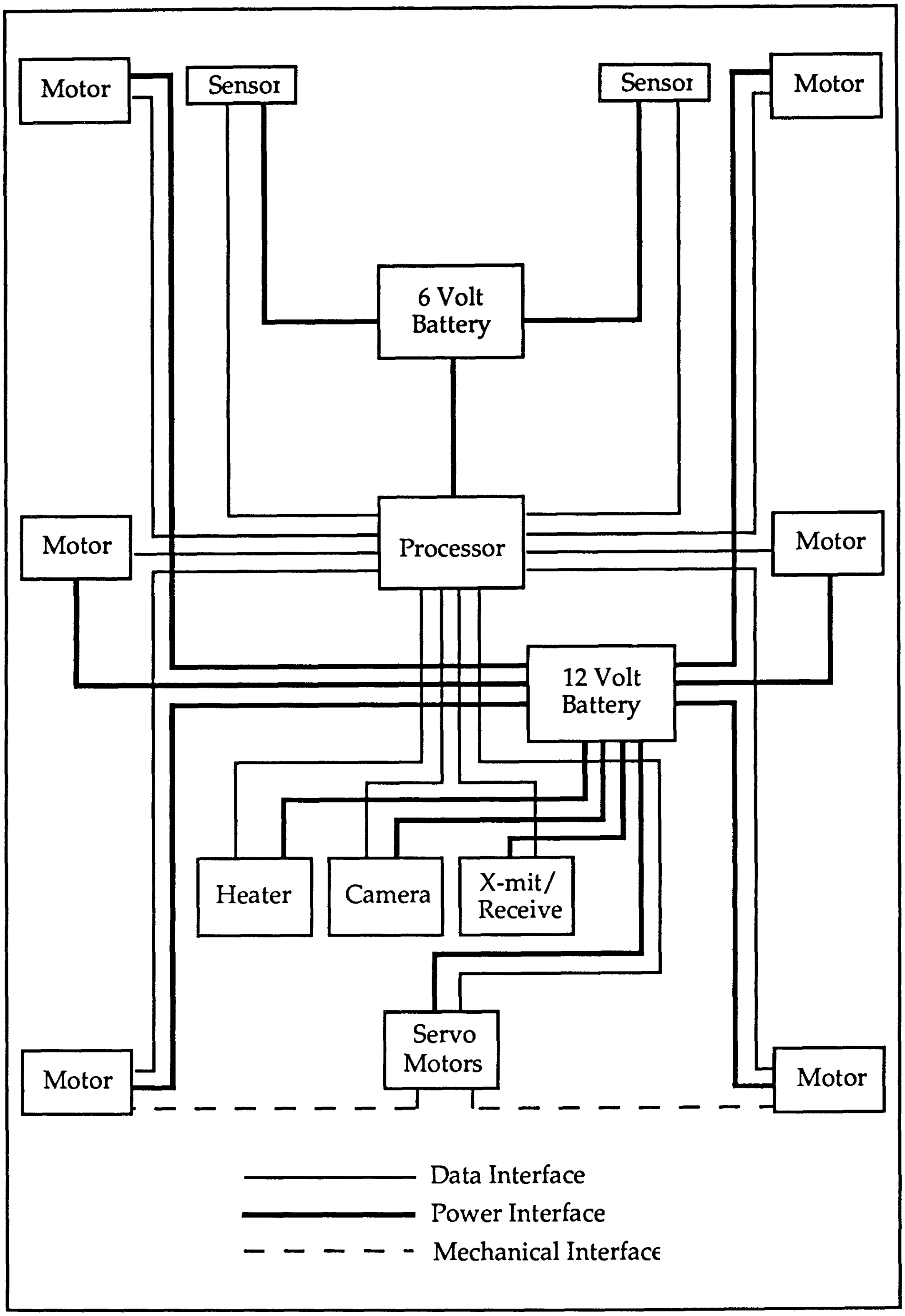

Figure 4.1b - System Interface Diagram

Thermal

The thermal system interfaces with:

- the power system
- the processing system
- the communication system
- the guidance and navigation system

Maneuvering

The maneuvering system interfaces with:

- the 12 volt power bus
- the processing system

Structure

The structure supports all of the other subsystems.

4.2. RESOURCE BUDGETS

Mass Budget

Preliminary Mass Allocation

Figure 4.2a illustrates the preliminary mass allocation that was made when the five kilogram constraint was imposed. This allocation used minimum engineering data. It assumed the power system required more mass than any other subsystem. Otherwise, it allocated the mass equally, saving ten percent of the total as a design margin. The preliminary allocation provided insight into how little mass was available for each of the subsystems.

Subsystem	Grams
Power	1000
Processing	500
Communication	500
Guidance & Navigation	500
Vision	500
Thermal	500
Structure	500
Maneuvering	500
Contingency	500
Total	5000

Figure 4.2a - Preliminary mass allocation

Prototype Mass

Figure 4.2b shows how the mass was actually distributed for the phase one prototype vehicle. The prototype was designed with a ten kilogram mass constraint. As shown in the figure, the prototype's mass was well within that constraint. The mass margin was gratifying because the prototype was not designed to rigorous standards. By simply designing with the constraint in mind, the prototype was completed with mass to spare.

Prototype Part	Grams	Quantity	Total Grams
Tire	215	6	1290
Hub	114	6	684
Drive Motor	166	6	996
Servo Motor	96	2	192
Servo Saver	5	2	10
Steering Block	24	4	96
Tierod	4	4	16
Center Motor Attachments	25	2	50
Camera & Lens	233	1	233
Processor	187	1	187
Sonic Sensor	25	5	125
Touch Sensor	75	2	150
Compass	119	1	119
Receiver/X-mitter & Antenna	271	1	271
Servo Batteries	307	1	307
Processor Batteries	105	1	105
Main Batteries	435	1	435
Lower Structural Plate	95	3	285
Upper Structural Plate	65	2	130
Suspension Wires	2	4	8
Suspension Bracket	11	8	88
Sonic Sensor Bracket	24	1	24
Miscellaneous Structure/Wiring	941	1	941
Total System			6742

Figure 4.2b - Prototype mass allocation

Final Mass Allocation

Figure 4.2c shows how mass was allocated for the space qualified rover. The differences between the prototype allocations and the space qualified allocations were based on weight savings that were known to be feasible. For example, the margin of safety designed into the wheel hubs and the structure can be lowered. In the prototype vehicle, designs were left intentionally robust since there was no need to minimize the mass. In addition, expensive, space-qualified materials such as titanium can be substituted for aluminum and steel if the mass savings justify the expense. Additional mass savings will result from building light, wire-frame tires instead of using heavy pneumatic ones.

Rover Part	Grams	Quantity	Total Grams
Tire	50	6	300
Hub	70	6	420
Drive Motor	100	6	600
Servo Motor	70	2	140
Servo Saver	5	2	10
Steering Block	20	4	80
Tierod	5	4	20
Center Motor Attachments	15	2	30
Camera & Lens	200	1	200
Processor	175	1	175
Proximity Sensor	20	5	100
Touch Sensor	50	2	100
Yaw/Pitch Sensor	75	1	75
Receiver/X-mitter & Antenna	150	1	150
Lower Structural Plate	60	3	180
Upper Structural Plate	30	2	60
Suspension Wires and Brackets	10	4	40
Sonic Sensor Bracket	20	1	20
Miscellaneous Structure	300	1	300
Batteries	1350	1	1350
Power Distribution	150	1	150
Contingency	500	1	500
Total System			5000

Figure 4.2c - Space-qualified rover mass allocation

Power Budget

Preliminary Power Allocation

Figure 4.2d shows the power budget before any design work had been done. The numbers in the table were based on the JPL micro-rover study discussed in Section 3.4, and on some hardware that already existed in the lab.

The JPL study involved a six-wheeled rover with requirements different than those for this project. The two projects were similar enough that the maneuvering and processing requirements were comparable. The maneuvering system in that study had power requirements listed for cruising on hard ground, moving over sandy soil, and climbing through rough terrain. These values were 0.1, 3, and 8 watts respectively. The processor needed 0.3 watts for peak power and 0.2 watts in a sleep mode. The estimates for data transmission and reception were also based on the JPL study. Only one watt was required because the study assumed there was a communications link in a lander within five kilometers of the rover. These values seemed like a reasonable place to start.

It is important to remember that in a systems design problem such as this, all parameters are interdependent, and iteration is required before the design can be optimized. In the beginning, assumptions must be made so that analysis can begin. Later on, the assumptions can be revisited to ensure that the analysis is valid.

Subsystem	Power (watts)	Time Used (hours/day)	Energy (watt-hrs/day)
Maneuvering	0.1, 3, 8		5
Processor	0.3, 0.2	4, 20	5.25
Receiver	1	0.5	0.5
Transmitter	4	0.1	0.4
Camera	3	0.1	0.3
Sensors	1	1	1
Heater Contingency	0.25	10	2.5
Total			15

Figure 4.2d - Preliminary power allocation

The camera and sensor estimates were based on hardware used by team members for the phase zero prototype and other design projects. The camera and transmitter worked together to transmit images to the person controlling the vehicle. The camera used three watts and the transmitter used four watts. The energy required by these systems depended on how they were operated. Continuous use of the camera demanded far more energy than occasional image transmissions. The preliminary power allocation assumed that the camera and transmitter would be used for six minutes each day to send images to Earth.

The heater requirements were based on a simple thermal analysis of an insulated rover. The analysis showed that if the rover was covered in gold foil, it would need cooling rather than heating. A contingency of 2.5 watt-hours of energy was allocated to the thermal system because the thermal analysis was rough, and quite sensitive to the initial assumptions. The initial estimate of the total rover energy requirements was 15 watt-hours per day.

Prototype Power Allocation

Figure 4.2e shows how the power was actually used for the phase one prototype vehicle. It required significantly more than 15 watt-hours because the motors were not up to specifications. Free motors from the laboratory were used to save money.

Subsystem	Power (watts)	Time Used (hours/day)	Energy (watt-hrs/day)
Maneuvering	6, 18, 30	0.1, 0.2, 0.4	16.0
Processing - awake	0.8	6.5	5.5
Processing - asleep	0.0	18	0.001
Data Receiver/X-mitter	1.2	0.3	0.4
Video Transmitter	1.2	0.1	0.1
Camera	2.6	0.1	0.3
Sensors	1.2	0.9	1.1
Total			23.3

Figure 4.2e - Prototype power allocation

Final Power Allocation

Figure 4.2f shows the power allocation for the space-qualified rover. The power profile shown in Figure 4.2g was based on the final power allocation and the schedule of subsystem performance shown in Figure 3.5c.

Subsystem	Power (watts)	Time Used (hours/day)	Energy (watt-hrs/day)
Maneuvering	3, 6, 11	0.1, 0.2, 0.4	5.9
Processing - awake	1.2	5.0	6.0
Processing - asleep	0.00006	19.5	0.001
Receiver/X-mitter	3.0	0.3	0.9
Camera	2.0	0.1	0.2
Sensors	1.2	0.9	1.0
Thermal Contingency	0.20	5.0	1.0
Total			15.0

Figure 4.2f - Final power allocation

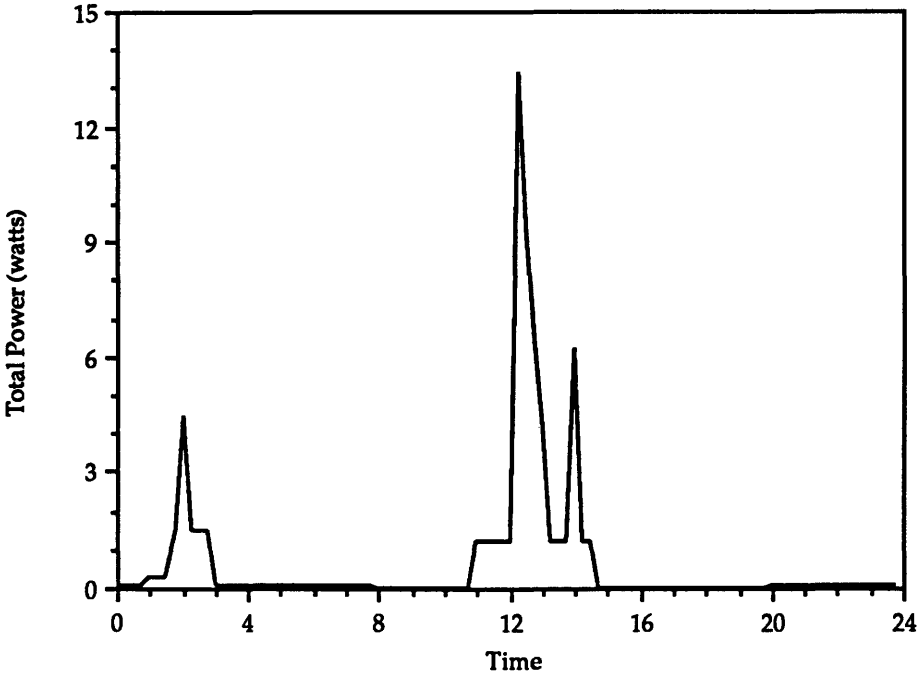

Figure 4.2g - Power profile for the space-qualified rover

4.3. POWER SYSTEM TRADEOFF

As discussed in Section 3.2, the largest design constraint was the five kilogram limit. The mass constraint limited both the amount of hardware included in the design, as well as the amount of power available. The power was constrained because all of the power had to be generated on the rover, but only some of the mass could be allocated to that function. The power generation system design had a big impact on the remainder of the design.

There were three basic options for supplying power to the rover: solar arrays with battery backup, primary batteries, and a nuclear radio-isotope thermal generator (RTG). Solar arrays convert sunlight directly to electricity, and store excess capacity in rechargeable secondary batteries for use when the sun does not shine. Solar arrays work best in situations where there is a reliable supply of sunlight, where the orientation of the solar arrays can be accurately controlled, and where the daily power requirements match the supply from the sun. Primary batteries store a limited amount of power for one-time use.

They are good for low power situations because they are simple and convenient. They are good for continuous use because the supply is always available, but they have limited life since they cannot be recharged. RTGs convert the heat of nuclear decomposition directly into electricity. They are ideal for long life, high power applications that require a lot of heat. Other space power systems exist, such as beamed microwaves, nuclear reactors, and solar dynamic cycles, but they are either too big for a small vehicle, or limit mission flexibility by depending on other hardware.

The tradeoff study below determined which of these systems was best for the Mars micro-rover. It used the power estimates that were available at the beginning of the design effort, but applied equally to the final power budget presented in Section 4.2. The discrepancies between the two will be discussed at the end of the section.

Decision Criteria

Three criteria described the impact of the various types of power systems.

1. Mass
2. Size
3. Simplicity

As previously discussed, mass was the primary constraint on the design of the system, so it was considered in the selection of the power system. Although there was no inherent volume constraint on the rover, the mass constraint clearly imposed some upper bound on the rover's size. The power system had to fit within that upper bound, and mesh with the other components in the design.

Simplicity was an issue because, all else being equal, simple was better. It was desirable to minimize the number of places where problems could arise in the system's operation. Similarly, the power system had to be reliable. With such a tight mass constraint, redundant hardware was difficult to justify, so the power system was likely to be a single point failure that could kill the whole system. It was important to choose a power system that would work well under a wide variety of unexpected conditions.

Assumptions

The following assumptions were used in the power system tradeoff study.

1. The rover required 15 watt-hours of electricity per day; approximately 10 watts-hours during sunlight and 5 watt-hours during darkness.
2. The heaviest load was 10 watts for maneuvering through rough terrain.
3. The rover's operational cycle was the same every day.
4. Power distribution equipment did not impact the tradeoff.

The rover's total energy requirements were based on the preliminary power budget shown in Figure 4.2d and the power profile shown in Figure 4.2g. In addition to the total energy requirements, the power system design depended on the highest power needed at any one time. Power systems operate most efficiently when supplying a constant load. Peak loading can drain the system unnecessarily, and may require additional storage devices if the peaks are beyond the capability of the base system. Since it is better to maintain a flat power profile versus one that has many peaks, the power system tradeoff assumed that power intensive systems would not be used concurrently. For example, the camera and the transmitter would not be used when the rover was maneuvering. Based on the power profile in Figure 3.5b, the highest load would occur when the rover was climbing. At that time, the motors require 8 watts, the processor require 0.3 watts, and the sensors require one watt. Allowing for some margin, the tradeoff assumed the highest load was ten watts.

The daily operating cycle was assumed to be constant for two reasons. It simplified the analysis of the solar array option because the arrays generate the same amount of power each day. Since the lifetime power requirements were just a multiple of the daily requirements, it also simplified the relationship between daily power requirements and rover lifetime for the primary battery case.

Power distribution equipment did not affect the power system tradeoff because the same equipment was required for each of the systems. Consequently, power distribution mass was not considered in the analysis.

The next three sections analyze the options of solar arrays, primary batteries, and RTGs.

Solar Array Analysis

Assumptions

The following assumptions were specific to the solar array analysis:

1. The solar arrays would not track the sun.
2. The solar arrays would be horizontal all day.
3. The specific power of state of the art photovoltaic cells in low Earth orbit is 110 watts/kilogram.
4. State of the art photovoltaic cells in low Earth orbit provide 160 watts/square meter.

Sun tracking would enable the solar arrays to always remain perpendicular to the sun vector, the configuration that maximizes the power generated. Since the rover would be moving over uneven terrain and in and out of shadows, the implementation of a sun tracking system would be very complex. Instead, the study assumed that the arrays would be horizontal all day. Although this assumption was not entirely accurate in the case of moving over rough terrain, it produced a more conservative estimate of the power generated than the ideal case would have. The assumptions for state of the art power per unit mass and power per unit area provided good first cut estimates for the mass and size of the power system, based solely on the overall daily power requirements.

Determine the power required

The goal was to find the mass and size of a solar array system to provide 15 watt-hours of electricity per day. The study assumed that 10 watt-hours would be used during sunlight hours and 5 during darkness. The solar array would have to be sized to produce the peak power needed or else there would have to be a peaking system that stored energy for periods when more than the average load was needed.

Wertz and Larson define the following equation for the power a solar array must generate during sunlight hours to satisfy demand and charge the battery

[Wertz and Larson, 1991, page 357]. The equation assumes that the power profile is fairly flat.

$$P_{sa} = \left[\frac{P_d T_d}{X_d} + \frac{P_e T_e}{X_e}\right] \cdot \frac{1}{T_d} \qquad \text{[Eq. 4.3a]}$$

P_{sa} = Power solar array must provide during sunlight hours
P_d = power required during sunlight
P_e = power required during eclipse
T_d = sunlight hours
T_e = eclipse hours
X_d = path efficiency through array
X_e = path efficiency through batteries

Wertz and Larson offered characteristic values for X_d of 80% and X_e of 60%. In the rover's case, the power which the solar array had to produce was 1.7 watts.

$$P_{sa} = \left[\frac{10}{0.8} + \frac{5}{0.6}\right] \cdot \frac{1}{12} = 1.7 \text{ watts} \qquad \text{[Eq. 4.3b]}$$

Unfortunately, the rover's power profile was not flat. The power required for maneuvering varied widely depending on the terrain traversed. Subsystems such as the camera and transmitter would be cycled on and off at different times during the day. If the arrays produced 1.7 watts throughout the day, some of it must be stored to meet the uneven usage.

Alternatively, the arrays could be sized for the largest load, and unused power could be shunted to a heat dissipater. This alternative increased the size of the array, but eliminated the need for additional storage capability. The peak load was ten watts as described in the assumptions. The array was also designed for this load so that the two options could be compared.

Determine the mass of the arrays

Several sources agreed that state of the art solar cells produce 110 watts/kilogram in low Earth orbit when the incident sunlight is normal to the cell. [Lockheed, 1988; Wertz and Larson, 1991, p. 352; Martinez-Sanchez, 1992]. Solar flux falls off as a function of inverse distance squared. Mars is 1.52 times as far from the Sun as Earth is. Consequently, the solar flux is only 43% as strong when it reaches Mars.

$$\left[\frac{1.00 \text{ a.u.}}{1.52 \text{ a.u.}}\right]^2 = 0.43 \qquad \text{[Eq. 4.3c]}$$

If the sun vector is not perpendicular to a solar cell, the power produced is reduced by the cosine of the angle between the surface normal and the sun vector as shown in Figure 4.3a.

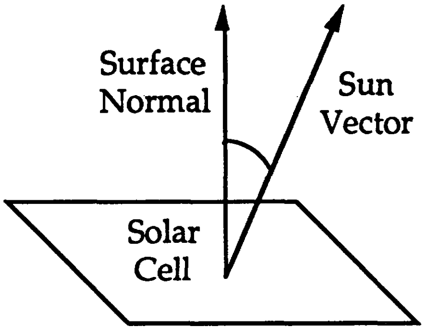

Figure 4.3a - Diagram of a solar cell and the angle made by the sun vector

In the rover's case, the sun angle would be constantly changing as the sun rose and set. To calculate the power produced by one cell during a day, the sun angle was integrated over 12 hours.

$$\int_0^{12} P_0 \cdot \cos\theta \cdot dt = 2P_0 \int_0^{6} \cos\theta \cdot dt \qquad \text{[Eq. 4.3d]}$$

$$\theta = -\frac{\pi}{2} \text{ when } t = 0,\ \theta = 0 \text{ when } t = 6,\ \theta = \frac{\pi}{2} \cdot \left(\frac{t}{6} - 1\right)$$

$$2P_0 \int_0^6 \cos\left[\frac{\pi}{2}\cdot\left(\frac{t}{6}-1\right)\right]\cdot dt = \frac{2P_0}{\frac{\pi}{12}}\left\{\sin\left[\frac{\pi}{2}\cdot\left(\frac{t}{6}-1\right)\right]\right\}_0^6 = \frac{24P_0}{\pi} \qquad \text{[Eq. 4.3e]}$$

P_0 = power produced when the sun vector is perpendicular to the cell

The Sun's motion reduced the average power by a factor of $\frac{2}{\pi}$.

$$\frac{\frac{24P_0}{\pi}}{12 \text{ hours}} = \frac{2P_0}{\pi} \qquad \text{[Eq. 4.3f]}$$

If the rover's arrays were horizontal at the equator during solar equinox, the sun vector would be perpendicular to the array at noon. Since the mission was not so constrained, there was an additional reduction based on the rover's latitude and season. The analysis assumed a 20% reduction of the available sunlight to cover a wide variety of situations.

Combining the distance, angle, and other effects discussed above, state of the art solar cells produce 24 watts/kilogram on the surface of Mars.

$$110 \cdot 0.43 \cdot \frac{2}{\pi} \cdot 0.80 = 24 \text{ watts/kilogram} \qquad \text{[Eq. 4.3g]}$$

Although additional factors, such as dust in the atmosphere, may reduce this value, it was a good estimate for this study. The mass of the solar array was simply the power required divided by the specific power. In the case where peaking power was stored, the mass of the arrays was 0.08 kilograms.

$$\text{Mass}_{\text{solar cells}} = \frac{P_{sa}}{24 \text{ watts/kg}} = \frac{2}{24}\text{ kg} = 0.08 \text{ kg} \qquad \text{[Eq. 4.3h]}$$

In the case where the arrays were sized for the greatest load, the mass of the arrays was 0.42 kilograms.

$$\text{Mass}_{\text{solar cells}} = \frac{10}{24}\,\text{kg} = 0.42\,\text{kg} \qquad \text{[Eq. 4.3i]}$$

Determine the area of the arrays

Sources also agreed that state of the art photovoltaic cells provide 160 watts/square meter in low Earth orbit. [Lockheed, 1988; Wertz and Larson, 1991, p. 352; Martinez-Sanchez, 1992]. On the surface of Mars this value would be reduced by the same factors discussed above. Thus the solar array would have a specific power equal to 35 watts/square meter.

$$160 \cdot 0.43 \cdot \frac{2}{\pi} \cdot 0.80 = 35\ \text{watts/kilogram} \qquad \text{[Eq. 4.3j]}$$

The area of the solar array was simply the power required divided by the power per unit area. In the case where peaking power was stored, the area of the arrays was 0.06 square meters.

$$\text{Area}_{\text{solar cells}} = \frac{P_{sa}}{35\ \text{watts/m}^2} = \frac{2}{35}\,\text{m}^2 = 0.06\,\text{m}^2 \qquad \text{[Eq. 4.3k]}$$

In the case where the arrays were sized for the greatest load, the area of the arrays was 0.29 square meters.

$$\text{Area}_{\text{solar cells}} = \frac{10}{35}\,\text{m}^2 = 0.29\,\text{m}^2 \qquad \text{[Eq. 4.3l]}$$

Determine the required battery capacity

The secondary battery had to supply 5 watt-hours of electricity to keep the rover alive at night. The rover's nighttime power requirements were fairly constant. The heater requirements would vary as the external temperature changed. There would be a peak when the transmitter was used, but these deviations would be small.

The battery was sized for both of the cases discussed above. If the peak power was supplied by the secondary battery, the battery would require greater capacity than it would otherwise. As shown in the power profile in Figure 4.2g, approximately four of the watt-hours used during the daytime would exceed the average load. Those watt-hours would have to be stored in the secondary battery. If there was no peak load requirement, the battery capacity would only be needed to accommodate the average power requirements during hours of darkness.

The rated capacity of the battery depended primarily on the depth to which it would be discharged each night. Depth of discharge directly impacts the number of charge/discharge cycles a rechargeable battery can undergo. Since the rover's lifetime is measured in days rather than years, the battery could be discharged almost completely. Figure 4.3b shows that it is possible to discharge nickel hydrogen batteries to depths greater than 80% when fewer than 1000 charge/discharge cycles are required.

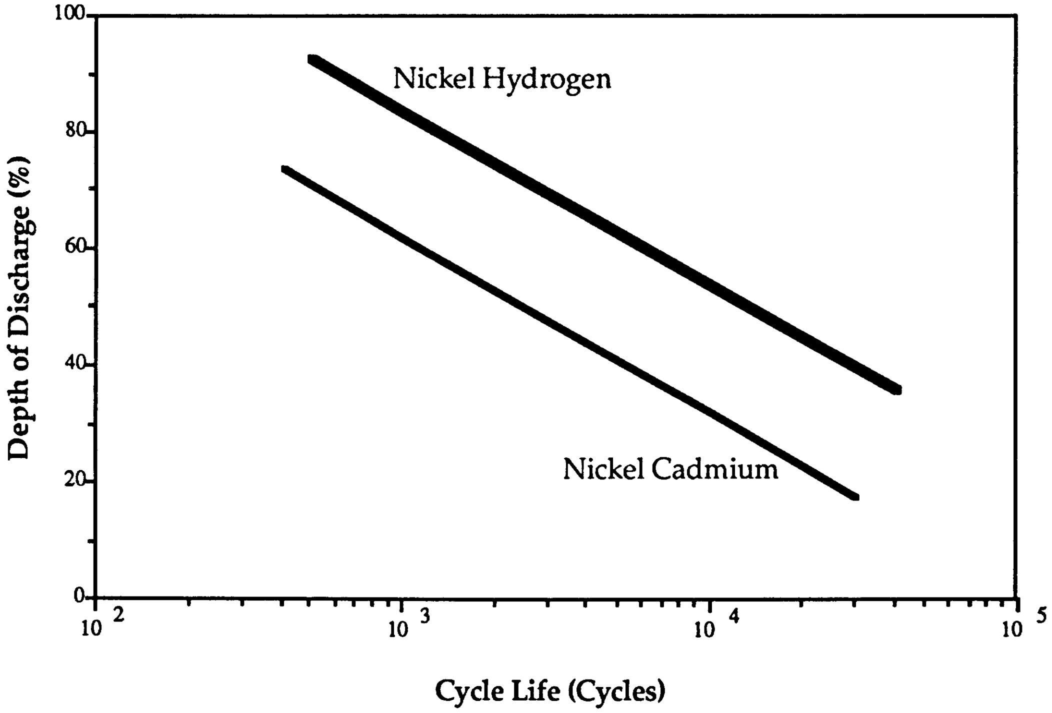

Figure 4.3b - Tradeoff between depth of discharge and charge cycles [Wertz and Larson, 1991, page 363]

Assuming a depth of discharge of 90%, the batteries had to have a total capacity of 9.9 watt-hours in the 1.7 watt solar array case.

$$\text{Capacity} = \frac{\text{Power Required}}{\text{Depth of Discharge}} = \frac{9\ \text{watt-hours}}{0.90} = 9.9\ \text{watt-hours} \qquad [\text{Eq. 4.3m}]$$

They required 5.5 watt-hours in the 10 watt solar array case.

$$\text{Capacity} = \frac{5\ \text{watt-hours}}{0.90} = 5.5\ \text{watt-hours} \qquad [\text{Eq. 4.3n}]$$

Determine the battery mass

The battery mass was equal to the rated capacity divided by the specific energy of the battery. As shown in Figure 4.3c, there are several types of secondary batteries for space applications with widely varying specific energy densities. Due to the cost and technology constraints imposed in Chapter 3, the only options to be considered in this tradeoff study were nickel cadmium, and nickel hydrogen with an individual pressure vessel design. Since nickel hydrogen batteries have a greater capacity for a given weight and system mass was a primary decision criterion, the analysis assumed that 40 watt-hours/kilogram were available.

Secondary Battery Couple	**Specific Energy Density (w-hr/kg)**	**Typical Application**
Nickel cadmium	25 - 30	Space-qualified, extensive database
Nickel hydrogen (individual pressure vessel design)	25 - 40	Space qualified for GEO only
Nickel hydrogen (common pressure vessel design)	45 - 60	Under development
Sodium sulfur	140 - 210	Under development

Figure 4.3c - Characteristics of selected secondary batteries
[Wertz and Larson, 1991, page 362]

With nickel hydrogen batteries, the mass for the 1.7 watt solar array was 0.25 kilograms.

$$M_{battery} = \frac{\text{Capacity}}{\text{Specific Energy}} = \frac{9.9 \text{ watt-hours}}{40 \text{ watt-hours/kg}} = 0.25 \text{ kg} \qquad \text{[Eq. 4.3o]}$$

The mass of the batteries for the 10 watt solar array was only 0.14 kilograms.

$$M_{battery} = \frac{\text{Capacity}}{\text{Specific Energy}} = \frac{5.5 \text{ watt-hours}}{40 \text{ watt-hours/kg}} = 0.14 \text{ kg} \qquad \text{[Eq. 4.3p]}$$

Summary

To summarize the analysis above, there were many solar array systems that could supply adequate power to the rover. Figure 4.3d lists the parameters for the systems on the extremes. If the battery supplied power for peak loads, a 1.7 watt solar array covering 0.06 square meters with a mass of 80 grams, combined with a nickel hydrogen battery with a 9.9 watt-hour capacity and a mass of 250 grams could be used. Alternatively, if the solar array was big enough to supply the peak loads, a 10 watt solar array covering 0.29 square meters with a mass of 420 grams, combined with a nickel hydrogen battery with a 5.5 watt-hour capacity and a mass of 140 grams could be used.

	Array sized for average load	Array sized for peak load
Array power (watts)	1.7	10
Array mass (grams)	80	420
Array area (sq. meters)	0.06	0.29
Battery capacity (w-hrs)	9.9	5.5
Battery mass (grams)	250	140
System mass (grams)	330	560

Figure 4.3d - Summary of solar array system parameters

Margin

The previous analysis focused on the minimum system requirements for a solar array power system. Since a loss of power implied failure of the rover, it was wise to increase the system's robustness by including a margin to survive for one day without sunlight. In such a case, the rover would enter a stay-alive mode, using power only for processing and thermal control. The stay-alive mode required 7.8 watt-hours for one day. Such a margin increased the required capacity of the battery by 8.7 watt-hours and the mass by 220 grams.

$$\frac{7.8}{0.9} = 8.7 \text{ watt-hours} \qquad \frac{8.7}{40} = 220 \text{ grams}$$

Charge/discharge equipment

It was also important to consider the charge/discharge equipment. Wertz and Larson suggest that charge/discharge equipment accounts for approximately ten percent of the mass of a solar power system [Wertz and Larson, 1991, page 365]. The mass of the solar arrays and batteries was either 330 or 560 grams. Therefore, the charge/discharge equipment required 37 or 62 grams.

$$\frac{1}{9} \cdot 330 = 37 \text{ grams} \qquad \frac{1}{9} \cdot 560 = 62 \text{ grams}$$

Thus the total system mass would be 367 or 612 grams.

Other factors

Solar arrays with secondary batteries are perhaps the most common choice for powering space systems. Their reliability is unquestionable, their cost and weight well known, and they require no unusual certification processes. Unlike the primary batteries discussed below, solar arrays have virtually unlimited lives. They would not constrain the mission life by expiring before other failures keep the rover from continuing its mission.

In addition to the design factors discussed above, the operation of a solar power system was considered. The system required switching equipment to cycle once a day to charge and discharge the batteries. This hardware added complexity to the power system and provided additional failure points.

A solar power system depends on the weather since any obscuring of the sunlight will eliminate power. Similarly, weather can have a significant impact on the performance of the solar array. Dust stirred up by the rover might coat the array, reducing its performance. A dust storm might totally destroy the array, although such a storm might also destroy the whole rover, thus making the concern irrelevant. Since little was known about the nature of the landing site, shadows were another concern. Requiring sunlight could restrict the rover's mobility.

Primary Battery Analysis

The primary battery analysis was simple compared to that of the solar array. A primary battery system was sized to provide the necessary power and energy requirements of the system. There were no additional requirements such as charge/discharge equipment.

As shown in Figure 4.3e, several types of primary batteries are available for space applications. As with secondary batteries, the different types have widely varying specific energy densities. From the options shown below, lithium sulfur dioxide was the best choice because it has a relatively high specific energy density. Its typical applications are on the order of days rather than hours or minutes.

Primary Battery Couple	Specific Energy Density (w-hr/kg)	Typical Application
Silver zinc	60 - 130	High rate, short life (minutes)
Lithium thionyl chloride	175 - 440	Medium rate, moderate life (<4 hours)
Lithium sulfur dioxide	130 - 350	Low/medium rate, long life (days)
Lithium monoflouride	130 - 350	Low rate, long life (months)
Thermal	90 - 200	High rate, very short life (minutes)

Figure 4.3e - Characteristics of selected primary batteries
[Wertz and Larson, 1991, page 361]

Determine battery mass

Figure 4.3e shows lithium sulfur dioxide batteries with specific energy densities as high as 350 watt-hours/kilogram. The latest specifications were obtained from major battery manufacturers such as PowerConversion, Inc. Their Eternacell SDX lithium sulfur dioxide batteries have energy densities as high as 330 watt-hours/kilogram.

The required capacity of the primary battery system is 15 watt-hours per day. Since the batteries would only be used once and drained until no energy remained, the depth of discharge was 100%. A system providing 15 watt-hours of energy with the best lithium sulfur dioxide battery would require a mass of 45 grams.

$$\frac{15}{330} = 45 \text{ grams}$$

Since the daily duty cycle was constant, the total system mass was 1.35 kilograms.

$$0.045 \text{ kg} \cdot 30 \text{ days} = 1.35 \text{ kg}$$

It was interesting to note that the break-even point for mass between solar and battery systems was somewhere between seven and twelve days. If more than five days were required, a solar system would weigh less than a battery system.

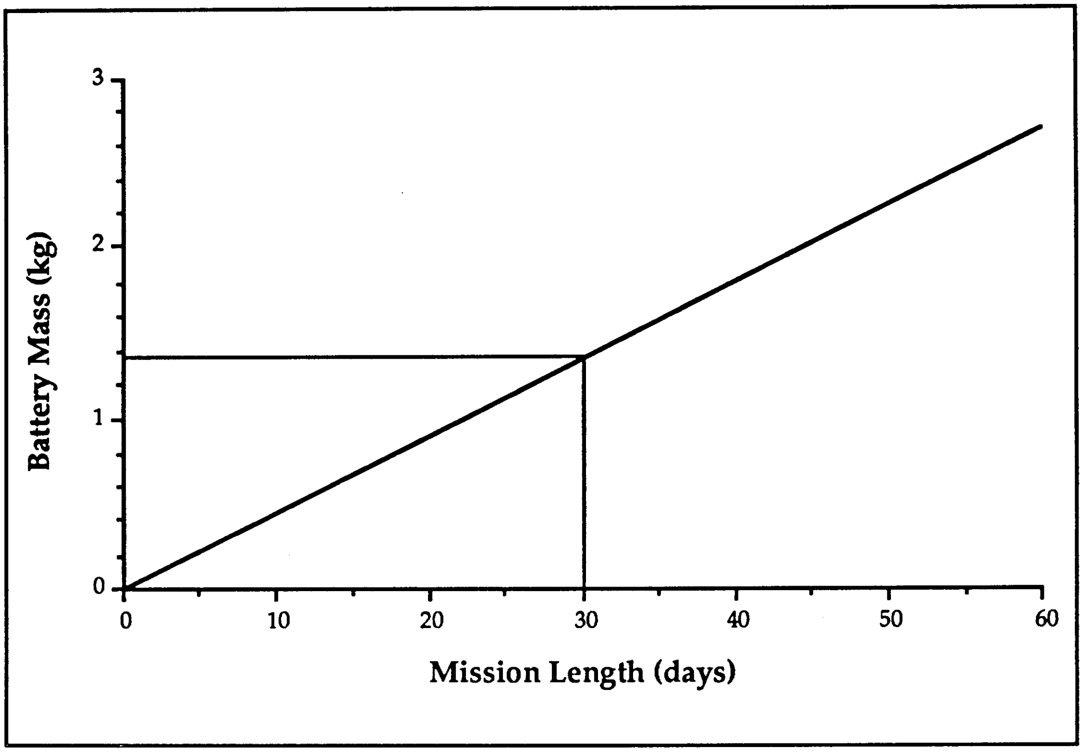

Figure 4.3f - Graph of primary battery system mass vs. mission length

Other factors

Primary batteries had the advantage of being very simple and reliable. Their performance was independent of most external factors. Their disadvantage was their limited lifetime. As the batteries start to run out of energy, the voltage across them will drop below the rated voltage. The rover's performance will correspondingly degrade. When the batteries die, so will the rover.

Nuclear Radioisotope Thermal Generator Analysis

Determine mass and size

The JPL mission discussed earlier used a nuclear RTG for power generation. The JPL rover had a mass of 17 kilograms and used an RTG with a mass of 3.5 kilograms. The RTG produced 9 watts continuously. A capacitor bank was used to provide peaking power on demand. Such a system would more than cover the needs of this project. During the night, the excess capacity could be rejected with heaters, whereas during the daytime, radiators would be required.

Other factors

RTGs had the advantage of being long lived and very reliable. They had the disadvantages of being expensive, hot, radioactive, heavy, and politically undesirable. They also raised policy issues such as obtaining safety approval for launch. An RTG was unsuitable for a 30 day mission because its primary advantage of long life was not one of the mission goals, and did not outweigh the costs.

Conclusion

As discussed earlier, three criteria affected the decision between the three types of power systems. The criteria were mass, size, simplicity. The rating of each option against the criteria is summarized in Figure 4.3g and discussed below.

	Solar Array	Primary Battery	Nuclear RTG
Mass	+	0	-
Size	-	+	0
Simplicity	-	+	0

Legend: + is best, 0 is neutral, - is worst

Figure 4.3g - Summary of the three power systems rated against four criteria

The solar array required the least mass, while the nuclear RTG required the most. In the preliminary mass allocation, the power system was allowed one kilogram. Based on that allocation, the solar array was the only acceptable choice. The primary battery system was a close second since it demanded only 1.35 kilograms. The RTG was an unacceptable choice since it required 70% of the total mass.

Size was primarily a concern for the solar array. Even the smallest array required more area than the rover's cross-section. Although size did not rule out the solar array, it was a disadvantage because the rover would have to include an unnecessarily large structure.

Simplicity referred to mechanical simplicity and operational simplicity. Primary batteries were clearly the simplest option. All that was required was a switch to turn them on and off, otherwise they would take care of themselves. An RTG is a complicated device to build, but once it is sealed it is as simple as a battery. It creates an operational problem, however, because it produces a considerable amount of excess heat that has to be rejected. The solar array was the most complicated choice both mechanically and operationally. Mechanically, it had to be switched every day between the array and the battery, and the battery had to be recharged every day. Operationally, it required the rover to maximize its sun exposure. The array would prevent the rover from going into canyons, caves, or other areas where sunlight would be limited. Insufficient power was also a concern if the rover's position did not allow the array to remain nearly perpendicular to the sunlight.

In conclusion, the primary battery system was the best choice for the project at this stage. Although it was not the lightest system, its mass was reasonable and could be reduced by increasing the rover's power efficiency. Its mechanical and operational simplicity were great assets for an undefined mission such as this. With serious researchers looking into better batteries for Earth and space applications, it is quite possible that a technological breakthrough could occur before launch, making batteries an even better choice by extending the rover's mission life.

Adjustments for Final Power Allocation

The main difference between the preliminary and final power allocations, which were discussed in Section 4.2, was the maximum load expected. In the final power allocation shown in Figure 4.2f, the motors required a maximum of 11 watts, the processor demanded 1.2 watts, and the sensors drew 1.2 watts. Therefore, the maximum load was 13.4 watts instead of the 10 watts used in the analysis. The difference gave greater credence to the decision to use batteries because a solar array design would be bigger and heavier than previously assumed, while batteries required roughly the same mass.

4.4. COMMUNICATIONS TRADEOFF

After the power system, the communication system was the next largest driver of the micro-rover's design. As mentioned in Section 3.1, a major goal of the design effort was to minimize dependence on external hardware. Ideally, the rover would communicate directly with Earth. No other hardware would be required, and the only constraint on communications would be the viewing angle between the rover and Earth. Unfortunately, direct communication required unreasonable amounts of power or huge antennas. The power and size requirements were reduced by using a communications link in Mars' orbit. The large power and antenna requirements were moved onto the orbiter, leaving the rover with only a small antenna and minimal power requirements. The disadvantage of the scheme was that the rover depended on the presence of a Mars' orbiter to successfully perform its mission. The following tradeoff study shows why the orbiting communications link was the best option.

Decision Criteria

Two parameters determined whether or not a communication link was viable. The parameters were the input power required and the mission flexibility the option allowed. As discussed in Section 4.3, the maximum power needed is ten watts when the rover is maneuvering through rough terrain. A good communication link option requires less than ten watts. As discussed in Section 3.4, the requirement to maximize mission flexibility also had to satisfied. There were other constraints on the design of the system. Parameters such as antenna size, subsystem mass, and operational requirements had to be reasonable.

Assumptions

General assumptions

This section discusses the general tradeoff assumptions.

1. The signal to noise ratio had to be at least 10.
2. All antennas had 55% efficiency.
3. There was a 50% power loss between power input and power transmitted.
4. The maximum size for the rover's antenna was 400 square centimeters, the maximum expected cross-sectional area of the rover.
5. The rover would transmit one video image per day.
6. A video image contained one megabit of data.

The main question to be resolved was how much power the rover needed to supply for data transmission. Better communications can be achieved by increasing the transmission power, reducing the rate of transmission, or increasing the energy collection of the receiver. Other methods exist, but there are limits to what is practical. The figure of merit in communication theory is the signal to noise ratio, which is a description of how strong the signal of interest is relative to any undesired signals, i.e. the noise.

Phil Konop at Draper Laboratory provided various suggestions on reasonable numbers for this study. The signal to noise ratio depends on the tolerable error probability. For a mission such as this, an error probability of one in a million was acceptable; that is to say for every million bits received on Earth one of them could be bad. Based on this error rate, standard signaling curves suggested that the signal to noise ratio had to be around 10.

Antenna efficiency is a result of imperfections in the manufactured antenna. Typical antenna efficiencies are between 50% and 70% [Wertz and Larson, 1991, page 459]. For this study, a conservative figure of 55% was used for all antennas. In addition to the antenna inefficiency, there was a 50% loss between the input power and the transmitted power. This power reduction was due to the characteristics of the hardware used to convert electrical energy into transmitted radio energy.

The number of bits in a video image depend on the resolution of the image and the level of data compression. Joseph Stampleman of the MIT Media Lab provided details on how much information is inherent in a video image. He suggested that virtually any figure on the order of one megabit was a reasonable assumption. It was possible to reduce the bit stream by using data compression, however, compression results in a loss of resolution. The tradeoff study assumed that an image required one megabit of data.

The following sections discuss the assumptions specific to each of the options.

Rover to Earth

1. The maximum transmission distance was 400 million kilometers.
2. The data rate was at least 280 bits per second.
3. The Earth receiver was at 290° Kelvin.
4. The Earth antenna had an effective aperture of 3850 square meters.

The distance between Earth and Mars varies from 50 million to 400 million kilometers, depending on their orbital positions. Since the rover's launch date was undetermined and one of the design criteria was mission flexibility, all scenarios had to be accounted for. Rover-to-Earth calculations were based on the worst case figure of 400 million kilometers.

Earth could be in view of the rover's antenna for a limited time during each Martian day. The window depended on the relative position of Earth and Mars, and the degree of freedom designed into the rover's antenna. For an antenna with a universal joint and high pointing accuracy, the maximum window was 12 hours 20 minutes, or one-half of a Martian day. Assuming the antenna could not swivel, and had a beam only 20° wide, the window narrowed to 80 minutes.

$$\frac{20\ \text{deg}}{180\ \text{deg}} \cdot 12\ \text{hours}\ 20\ \text{minutes} \cong 80\ \text{minutes}$$

Since the Earth to rover communication also had to fit within the 80 minute window, the rover had only 60 minutes to transmit its daily images. The data rate had to be at least 560 bits per second in order to transmit two megabits in 60 minutes.

$$\frac{2 \cdot 10^6 \text{ bits}}{60 \text{ minutes}} \cong 560 \text{ bits per second}$$

The size of the receiving antenna has a direct impact on the amount of radiated energy it collects. The Earth antenna was assumed to have an effective aperture of 3850 square meters, comparable to the 70 meter JPL Deep Space Network antenna.

Rover to Mars Orbiter

1. The link used the Mars Balloon Relay on the Mars Observer Spacecraft
2. The transmission distance was 400 kilometers.
3. The data rate was at least 2000 bits per second.
4. The orbiting receiver was at 200° Kelvin.
5. The orbiting antenna had an effective aperture of 1 square meter.

As discussed in Section 3.1, the Mars Balloon Relay on the Mars Observer spacecraft would be used for communications by the French-Soviet Balloon mission. The study assumed the Relay was a representative orbiting communications link. The Mars Observer orbits at a nominal altitude of 400 kilometers [JPL, 1991b].

Mars Balloon Relay passes last for ten minutes. Two of those minutes were allocated for receiving commands. The Mars Balloon Relay is capable of receiving 128 kilobits per second [Goss, 1992]. In order to transmit a one megabit image in eight minutes, the data rate must be at least 2000 bits per second.

$$\frac{10^6 \text{ bits}}{8 \text{ minutes}} \cong 2000 \text{ bits per second}$$

Rover to Mars Lander

1. The maximum transmission distance was 3 kilometers.
2. The data rate was at least 2000 bits per second.
3. The lander's receiver was at 298° Kelvin.
4. The lander's antenna had an effective aperture of 1 square meter.

Since the rover's mission was to traverse 100 meters per day for 30 days, the maximum distance to the lander was estimated as three kilometers.

A minimum data rate was not required because there was no limit on the amount of time available. Two thousand bits per second was used as the minimum to highlight the differences between an orbiter link and a lander link.

Theory

The amount of energy the rover had to transmit depended on the required strength of the received signal, the transmission distance, and the characteristics of the receiver. This section discusses the equations that apply to a basic communications link, and develops a model for examining the design options. The equations below are based on Section 7.5 of Agrawal [Agrawal, 1986].

Find the power required by the receiver

The signal to noise ratio required at the receiver and the noise inherent in the receiver defined how much energy is required by the receiver.

$$E = \frac{S}{N} N_T \qquad \text{[Eq. 4.4a]}$$

E = Energy at the receiver

$\frac{S}{N}$ = Signal to noise ratio

N_T = Thermal noise at the receiver

The energy of a data bit at the receiver is:

$$E = \frac{P_R}{R} \qquad \text{[Eq. 4.4b]}$$

P_R = Power at the receiver

R = Data rate

The noise at the receiver depends on the temperature and the noise figure:

$$N_T = \kappa \cdot T_s \cdot B \qquad \text{[Eq. 4.4c]}$$

κ = Boltzmann's constant
T_s = System noise temperature
B = Receiver noise bandwidth

Combining Equations 4.4a, 4.4b, and 4.4c, the power at the receiver is,

$$P_R = \frac{S}{N} N \cdot R = \frac{S}{N} \kappa \cdot T_s \cdot B \qquad \text{[Eq. 4.4d]}$$

Find the power transmitted by the rover

The power at the receiver depends on the power transmitted, the antenna gains, the distance between the antennas, and the wavelength of the transmission. In particular, the power at the receiver is:

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi r)^2} \qquad \text{[Eq. 4.4e]}$$

P_T = Transmission power
G_T = Antenna gain of transmitter
G_R = Antenna gain of receiver
λ = Wavelength
r = Transmission distance

Putting Equation 4.4d into 4.4e and solving for P_T yields:

$$P_T = \frac{\frac{S}{N} \kappa T_S B \cdot R \cdot (4\pi r)^2}{G_T G_R \lambda^2} \qquad \text{[Eq. 4.4f]}$$

The wavelength is:

$$\lambda = \frac{c}{f} \qquad \text{[Eq. 4.4g]}$$

c = Speed of light

f = Transmission frequency

The gains for the transmitter and the receiver are related to the respective antenna's efficiency and capture area by:

$$G = \frac{4 \cdot \pi \cdot \eta \cdot A}{\lambda^2} \qquad \text{[Eq. 4.4h]}$$

η = Antenna efficiency

A = Antenna capture area

Finally, the input power is twice the power of transmission due to conversion losses during the transmission process. Combining Equations 4.4f, 4.4g, and 4.4h yields the governing equation for input power required for the rover:

$$P_i = \frac{2 \cdot \frac{S}{N} \cdot \kappa T_S B \cdot R \cdot \lambda^2 \cdot r^2}{A_T A_R \eta^2} \qquad \text{[Eq. 4.4i]}$$

P_i = Input power required

Analysis

Three spreadsheets, one for each of the options, were developed using the equations and assumptions defined above. The spreadsheets analyzed how five aspects of the communication link contributed to the input power required. The five parameters were:

- transmission distance

- data rate
- transmission frequency
- transmitting antenna area
- receiving antenna area

Each of the five parameters appeared in Equation 4.4i which governed the input power required. Based on the results of the three spreadsheets, a most reasonable case was developed for each link option. The cases were based on a combination of existing hardware, mission parameters, and personal judgment of the best attainable values for each parameter. They are shown in Figure 4.4a. The other spreadsheets are included in the appendix.

	Earth	**Orbiter**	**Lander**
Data Rate [bits per second]	300	2000	2000
Receiver Power [W]	**1.20E-13**	**5.52E-13**	**8.22E-13**
Transmission Frequency [Hz]	3.00E+11	4.00E+08	3.00E+07
Wavelength [m]	**0.001**	**0.75**	**10.00**
Transmit Antenna Aperture [m^2]	0.04	0.04	0.04
Receiver Antenna Aperture [m^2]	3850	3	1
Input Power [W]	**825**	**3**	**0.1**

Figure 4.4a - Input power required for the three types of communications links

It is important to note that this tradeoff study focused on relative differences and approximate values, not design requirements. In the Earth-direct case, the input parameters were pushed very close to the practical limits. In the other two cases, the input parameters still had some margin, but the values used were representative of what is possible.

The Earth-direct option required more than 200 times the power of an orbiter link, and an orbiter link required 30 times the power of a lander link. Remembering that a good communication solution would use less than ten watts, it became clear that the Earth-direct option was not feasible. Even though direct communication with Earth maximized mission flexibility it required far too much power to be considered. Both the orbiter and lander links, however, had reasonable power needs. Although the orbiter link required significantly more than the lander link, either one was feasible from a power perspective.

Three factors influenced the decision between an orbiter link and a lander link. The first was hardware dependence. As mentioned in Chapter 3, it was undesirable to require any hardware for the mission that was not part of the rover. Both options required additional hardware. The question was: which option maximized mission flexibility? The second factor was the input power required. Clearly, less power was better. The final factor was simplicity. All else being equal, the simpler, more reliable design was the better one.

Maximizing mission flexibility was very important to maximize the possibility of launch. If the design assumed there would be a lander link and only allocated a little power for communications, the design would have to be modified significantly to communicate through a less convenient link. On the other hand, if the design assumed that an orbiter link was required, flexibility would be retained to use more convenient links.

Analysis of the power profile data plotted in Figure 3.5b showed that if the power required for transmission was three watts, then communication would account for approximately 6% of the total energy requirements. On the other hand, if 0.3 watts were required, then communication would account for only 1%. Using the lander link would save 5% of the rover's total energy budget. Doing so would save 5% of the battery mass required for the power system. Based on the numbers from Section 4.3, the difference between an orbiter link and a lander link was approximately 68 grams.

Design simplicity versus flexibility was the only tradeoff remaining. In the phase zero prototype designed in 1991, a dedicated video transmitter with a range of five miles was used. It required very little mass and volume, and only a 15 centimeter whip antenna. It had no moving parts and transmitted real-time video at 30 images per second. In comparison, an orbiter link requires a larger antenna with steering capability. Successful communications depended on the rover's orientation and its ability to find the communications orbiter. The lander link was definitely simpler.

On the other hand, the orbiter link provided more mission flexibility. The orbiter containing the link hardware did not have to be included on the same mission as the rover. It could already be in orbit when the rover arrived. For example, the Mars Balloon Relay will be launched in September, 1992, on the Mars Observer spacecraft. It will be operating in Mars' orbit whether or not the rover was designed to use it. Therefore, designing to use it did not constrain mission flexibility, whereas requiring a lander link did.

	Rover to Earth	Rover to Orbiter	Rover to Lander
Mission Flexibility	+	0	-
Input power	-	0	+
Simplicity	-	0	+

Legend: + is best, 0 is neutral, - is worst

Figure 4.4b - Summary of the three communication links evaluated against three criteria

Conclusion

Although over-designing the rover was not desirable given the tight, five kilogram mass constraint, it seemed warranted in the case of the transmitter because the rover was still independent of a particular mission. Since some external hardware was required to communicate with Earth, it made sense to choose the option that maximized flexibility without significantly impacting the power or mass constraints. The communications subsystem was designed with the assumption that there was an orbiting link. In particular, it was designed to work with the Mars Balloon Relay on the Mars Observer spacecraft.

CHAPTER 5
SUBSYSTEM DEFINITIONS

Previous chapters discussed how the rover design requirements were developed. Chapter 5 presents a complete set of system specifications that define the rover as it was currently understood. The specifications apply to the final version of the rover. They do not necessarily describe the prototype versions of the rover, because compromises had to be made to meet budgetary and schedule constraints.

The chapter has eight sections. The first seven are devoted to the specifications for each of the subsystems. The last presents the test plan, which will be used to verify that all of the design requirements have been met when the design is complete.

5.1. POWER

Power Description/Requirements

The power system consists of the battery packs (primary and secondary), the power distribution hardware, and the surge protection hardware as shown in Figure 5.1a. It provides 450 watt-hours of electricity.

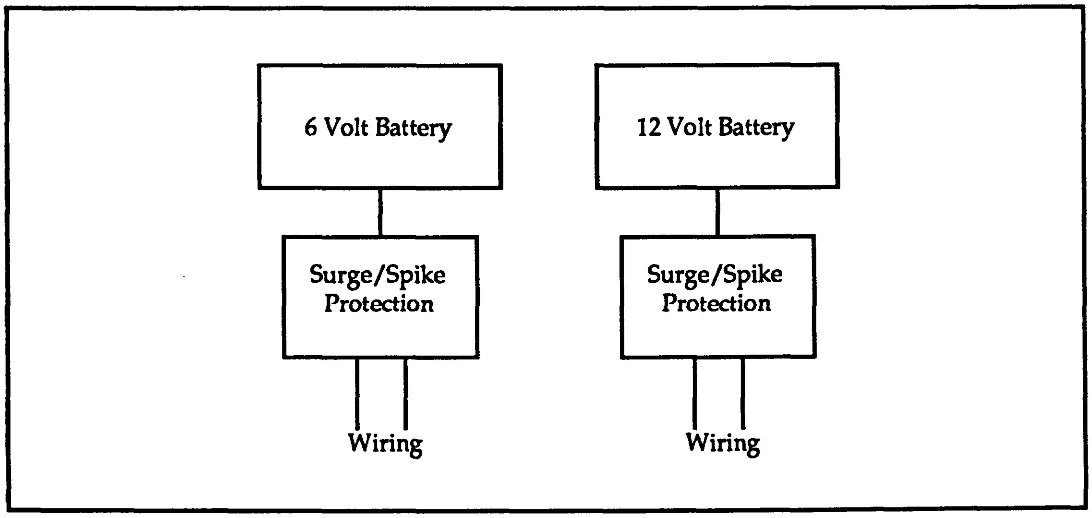

Figure 5.1a - Power block diagram

- The primary battery pack must have a 12 volt bus.
- The primary battery pack must have a capacity of 20 amp-hours: 15 amp-hours for the motors, 2.0 for the communications system, 0.5 for the camera, and 2.5 for the thermal system.
- The secondary battery pack must have a 6 volt bus.
- The secondary battery pack must have a capacity of 35 amp-hours: 30 amp-hours for the processor, and 5 for the sensors.
- Neither power bus will be regulated.
- The secondary battery pack is required to isolate the sensitive electronics from the surges flowing through the primary bus, as well as providing a lower voltage.
- All of the batteries must have a shelf life that will survive from launch through landing before being turned on. Depending on the mission, this could range from three months to two years.

Power Interfaces

As shown in Figure 5.1b, the power system provides power to all the subsystems that require it.

- The primary battery pack provides 12 volts of power to the communications system, the vision system, the maneuvering system, and the thermal system. These systems have irregular duty cycles, causing large variations in the current drawn out of the primary bus.
- The interfaces with sensitive hardware such as the camera and the transmitter will require surge and spike protectors to prevent them from being damaged when different systems are turned on and off.
- In general, the maneuvering system will be shut off before the communications or vision system is used. This will change if the camera is used for navigation.
- The thermal system will primarily be used at night, so it should only conflict with the communications system.

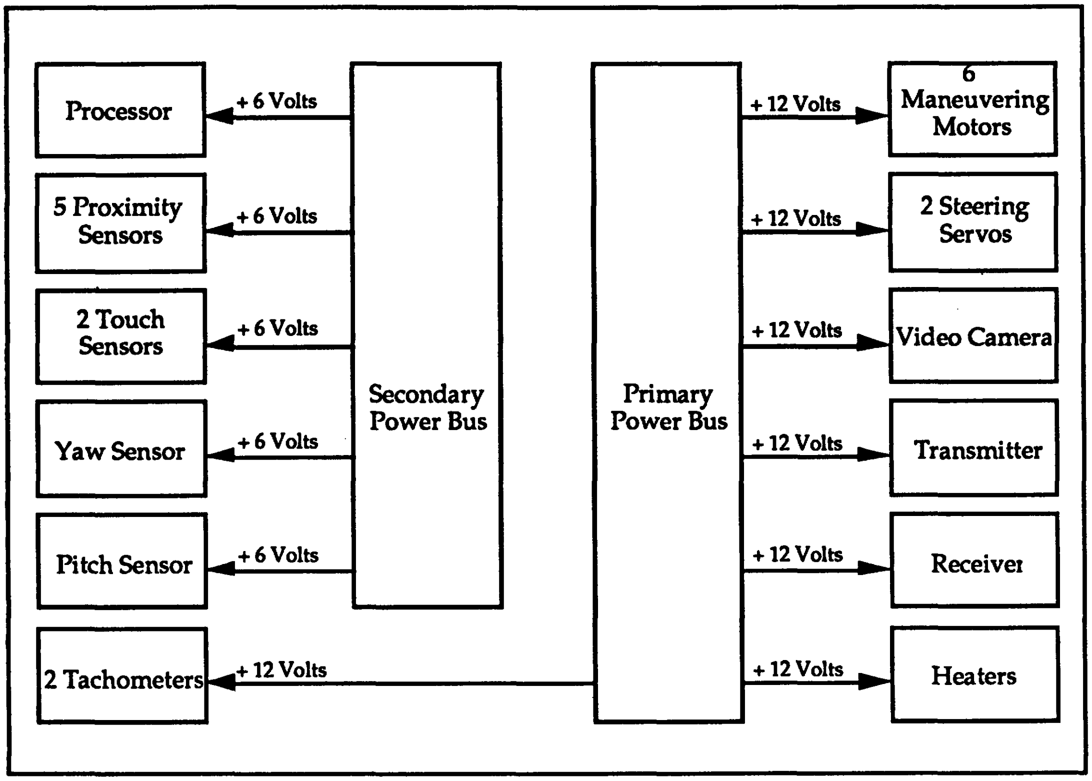

Figure 5.1b - Power interface diagram

- The secondary battery pack provides 6 volts of power to the processing system and the guidance and navigation system. These systems contain power sensitive hardware, so the circuit to which they are connected is isolated from the primary power bus.
- The processing system has a continuous duty cycle with two states. When it is awake, it is active all of the time. When it is asleep, its clock speed and power requirements drop to virtually zero. The sleep mode can be automatically interrupted by an external input.
- The sensors in the guidance and navigation system will be pulsed as necessary when the rover is maneuvering. They receive power through the processor board at the processor's command.

Power telemetry required

The following telemetry points must be supplied to the processor for transmission to Earth:

- The voltage across the primary battery pack
- The capacity remaining in the primary battery pack

- The voltage across the secondary battery pack
- The capacity remaining in the secondary battery pack

5.2. PROCESSING

Processor Description/Requirements

The processing system is currently built around a Motorola 6811 chip. It will include other chips as necessary, and a clock to keep time. It has a data bus that interfaces with RAM, an input buffer, and an output latch. It also has connectors for RS-232 interfaces and analog interfaces.

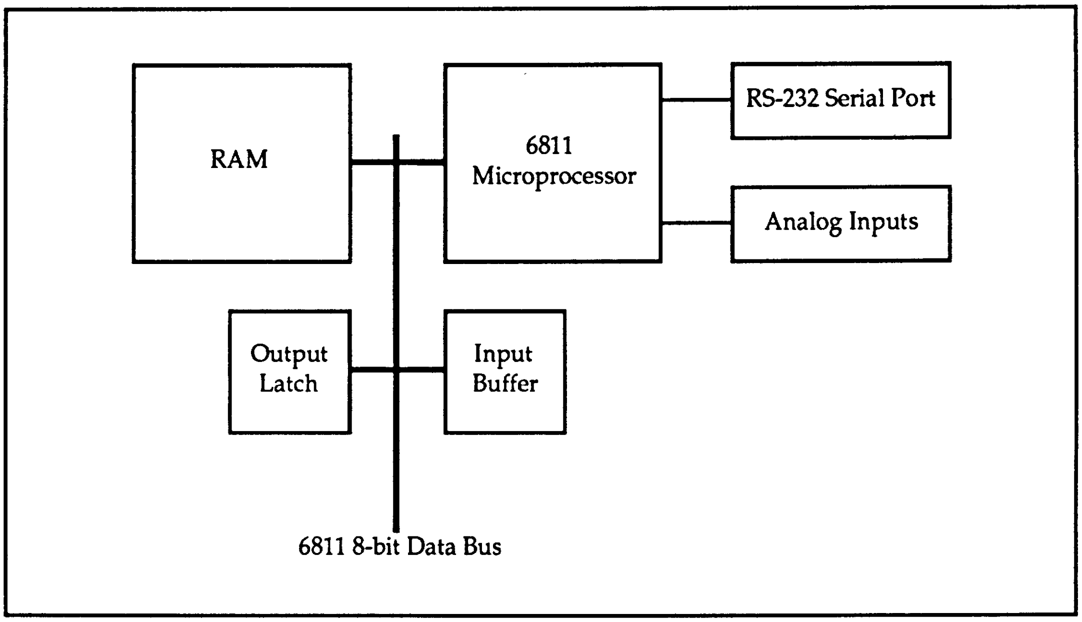

Figure 5.2a - Processing block diagram

The processing system issues on/off commands, controls complex subsystem behaviors, formats video and telemetry data for transmission, implements commands received by the communication subsystem, maintains knowledge of the rover's position and destination vectors, and coordinates the rover's activities throughout the mission.

The design of the processing system will develop during the rest of the project. Its control capabilities will be enhanced, and image processing will be added to the navigation logic if the capability becomes available. The following requirements apply to the processing system independent of the chips in the design.[3]

- The processor must have a clock.
    - The clock must coordinate communication sessions with the Mars Balloon Relay.
    - The clock must coordinate maneuver activities before a communication window.
    - The clock must coordinate sensor calibrations.
- The processor must be able to control six motors independently.
    - In general, the power to each wheel will be equal, but in some circumstances it will be different.
    - The processor currently controls the motors with pulse width modulation. By varying the length of the pulses, the processor varies the mechanical power generated.
- The processor must be able to control two servo motors independently for steering.
    - The processor sends commands to the servo motors defining the angle to which each should move relative to the rover's center line.
    - In general, the front and rear wheels steer in opposite directions to coordinate a turn.
- The processor must be able to communicate with five proximity sensors.
    - The proximity sensors are currently multiplexed through one port. The processor rotates among them.
    - The sensors are activated by pulsing power to them.
    - The proximity sensors are currently Polaroid ultrasonic sensors.
- The processor must be able to communicate with two touch sensors.
    - The touch sensors are multiplexed through one port. The processor switches between them.
    - The sensors are activated by pulsing power to them.
- The processor must be able to communicate with two tachometers.

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[3] Work on the phase one prototype indicates that the Motorola 6811 microprocessor is too slow for later versions. The next version requires a faster clock speed and more memory.

  - At least two different wheels will have tachometers so that wheel slip can be averaged out.
- The processor must be able to communicate with the yaw sensor.
  - The yaw sensor will be calibrated at least once per day.
  - The yaw sensor is currently an electronic magnetic compass.
- The processor must be able to communicate with the pitch sensor.
- The processor must keep track of the rover's position and destination vectors.
  - The navigation algorithm integrates the tachometer, yaw, and pitch data to maintain knowledge of where the rover has gone since the last communication with Earth.
- The processor must receive and store telemetry data from each of the other subsystems for later transmission.
- The processor must be able to receive and store at least one image from the video camera for later transmission.
  - The processor must be able to isolate a single video image from a continuous stream of real-time video.
- The processor must multiplex all telemetry and image data into a single data stream that will be sent to the transmitter.
- The processor must receive Earth commands from the receiver.
- The processor must interpret and implement the Earth commands.

Processor Interfaces

The processing system has data interfaces with all of the other systems except the structure. The data interfaces shown in Figure 5.2b are independent of the data type. The 6811 processor is currently capable of accepting digital, analog, and RS-232 formats. It is important to keep track of the data formats so that all subsystem designers will understand how the hardware interfaces with the processor.

- The processor is powered by the secondary power bus.
- The processor issues on/off commands to the communications system, the vision system, the maneuvering system, the guidance and navigation system, and the thermal system.
- The processor has data interfaces with each of the sensors.

- The processor controls the six maneuvering motors and the two steering servo motors.

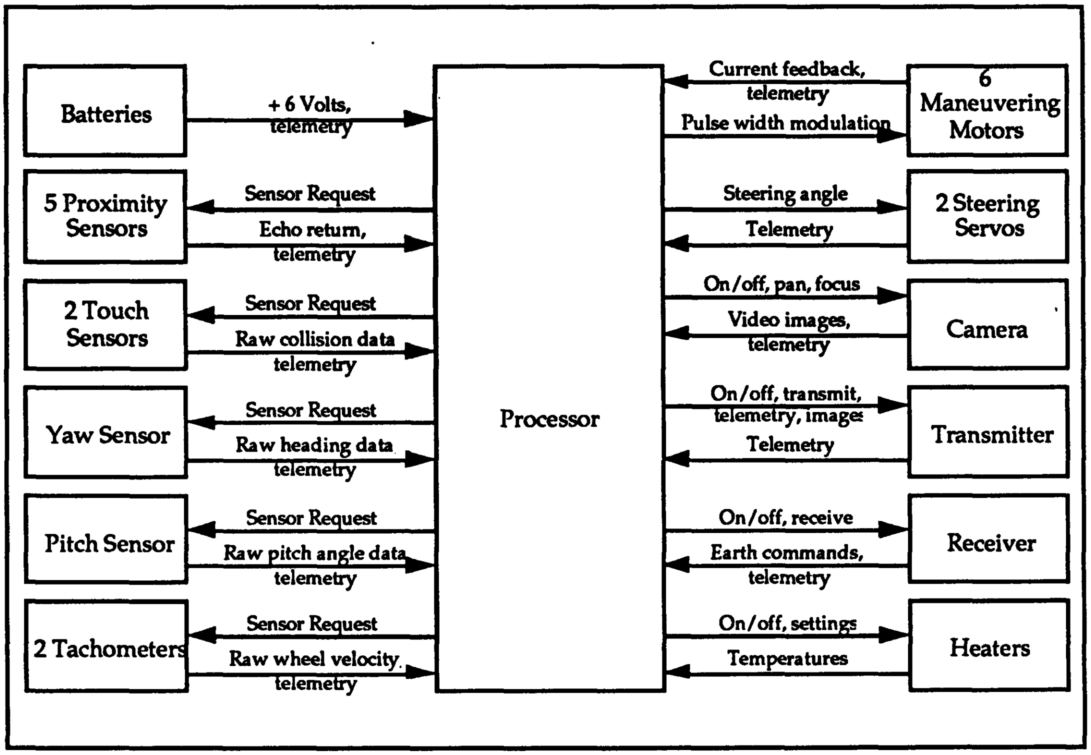

Figure 5.2b - Processing interface diagram

- The processor receives image data from the camera.
- The processor receives command data from the receiver.
- The processor receives telemetry data from each of the subsystems.

Processor telemetry required

The following telemetry points must be supplied for transmission to Earth:

- The health status of the microprocessor.
- The health status of other processing chips.
- The health status of the memory.

5.3. COMMUNICATION

Communication Description/Requirements

The communications system consists of a transmitter, a receiver, and an antenna as shown in Figure 5.3a.

- The transmitter sends signals twice a day, at 2 pm and 2 am, to the Mars Balloon Relay on the Mars Observer spacecraft. Each orbiter pass lasts ten minutes. The Mars Balloon Relay sends the signals on to Earth. The rover can transmit during both of the communication windows.
- The transmissions must be on UHF frequency 401.5275 megahertz.
- The data rate must be less than 2000 bits/second.
- The power transmitted must be at least 3 watts.

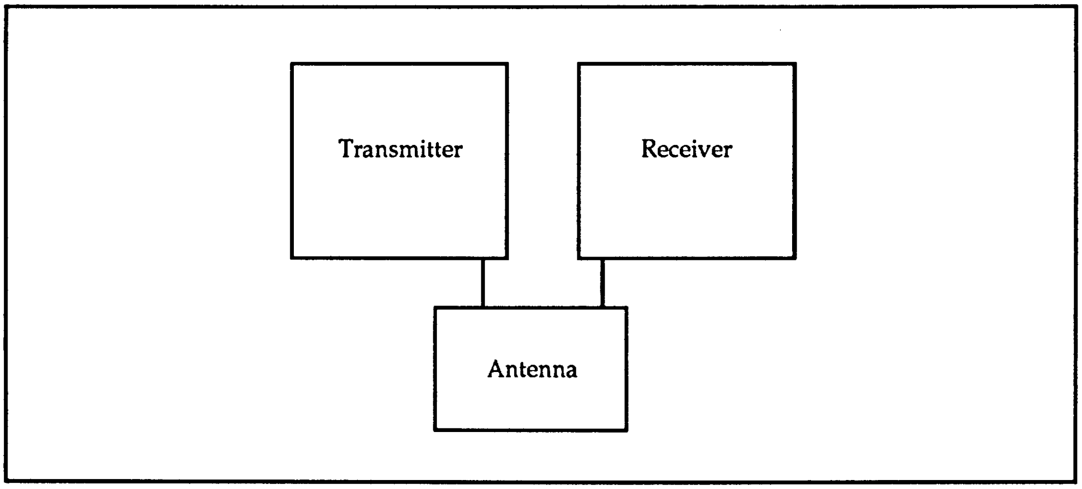

Figure 5.3a - Communication block diagram

The data receiver can receive signals from Earth via the Mars Balloon Relay twice a day during the same windows mentioned above. The operating assumption is that most commands will be received during the 2 am window. By then, the Earth operators will have had adequate time to examine the image transmitted during the 2 pm window and plot a new course for the rover to follow.

- The incoming data will be on UHF frequency 437.100 megahertz.
- The data rate will be 128 kilobits/second.
- The signal strength will be -114 dBm.

Communication Interface Diagram

The communication system interfaces with the primary power bus, the processing system, the vision system, and the thermal system as shown in Figure 5.3b.

- The primary power bus provides power to the transmitter and receiver during the communication windows with the Mars Balloon Relay.
- The processing system commands the transmitter to transmit and the receiver to receive.
- The processor sends multiplexed image and telemetry data to the transmitter and gets command data from the receiver.

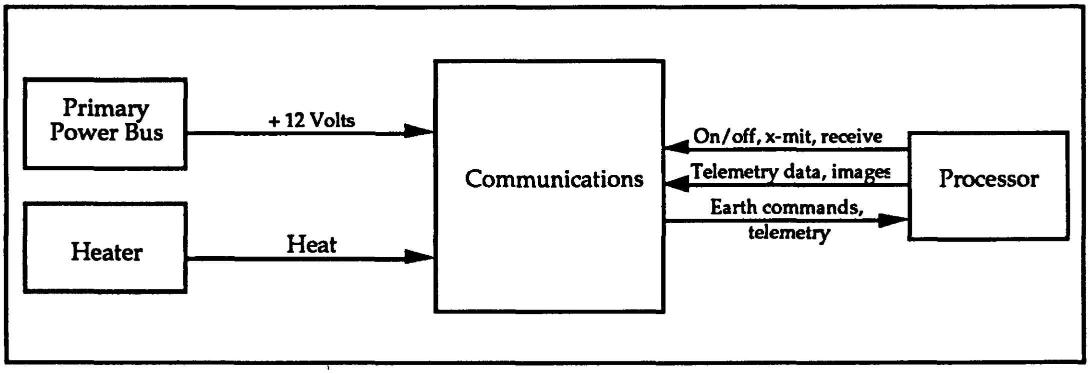

Figure 5.3b - Communication interface diagram

Communications telemetry required

The following telemetry points must be supplied to the processor for transmission to Earth:

- The health status of the transmitter.
- The health status of the receiver.

5.4. GUIDANCE AND NAVIGATION

Guidance and Navigation Description/Requirements

The guidance and navigation system must be able to detect obstacles, and sense changes in heading, attitude, and position. It includes five proximity sensors, two touch sensors, a pitch sensor, a yaw sensor, and two tachometers as shown in Figure 5.4a.[4]

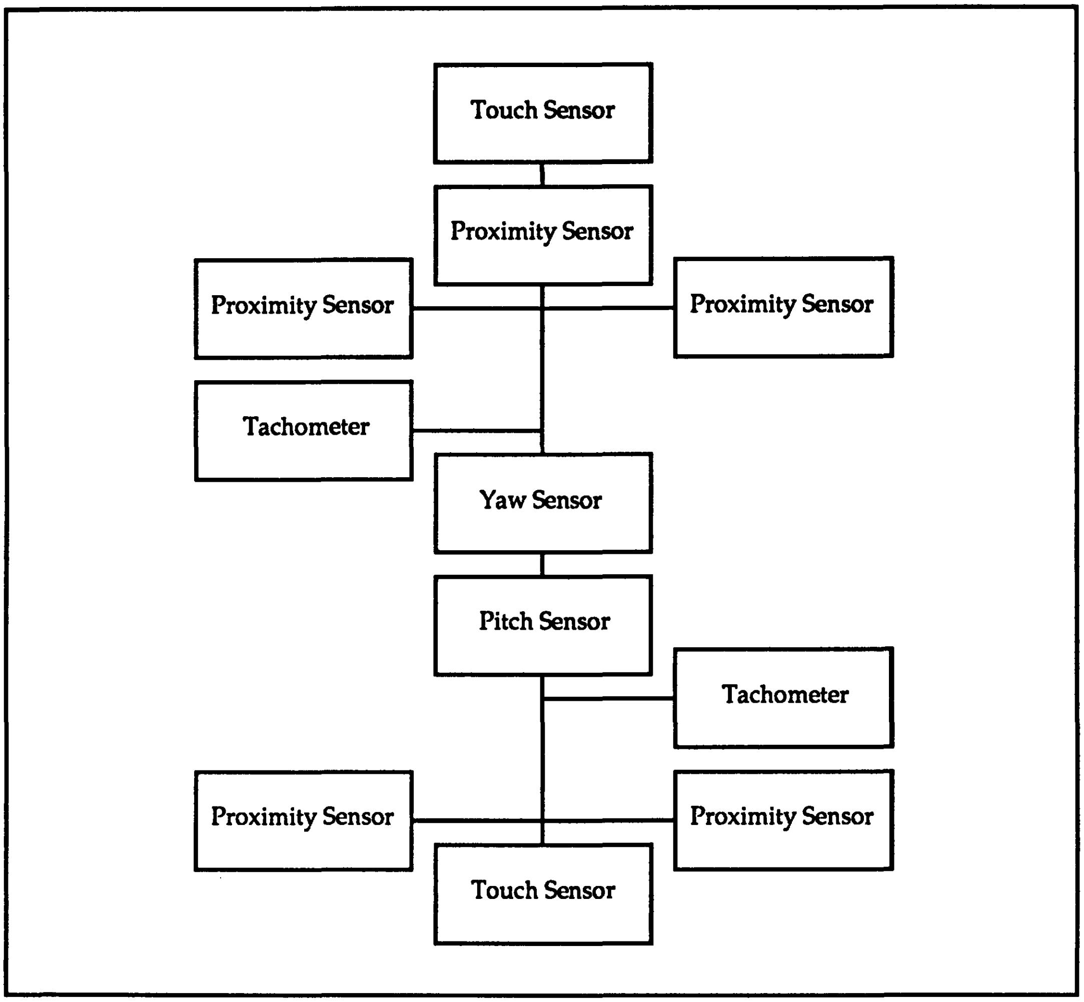

Figure 5.4a - Guidance and navigation block diagram

- The proximity sensors must detect obstacles within ten meters of the front and rear of the rover. They should focus on the 60° arc directly in front of the rover and the 30° arc directly behind the rover.
- The touch sensors must detect hazards within five centimeters of the front and rear of the rover.

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[4] The rationale for the Guidance and Navigation requirements in this section will be presented in detail in Bill Kaliardos' masters thesis for the Department of Aeronautics and Astronautics at MIT, to be published around December, 1992.

- The pitch sensor must detect changes in inclination greater than 5°.
- The yaw sensor must detect changes in heading greater than 3°.
- The tachometers must be accurate to one revolution per minute (rpm) on speeds less than 100 rpm.
- The guidance and navigation system must be accurate within ten percent of the distance traveled. If the rover traverses 100 meters, the position estimate must be within ten meters of the actual position.

Guidance and Navigation Interfaces

The guidance and navigation system interfaces with the secondary power bus and the processing system as shown in Figure 5.4b.

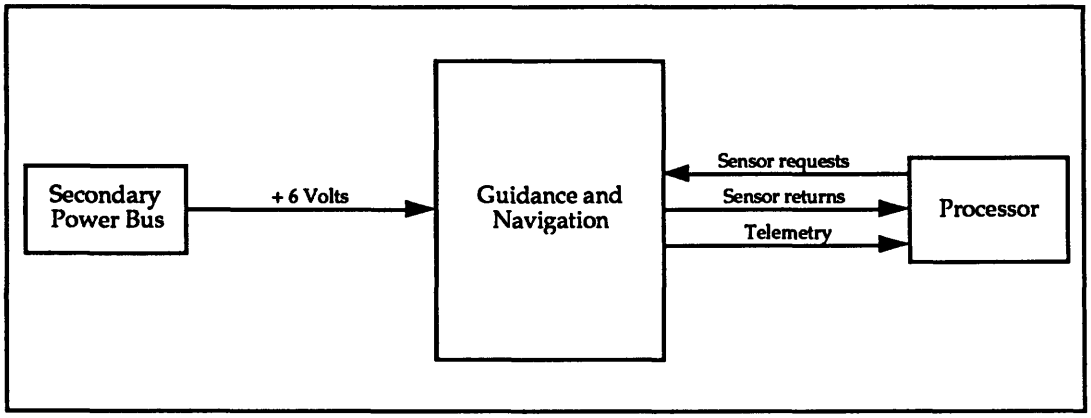

Figure 5.4b - Guidance and navigation interface diagram

- The secondary power bus provides power to the sensors through the processor whenever the processor pulses the sensors for data.
- The processor determines when each sensor should pulse.
- The sensors send their data to the processor which analyzes and acts upon the data.

Guidance telemetry required

The following telemetry points must be supplied to the processor for transmission to Earth:

- The health status of each of the proximity sensors.
- The health status of each of the touch sensors.

- The health status of the yaw sensor.
- The health status of the pitch sensor.
- The health status of each of the tachometers.

5.5. VISION

Vision Description/Requirements

The vision system consists of a charge coupled device (CCD) camera mounted on a panning motor as illustrated in Figure 5.5a. It provides at least two pictures per day for transmission back to Earth, and continuous video if necessary for guidance and navigation.

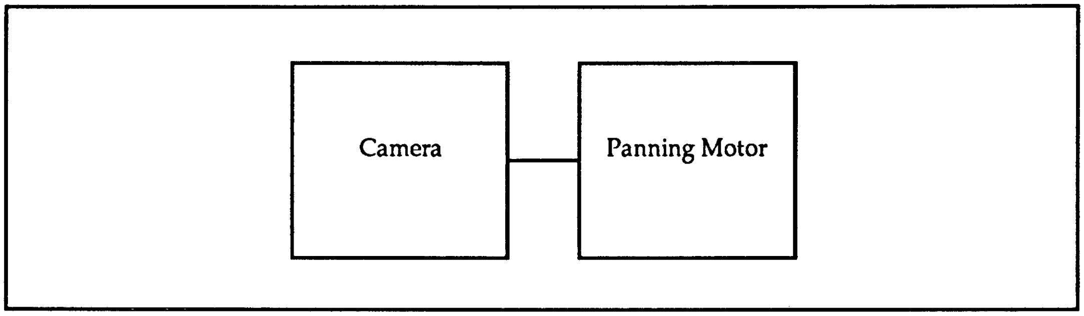

Figure 5.5a - Vision block diagram

- The camera must resolve one meter details up to 100 meters away so that the rover's position can be tracked in the pictures.
- The field of view must be wide enough to account for the rover's ten percent navigation error. Therefore, it must be at least 12° wide.

Vision Interfaces

The vision system interfaces with the primary power bus, the processing system, and the video transmitter as shown in Figure 5.5b.

- The primary power bus provides power to the camera and panning motor when the processor commands the camera to be on.
- The processing system tells the camera when and where to look.
- The camera sends images to the processor where they are multiplexed with telemetry data before transmission to Earth. The processor can

also process the video output if the ability to use such data for navigation becomes available.

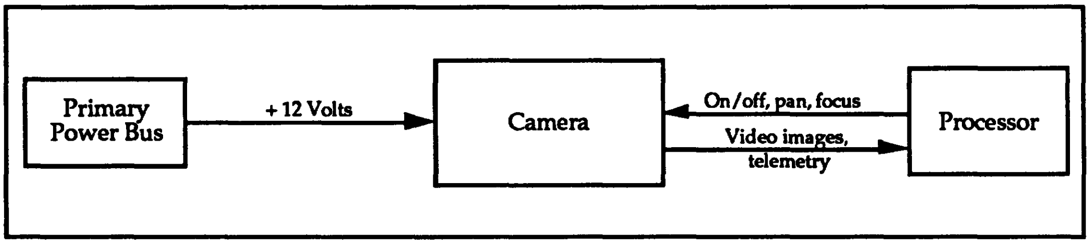

Figure 5.5b - Vision interface diagram

Vision telemetry required

The following telemetry points must be supplied to the processor for transmission to Earth:

- The health status of the camera.
- The health status of the panning motor.

5.6. THERMAL

Thermal Description/Requirements

The thermal system consists of one or more heaters, thermostats, and insulation as shown in Figure 5.6a.

- The Martian surface varies between 25° and -125° Celsius.
- The temperature of the batteries must not fall below -50° Celsius.
- The temperature of the processor must not fall below -50° Celsius.
- The temperature of the sensors must not fall below -50° Celsius.
- The temperatures of the transmitter and receiver must not fall below -50° Celsius.

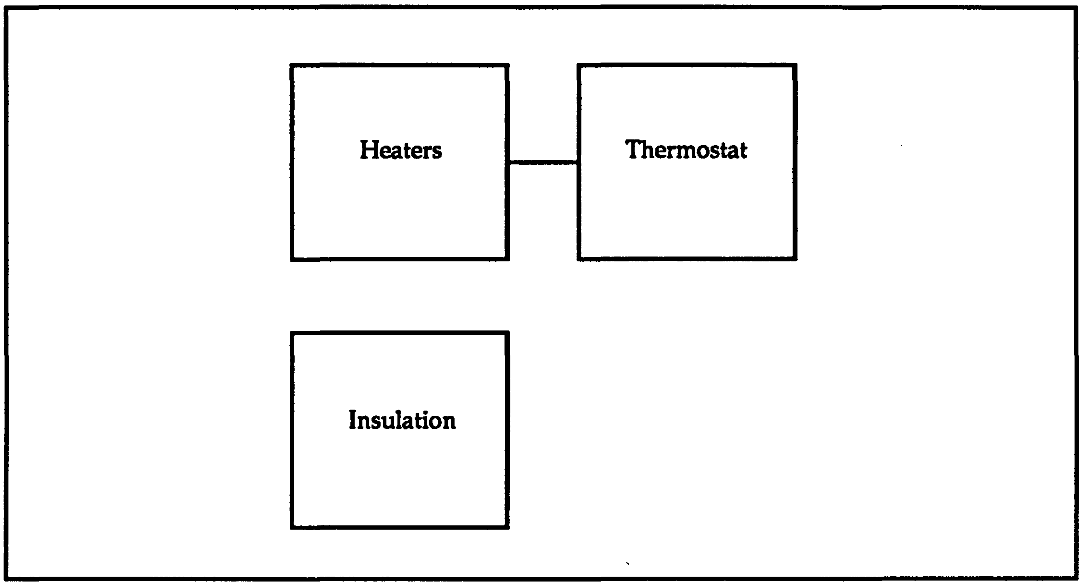

Figure 5.6a - Thermal block diagram

Thermal Interfaces

The thermal system interfaces with the primary power bus, the processing system, the guidance and navigation system, and the communication system as shown in Figure 5.6b.

- The heater regulates the thermal environment of sensitive hardware by switching on or off, depending on what temperature the thermostat measures.
- The heater receives power from the primary bus. It supplies heat when necessary to the microprocessor, the transmitter, the receiver, the camera, and the batteries.
- Most other systems will not be used until the ambient temperature warms the hardware within an acceptable range, making additional heat unnecessary.

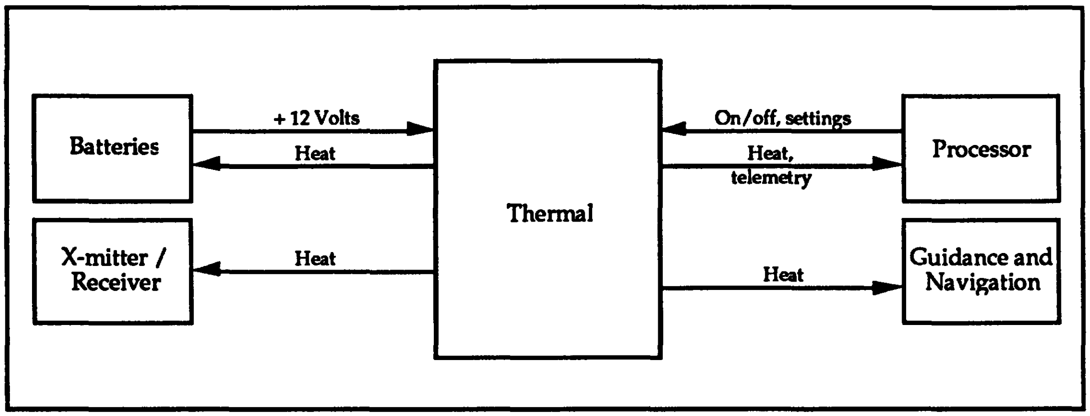

Figure 5.6b - Thermal interface diagram

Thermal telemetry required

The following telemetry points must be supplied to the processor for transmission to Earth:

- The health status of the heaters.
- The health status of the thermostats.
- The temperatures measured by the thermostats.

5.7. STRUCTURE AND MANEUVERING

Structure and Maneuvering Description/Requirements

Top and side views of the rover are shown in figures 5.7a and 5.7b. The structure consists of the flexible frame with three platforms and two sets of steel wire connectors, and all the other hardware that holds the system together. The structure supports the steering mechanisms which attach to the two forward motors and the two rear motors. It directly supports the two middle motors.

- The structure must support the rover in Earth's gravity.
- The structure must support the rover in Mars' gravity = 1/3 g.
- The structure must support the rover during launch and transit loads in the launch and transit configurations. These loads could reach ±5.5 g's as discussed in Section 3.5.

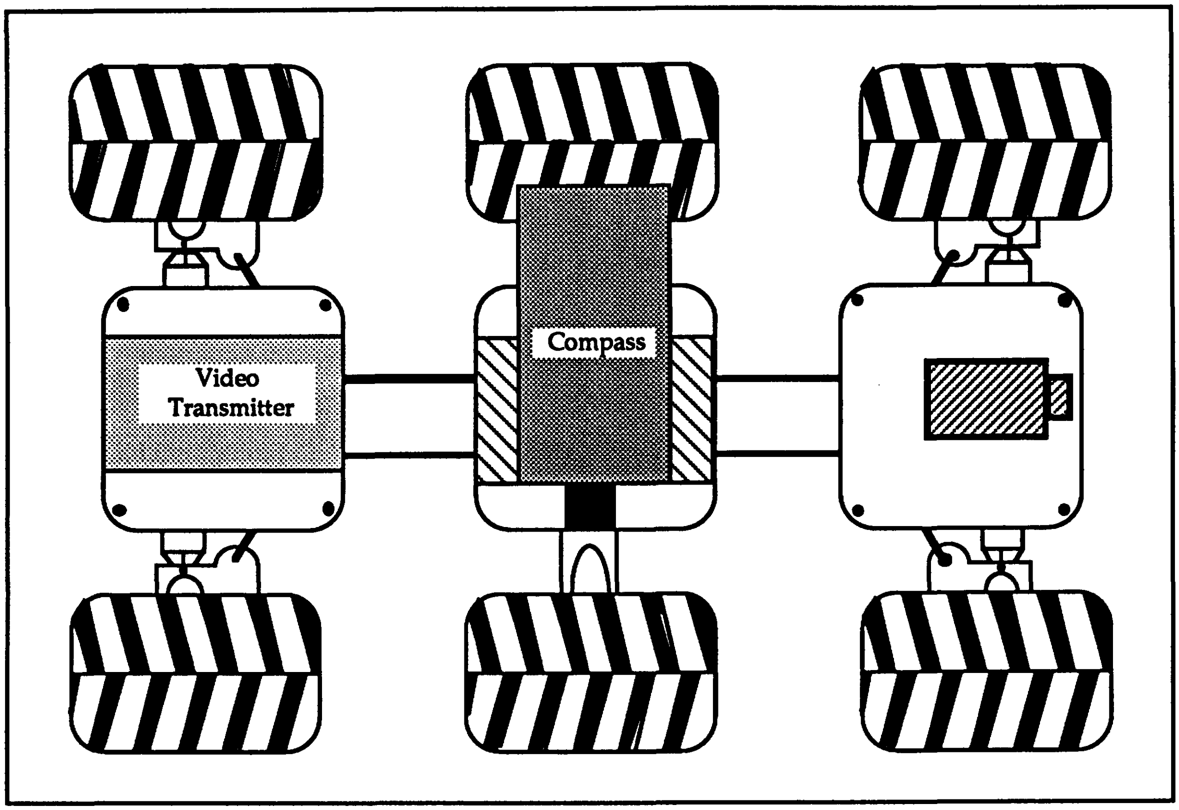

Figure 5.7a - Top view of phase one prototype rover

The maneuvering system consists of 6 wheel hubs, 6 tires, 6 drive motors, 4 steering blocks, and 2 steering servo motors. It implements the control commands issued by the processor.

- The rover must be able to climb obstacles as tall as a wheel diameter, approximately 15 centimeters.
- The rover must travel at an average of 0.2 kilometers/hour.

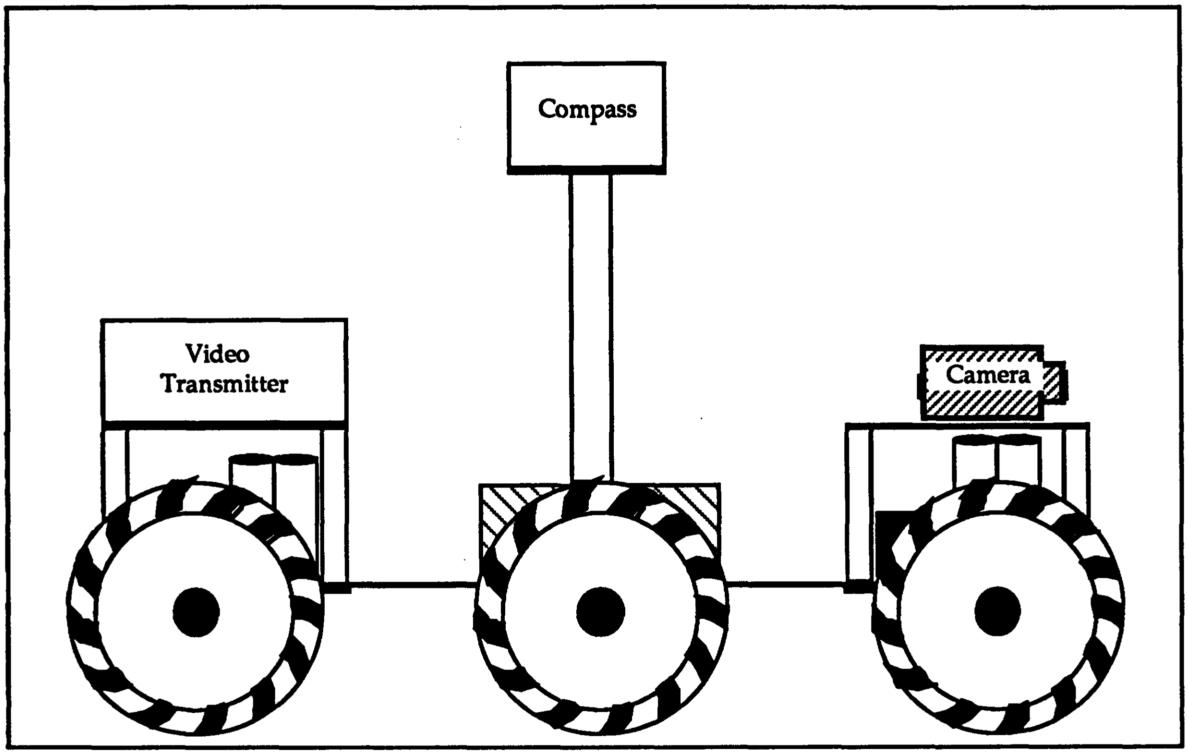

Figure 5.7b - Side view of phase one prototype rover

Structure and Maneuvering Interfaces

The structure physically supports all other subsystems. The maneuvering system interfaces with the primary power bus and the processing system as shown in Figure 5.7c. The primary power bus provides power to the drive motors and the steering servos when the processing system commands a maneuver. The processor commands the maneuvering system where to go.

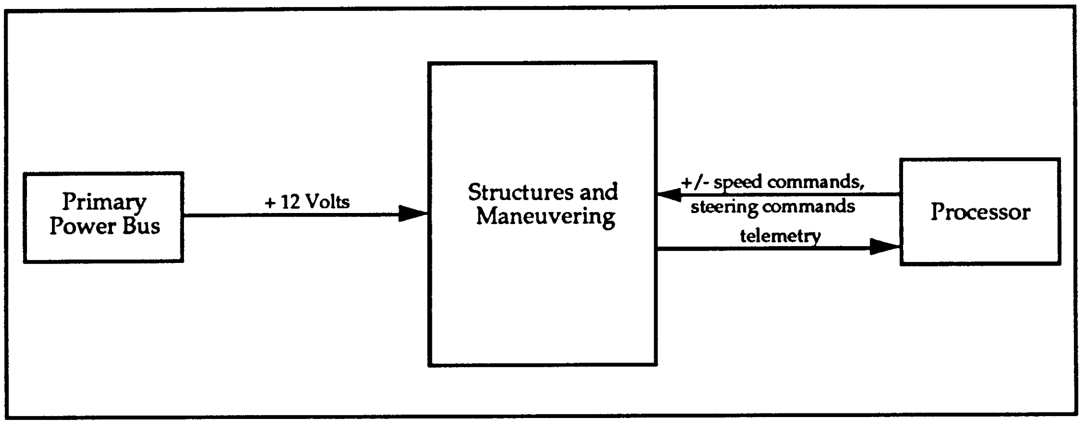

Figure 5.7c - Structure and maneuvering interface diagram

Structure and Maneuvering Telemetry Required

The following telemetry points must be supplied to the processor for transmission to Earth:

- The health status of the drive motors.
- The health status of the servo motors.

5.8. REQUIREMENTS VERIFICATION TEST PLAN

A rigorous test program is fundamental to establishing confidence in the rover's capabilities. The system must show that it satisfies every design requirement, or else the requirement must be waived. In addition, the system must be overstressed to prove that it is capable of satisfying the mission under a variety of unexpected circumstances. This section identifies the tests that must be performed to ensure that the design is acceptable.

System Verification

The following tests must be performed to verify that the rover can satisfy the system requirements.

- Survive five 30 day test periods in the Jet Propulsion Laboratory's California desert test ground, undergoing all operations as realistically as possible.

- Thermally cycle the rover between 25° and -125° Celsius 100 times. Then conduct all maneuvers to ensure that there is no system degradation.
- Operate the rover with modified dynamic characteristics, i.e. weight and spring constants, simulating Mars' gravity and ensuring that the vehicle will perform properly under Mars' conditions.

Subsystem Verification

The following tests must be performed to verify that the design satisfies each of the subsystem requirements.

Power

- The voltage of the primary battery pack must be tested during vehicle operation to show that it maintains a 12 volt bus under the following conditions and during the transients between them:
  - no load
  - straight cruise maneuvers
  - straight climbing maneuvers
  - complex steering maneuvers
  - data transmission
  - data reception
- To show that the primary battery pack has the requisite capacity of 22 amp-hours, it must be operated until failure. It should be drained using a realistic set of operations, particular with duty cycles similar to those expected for real operations.
- To show that the secondary battery pack has the requisite capacity of 47 amp-hours, it must be operated until failure. It should be drained using a realistic set of operations, particular with duty cycles similar to those expected for real operations.
- The voltage of the secondary battery pack must be tested during vehicle operation to show that it maintains a 6 volt bus under the following conditions and during the transients:
  - all systems sleeping
  - processor performing complex tasks

  - guidance and navigation activities, including sensor readings, velocity commands, and steering commands
  - telemetry communications
- It must be shown that the voltage and current transients caused by switching subsystems on and off will not damage any of the other subsystems.
- Extra sets of batteries should be purchased as soon as the specifications are finalized so that they can be shelved and tested at least a year later to prove that the batteries will operate after launch and Mars transfer.

Processing

The processing system must respond to all of the commands issued by the test operator to prove that it controls all of the rover's functions. In particular, it must do the following:

- Receive commands from the operator.
- Operate each of the 6 motors individually and in any combination, at speeds from zero to the maximum.
- Steer the front wheels and rear wheels, both individually and in tandem, to any commanded steering angle.
- Accelerate the motors while adjusting the steering angle in a turn.
- Demonstrate power redirection when one or more wheels start slipping.
- Sense the presence of an object within the field of view of any of the 5 proximity sensors. If processor must determine when an object is in more than one sensor's field of view.
- Halt a straight line maneuver and a complex steering maneuver when an object is placed in the rover's path, within one foot of the rover.
- Halt a reverse maneuver when an object is placed in the rover's path within one foot of the rover.
- Sense the presence of an object with either of the two touch sensors.
- Halt simple and complex maneuvers when an object contacts either of the touch sensors.
- Initiate and complete continuous video transmission to the operator.
- Pan the camera as commanded by the operator.

- Command the frame grabber to capture a single video image for transmission.
- Command any telemetry transmissions requested by the operator.
- Calibrate the clock based on received data.
- Calibrate the yaw sensor based on external heading information.
- Monitor the distance traveled within 5% of the actual distance in a straight line maneuver of at least 100 meters.
- Monitor the rover's heading within 2° of the actual heading over a traverse greater than 100 meters.
- Track the rover's position to within 5% of the actual position during complex steered maneuvers of at least 100 meters.
- Maneuver to a commanded destination with only 5% error.

Communications

- Test the transmitter's response to UHF frequency 401.5275 megahertz.
- Ensure that the transmitter can send an image within 8 minutes.
- Ensure that the power transmitted is at least 3 watts.
- Test transmission capability over 400 kilometers to verify that communication with the Mars Balloon Relay will work.
- Test the receiver's response to UHF frequency 437.100 megahertz.
- Test reception capability over 400 kilometers to ensure that signals can be received from the Mars Balloon Relay.

Guidance/Navigation

- Calibrate the yaw sensor based on external heading information.
- Monitor the distance traveled within 5% of the actual distance in a straight line maneuver of at least 100 meters.
- Monitor the rover's heading within 2° of the actual heading over a traverse greater than 100 meters.
- Track the rover's position to within 5% of the actual position during complex steered maneuvers of at least 100 meters.
- Maneuver to a commanded destination with only 5% error.

Vision

- Test the camera's resolution outdoors in wide field applications to show that it can resolve features 100 meters away.
- Test the camera's field of view to verify that the rover's position will be traceable between daily images.
- Test the frame grabber to ensure that it retains resolution.

Thermal

- Test the thermal environment of the batteries, the processor, and the sensors when subjected to temperatures between 25° and -125° Celsius to ensure that they do not exceed their specifications.
- Test all systems at the lower end of the temperature specifications to ensure operation in extreme conditions.

Maneuvering

The following tasks should be completed 5 times each. They should also be performed with degraded voltage capability to show the performance of the rover with one or more battery cell failures.

- Climb a 5 inch vertical step.
- Climb a 35° incline for 10 meters.
- Maneuver across loose gravel for 50 meters.
- Maneuver across loose sand for 50 meters.
- Maneuver through a rocky field for 50 meters without colliding or flipping over.
- Autonomously extricate from a dead-end alley.

Structure

- Shake and bake the structure to ensure its integrity in Earth's gravity
- Test the structure under simulated launch loads, accelerations, and vibrations based on the launch vehicle chosen.

CHAPTER 6
CONCLUSION

6.1. SUMMARY

Systems engineering was a recurring theme throughout the micro-rover project. From the beginning, top down techniques were used to ensure that the design satisfied the objectives. The decision to build a Mars micro-rover was based on a broad analysis of the needs of the Space Exploration Initiative. Of all the possibilities examined, a micro-rover was considered to have the best probability of being launched on a variety of missions.

Systems engineering was then used to develop the system requirements for cost, mass, schedule, and performance. Three key performance parameters were discussed:

- A 30 day mission
- Daily traverses of 100 meters
- Transmission of 2 images per day

The necessary subsystems, their interfaces, and their requirements were also developed from the high level project goals. The five kilogram mass constraint derived from the Soviet-French balloon mission was the main determinant of the rover's design. Power and size had large impacts on the design, but they had already been constrained by the mass limitation.

Mass and power were each allocated three times. Initially they were allocated based on general information to provide a sense of what the rover would be like. The phase one prototype offered more realistic allocations, although the prototype was not designed to rigorous requirements. Final allocations were based on the system requirements and the lessons learned from designing the prototype.

When the rover had been specified in general, systems techniques were used to tradeoff the costs and benefits of the power, communications, and other subsystems. Well-defined criteria and analytical methods led to the decision to use a primary battery system for electrical power, and to use the Mars Balloon Relay as an orbiting communications link. Finally, the subsystem specifications were written, defining the rover's detailed capabilities.

6.2 FUTURE WORK

A significant amount of work remains to be done. The phase one prototype must be refined, tested, and made more robust to prepare for the Rover Expo in Washington, DC in September, 1992. It should demonstrate as many of the rover's capabilities as possible.

Thereafter, the final prototype will be designed to the specifications described in this thesis. The mass allocation includes a 500 gram margin that will be allocated to the hardware which is most expensive to design within the tight mass constraints. Several areas require significant changes to meet the final mass allocations. The pneumatic tires will have to be replaced with lightweight, springy wire wheels. Their mass must be reduced by approximately 75%. The drive motors and servo motors must be rigorously specified to reduce their mass by 40% and 30% respectively, while maintaining adequate performance. The structure must also be redesigned for minimal mass. The prototype was put together quickly, without concern for mass. The next vehicle can not include any unnecessary structure.

The power allocation does not include an explicit margin. The power allocated to the thermal system will serve as margin if it is not needed, but designers should not plan to use it. A power margin was not considered necessary because the allocations did not seem binding. Most of the requirements were based on existing hardware. The biggest change concerns the drive motors. Their power requirements must be reduced by almost two-thirds to meet the final allocation. Such a reduction is possible because the prototype motors were taken from the laboratory shelf to save money. By researching the market and defining proper specifications, motors can be found with the right combination of mass, power, and performance characteristics.

The processing system is the heart of a semiautonomous rover. Much work remains to be done in this area. The phase one prototype merely brushed the surface of the processing capability required for exploration. The processor's performance parameters remain unspecified because so little is currently known about what will be required. Design of the processing system should begin immediately and adequate resources should be allocated.

The communication system has been loosely specified to link with the Mars Balloon Relay, but the feasibility of doing so has not been proven. This interface should be examined and revisited if necessary.

Finally, the rover's appearance must be addressed. The phase one prototype was only designed for function. The next vehicle deserves a strong dose of aesthetic design. The rover must look the part if it will attract serious attention from the aerospace industry.

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APPENDIX

This appendix includes several spreadsheets used to reach conclusions discussed in Chapter 4. The first two pages focus on the power budgets for the prototype and final rovers. The last three pages show the summary of the analysis of the three communication link options.

A.1 PROTOTYPE POWER BUDGET ANALYSIS

Maneuvering	Climbing	Sandy	Cruise	Total
Voltage (volts)	12	12	12	
Current (amps)	2.5	1.5	0.5	
Power (W)	30	18	6	
% Time	0.5	0.3	0.2	
Speed (kph)	0.1	0.4	0.5	
Distance (m)	37	89	74	200
Time (hrs)	0.4	0.2	0.1	
Energy / day (w-hrs)	11.1	4.0	0.9	16.0

assume rover travels
200 meters/day to achieve
100 meter destination

Processing - awake	
Voltage (volts)	6
Current (amps)	0.14
Power (W)	0.84
Hours / day	6.5
Energy / day (w-hrs)	5.46

Processing - asleep	
Voltage (volts)	6
Current (amps)	1.00E-05
Power (W)	0.00006
Hours / day	18
Energy / day (w-hrs)	0.00108

Data Receiver/X-mitter	
Voltage (volts)	12
Current (amps)	0.1
Power (W)	1.2
Hours / day	0.3
Energy / day (w-hrs)	0.4

Video Transmitter	
Voltage (volts)	12
Current (amps)	0.1
Power (W)	1.2
Hours / day	0.1
Energy / day (w-hrs)	0.12

Camera	
Voltage (volts)	12
Current (amps)	0.22
Power (W)	2.64
Hours / day	0.1
Energy / day (w-hrs)	0.264

Sensors		
Voltage (volts)	6	
Current (amps)	0.2	
Power (W)	1.2	
Hours / day	0.9	maneuvering time plus 25%
Energy / day (w-hrs)	1.1	

A.2 FINAL POWER BUDGET ANALYSIS

Maneuvering	Climbing	Sandy	Cruise	Total
Voltage (volts)	12	12	12	
Current (amps)	0.9	0.5	0.3	
Power (W)	10.8	6	3.6	
% Time	0.5	0.3	0.2	
Speed (kph)	0.1	0.4	0.5	
Distance (m)	37	89	74	200
Time (hrs)	0.4	0.2	0.1	
Energy / day (w-hrs)	4.0	1.3	0.5	5.9

assume rover travels
200 meters/day to achieve
100 meter destination

Processing - awake	
Voltage (volts)	6
Current (amps)	0.2
Power (W)	1.2
Hours / day	5
Energy / day (w-hrs)	6

Processing - asleep	
Voltage (volts)	6
Current (amps)	1.00E-05
Power (W)	0.00006
Hours / day	19.5
Energy / day (w-hrs)	0.00117

Receiver/X-mitter	
Voltage (volts)	12
Current (amps)	0.25
Power (W)	3
Hours / day	0.3
Energy / day (w-hrs)	0.9

Camera	
Voltage (volts)	12
Current (amps)	0.17
Power (W)	2.04
Hours / day	0.1
Energy / day (w-hrs)	0.204

Sensors		
Voltage (volts)	6	
Current (amps)	0.2	
Power (W)	1.2	
Hours / day	0.9	maneuvering time plus 25%
Energy / day (w-hrs)	1.0	

A.3 ROVER TO EARTH COMMUNICATIONS ANALYSIS

Signal to Noise Ratio	10
Boltzman's Constant [J/K]	1.38E-23
System Noise Temperature [K]	290
Receiver noise bandwidth [Hz]	10000

Vary Data Rate

Data Rate [bits per second]	1.00E+02	1.00E+03	1.00E+04	1.00E+05	1.00E+06
Transmission Frequency [Hz]	3.00E+09	3.00E+09	3.00E+09	3.00E+09	3.00E+09
Wavelength [m]	**0.10**	**0.10**	**0.10**	**0.10**	**0.10**
Transmit Antenna Aperture [m^2]	0.03	0.03	0.03	0.03	0.03
Receiver Antenna Aperture [m^2]	2500	2500	2500	2500	2500
Input Power [W]	**5.64E+06**	**5.64E+07**	**5.64E+08**	**5.64E+09**	**5.64E+10**

Vary Frequency

Data Rate [bits per second]	1.00E+03	1.00E+03	1.00E+03	1.00E+03	1.00E+03
Transmission Frequency [Hz]	3.00E+11	3.00E+10	3.00E+09	3.00E+08	3.00E+07
Wavelength [m]	**0.001**	**0.01**	**0.10**	**1.00**	**10.00**
Transmit Antenna Aperture [m^2]	0.03	0.03	0.03	0.03	0.03
Receiver Antenna Aperture [m^2]	2500	2500	2500	2500	2500
Input Power [W]	**5.64E+03**	**5.64E+05**	**5.64E+07**	**5.64E+09**	**5.64E+11**

Vary Transmit Antenna

Data Rate [bits per second]	1.00E+03	1.00E+03	1.00E+03	1.00E+03	1.00E+03
Transmission Frequency [Hz]	3.00E+09	3.00E+09	3.00E+09	3.00E+09	3.00E+09
Wavelength [m]	**0.100**	**0.10**	**0.10**	**0.10**	**0.10**
Transmit Antenna Aperture [m^2]	10	1	0.1	0.01	0.001
Receiver Antenna Aperture [m^2]	2500	2500	2500	2500	2500
Input Power [W]	**1.69E+05**	**1.69E+06**	**1.69E+07**	**1.69E+08**	**1.69E+09**

Vary Receiver Antenna

Data Rate [bits per second]	1.00E+03	1.00E+03	1.00E+03	1.00E+03	1.00E+03
Transmission Frequency [Hz]	3.00E+09	3.00E+09	3.00E+09	3.00E+09	3.00E+09
Wavelength [m]	**0.100**	**0.10**	**0.10**	**0.10**	**0.10**
Transmit Antenna Aperture [m^2]	0.1	0.1	0.1	0.1	0.1
Receiver Antenna Aperture [m^2]	10000	1000	100	10	1
Input Power [W]	**4.23E+06**	**4.23E+07**	**4.23E+08**	**4.23E+09**	**4.23E+10**

	Best	**Reasonable**	**Worst**
Data Rate [bits per second]	300	1000	100000
Transmission Frequency [Hz]	3.00E+11	3.00E+09	3.00E+07
Wavelength [m]	**0.001**	**0.10**	**10.00**
Transmit Antenna Aperture [m^2]	1	0.1	0.01
Receiver Antenna Aperture [m^2]	10000	1000	100
Input Power [W]	**13**	**4.23E+07**	**4.23E+15**

A.4 Rover to Orbiter Communications Analysis

Signal to Noise Ratio	10
Boltzman's Constant [J/K]	1.38E-23
System Noise Temperature [K]	200
Receiver noise bandwidth [Hz]	10000

Vary Data Rate

Data Rate [bits per second]	1.00E+02	1.00E+03	1.00E+04	1.00E+05	1.00E+06
Transmission Frequency [Hz]	3.00E+08	3.00E+08	3.00E+08	3.00E+08	3.00E+08
Wavelength [m]	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
Transmit Antenna Aperture [m^2]	0.1	0.1	0.1	0.1	0.1
Receiver Antenna Aperture [m^2]	10	10	10	10	10
Input Power [W]	**2.92E-02**	**2.92E-01**	**2.92E+00**	**2.92E+01**	**2.92E+02**

Vary Frequency

Data Rate [bits per second]	1.00E+03	1.00E+03	1.00E+03	1.00E+03	1.00E+03
Transmission Frequency [Hz]	3.00E+09	3.00E+08	3.00E+07	3.00E+06	3.00E+05
Wavelength [m]	**0.10**	**1.00**	**10.00**	**100.00**	**1000.00**
Transmit Antenna Aperture [m^2]	0.1	0.1	0.1	0.1	0.1
Receiver Antenna Aperture [m^2]	10	10	10	10	10
Input Power [W]	**2.92E-03**	**2.92E-01**	**2.92E+01**	**2.92E+03**	**2.92E+05**

Vary Transmit Antenna

Data Rate [bits per second]	1.00E+03	1.00E+03	1.00E+03	1.00E+03	1.00E+03
Transmission Frequency [Hz]	3.00E+08	3.00E+08	3.00E+08	3.00E+08	3.00E+08
Wavelength [m]	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
Transmit Antenna Aperture [m^2]	1	0.1	0.01	0.001	0.0001
Receiver Antenna Aperture [m^2]	10	10	10	10	10
Input Power [W]	**2.92E-02**	**2.92E-01**	**2.92E+00**	**2.92E+01**	**2.92E+02**

Vary Receiver Antenna

Data Rate [bits per second]	1.00E+03	1.00E+03	1.00E+03	1.00E+03	1.00E+03
Transmission Frequency [Hz]	3.00E+08	3.00E+08	3.00E+08	3.00E+08	3.00E+08
Wavelength [m]	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
Transmit Antenna Aperture [m^2]	0.1	0.1	0.1	0.1	0.1
Receiver Antenna Aperture [m^2]	100	10	1	0.1	0.01
Input Power [W]	**2.92E-02**	**2.92E-01**	**2.92E+00**	**2.92E+01**	**2.92E+02**

	Best	**Reasonable**	**Worst**
Data Rate [bits per second]	2048	5000	128000
Transmission Frequency [Hz]	3.00E+08	3.00E+08	3.00E+08
Wavelength [m]	**1.00**	**1.00**	**1.00**
Transmit Antenna Aperture [m^2]	0.08	0.1	0.05
Receiver Antenna Aperture [m^2]	10	5	1
Input Power [W]	1	2.92E+00	7.47E+02

A.5 ROVER TO LANDER COMMUNICATIONS ANALYSIS

Signal to Noise Ratio	10
Boltzman's Constant [J/K]	1.38E-23
System Noise Temperature [K]	298
Receiver noise bandwidth [Hz]	10000

Vary Data Rate

Data Rate [bits per second]	1.00E+02	1.00E+03	1.00E+04	1.00E+05	1.00E+06
Transmission Frequency [Hz]	3.00E+07	3.00E+07	3.00E+07	3.00E+07	3.00E+07
Wavelength [m]	**10.00**	**10.00**	**10.00**	**10.00**	**10.00**
Transmit Antenna Aperture [m^2]	0.1	0.1	0.1	0.1	0.1
Receiver Antenna Aperture [m^2]	1	1	1	1	1
Input Power [W]	**2.45E-03**	**2.45E-02**	**2.45E-01**	**2.45E+00**	**2.45E+01**

Vary Frequency

Data Rate [bits per second]	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+05
Transmission Frequency [Hz]	3.00E+09	3.00E+08	3.00E+07	3.00E+06	3.00E+05
Wavelength [m]	**0.10**	**1.00**	**10.00**	**100.00**	**1000.00**
Transmit Antenna Aperture [m^2]	0.1	0.1	0.1	0.1	0.1
Receiver Antenna Aperture [m^2]	1	1	1	1	1
Input Power [W]	**2.45E-04**	**2.45E-02**	**2.45E+00**	**2.45E+02**	**2.45E+04**

Vary Transmit Antenna

Data Rate [bits per second]	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+05
Transmission Frequency [Hz]	3.00E+07	3.00E+07	3.00E+07	3.00E+07	3.00E+07
Wavelength [m]	**10.00**	**10.00**	**10.00**	**10.00**	**10.00**
Transmit Antenna Aperture [m^2]	1	0.1	0.01	0.001	0.0001
Receiver Antenna Aperture [m^2]	2500	2500	2500	2500	2500
Input Power [W]	**9.79E-05**	**9.79E-04**	**9.79E-03**	**9.79E-02**	**9.79E-01**

Vary Receiver Antenna

Data Rate [bits per second]	1.00E+03	1.00E+03	1.00E+03	1.00E+03	1.00E+03
Transmission Frequency [Hz]	3.00E+07	3.00E+07	3.00E+07	3.00E+07	3.00E+07
Wavelength [m]	**10.00**	**10.00**	**10.00**	**10.00**	**10.00**
Transmit Antenna Aperture [m^2]	0.1	0.1	0.1	0.1	0.1
Receiver Antenna Aperture [m^2]	10	1	0.1	0.01	0.001
Input Power [W]	**2.45E-03**	**2.45E-02**	**2.45E-01**	**2.45E+00**	**2.45E+01**

	Best	**Reasonable**	**Worst**
Data Rate [bits per second]	1024	10000	128000
Transmission Frequency [Hz]	3.00E+07	3.00E+07	3.00E+06
Wavelength [m]	**10.00**	**10.00**	**100.00**
Transmit Antenna Aperture [m^2]	0.08	0.05	0.01
Receiver Antenna Aperture [m^2]	1	1	0.1
Input Power [W]	**0.0**	**4.89E-01**	**3.13E+04**