Design of a Day/Night Lunar Rover

CMU-RI-TR-95-24

Peter Berkelman Mei Chen
Jesse Easudes John Hancock
Martin C. Martin Andrew B. Mor
Eric Rollins Alex Sharf
Jack Silberman Tom Warren
Deepak Bapna

The Robotics Institute
Carnegie Mellon University
Pittsburgh, Pennsylvania 15213

June 1995

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Carnegie Mellon University
Field Robotics Center
Pittsburgh, PA 15213

Peter Berkelman **Mei Chen**
Jesse Easudes **John Hancock**
Martin C. Martin **Andrew B. Mor**
Eric Rollins **Alex Sharf**
Jack Silberman **Tom Warren**
Deepak Bapna

Dr. William L. Whittaker, Instructor

Abstract

The pair of lunar rovers discussed in this report will return video and state data to various ventures, including theme park and marketing concerns, science agencies, and educational institutions.

The greatest challenge accepted by the design team was to enable operations throughout the extremely cold and dark lunar night, an unprecedented goal in planetary exploration. This is achieved through the use of the emerging technology of Alkali Metal Thermal to Electric Converters (AMTEC), provided with heat from a innovative beta-decay heat source, Krypton-85 gas. Although previous space missions have returned still images, our design will convey panoramic video from a ring of cameras around the rover. A six-wheel rocker bogie mechanism is implemented to propel the rover.

The rovers will also provide the ability to safeguard their operation to allow untrained members of the general public to drive the vehicle. Additionally, scientific exploration and educational outreach will be supported with a user operable, steerable and zoomable camera.

Introduction

The lunar rover system design consists of two rovers that will return video and state data in a variety of forms to commercial ventures, including theme park and marketing concerns, science agencies, and educational institutions.

Mission Needs

Providing imagery of the moon to a commercial theme park is the main goal of this mission. This imagery will drive Virtual Reality or Telepresence rides at the theme park, providing an immersive environment so that theme park patrons will feel that they are actually experiencing activity on the moon. Secondary goals include support of scientific exploration and analysis, educational outreach, and increasing national interest in and support of space exploration.

A planetary exploration rover based on the moon would set many precedents in the commercial and science space sectors. Currently, all commercial ventures into space have involved orbital spacecraft and provided communications or imagery of the Earth for various needs. Before the advent of personal mobile communications, these satellites have provided services to large commercial ventures. A rover sent to the moon would be the first non-orbital commercial space venture, and also the first space vehicle that is operable by any member of the general public.

A rover designed to complete this mission would break new ground on the robotics front. No robot has ever been designed to operate in an unstructured environment without maintenance or repair for an extended time. With the two year mission specified, this rover will extend the envelope of what is possible by robots today. Also, no robot before has been teleoperable by a wide range of people. With its safeguarding, appraising the environment for unsafe conditions, the rover will be able to check for malicious commands and stop itself if necessary. This ability will allow the rover to be operated by a large number of people, and will help pave the way for support of future missions to the moon.

There is great opportunity for scientific exploration and educational outreach with this mission. Scientists will be able to direct the rover toward interesting features on the moon, including craters and volcanic flow. The rover will allow for much more extensive scientific coverage of the moon than possible before and will allow mapping at a level of detail that has not been seen before for the lunar surface. Educational outreach for this program can be simple and extensive. The opportunity to drive a rover on the moon and examine some of the surface terrain would excite a classroom for weeks and provide the students with lasting memories and the desire to learn more about history and space.

Mission Objectives

The mission objectives for the rover system were derived from the mission needs mentioned above. The primary objectives are:

1. The rovers shall provide imagery of the moon;
2. The rovers shall provide state data (position, acceleration, power consumption, etc.);
3. The rovers shall provide views of each other while operating.

These objectives establish the primary capabilities that the system must provide. All three objectives evolved from the primary mission need to provide imagery suitable for a theme park. The rover state data will be used to control moving platforms which will be synchronized with the video data. The last objective will allow people to view the rover while operating on the moon from an external viewpoint. This method of viewing will complement the primary imagery and will also satisfy marketing concerns' needs for off-board rover views.

Secondary mission objectives were established after the primary mission objectives were determined. The capabilities to satisfy the secondary objectives are provided where they do not impinge on the primary objectives. These secondary mission objectives are:

1. The rovers must allow teleoperation of rovers by "amateurs" on Earth;
2. They must support scientific exploration;
3. They must support educational outreach.

The first objective supports non-expert use of the rover. "Amateur" operators would characterize rover use by both theme park patrons and the scientific and educational communities. These people will not be thoroughly trained in the operation of the rover, and safeguarding to protect the rover will be in operation at all times.

To support scientific exploration and educational outreach, a portion of the rover operating time will be dedicated to these pursuits. Although no mechanism on the rover is provided to physically interact with the lunar surface, a great deal of exploration and education can be achieved through visual means.

Traversal Route

The mission traverse is designed to visit sites that are remembered and cherished by adults world-wide. It is also designed to instill excitement and suspense, both regarding the uncertainty of when a site will first be visited, and whether or not the rover will discover its final destination, the Soviet Lunokhod 2 vehicle. The route is shown in Figure 1. The scale of Figure 1 is shown by the white box in Figure 2.

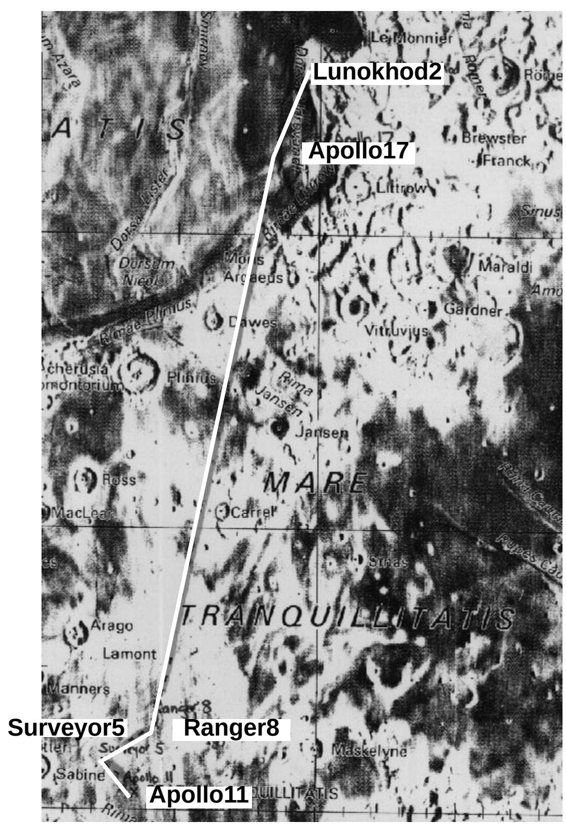

FIGURE 1. *Traversal Route*

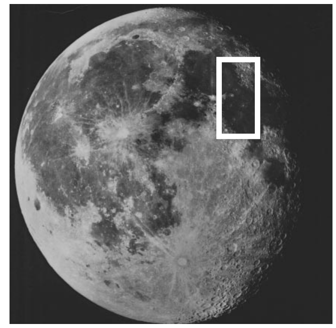

FIGURE 2. *Near Side of the Moon*

The traverse will begin with a landing near the Apollo 11 landing site. After spending a few months there, the rover will travel roughly 100km to the Surveyor 5 landing site, and then an additional 100km to the Ranger 8 landing site. Following these two visits, the rovers will begin their long trek across the Sea of Tranquility. This trek will last from 3 to 4 months until the rovers arrive at the Apollo 17 site. Here the rovers will be able to explore the area where humans last stood on the moon. After exploring the Apollo 17 site, the rovers will once again head northward and search for the stranded Lunokhod 2. This journey will last approximately 2 years, after which the rover should still be functional and able to perform further exploration and theme park based activities

Operating Modes

As previously stated, the rover will have to support theme park and science/educational operations. The basic difference between the two is the type of data sent back and the manner in which the rover is driven.

Theme Park Operations

Operations in support of a theme park is the main objective for the rover system, and there are two main modes for theme park operations, “trained” and “amateur” operator modes. During both of these modes, theme park patrons will experience the rover’s movements through virtual reality.

During trained operator mode, the rover will accept all of its commands from a trained operator in the command center. While the rover will autonomously perform local safeguarding, the operator will be able to override the safeguarding if deemed necessary.

While operating in amateur operator mode, in addition to the local safeguarding performed on-board the rover, the rover's commands from the operator will be sent through ground based safeguarding to eliminate malicious commands. The speed of the rover will also be curtailed, to further decrease the risk of the rover being damaged.

Science and Education Operations

While operating in science and education modes, similar amateur operator modes will be utilized. The main difference between these type of operations and theme park operations is the viewing mode. While scientists will be able to use the panoramic viewing mode associated with the theme park ride, a separate pan/tilt/zoom camera is implemented for in-depth visual exploration. This will allow scientists fine control of the imagery subsystem to examine specimens of interest on the lunar surface in detail.

Because educational institutions will not be able to set up panoramic viewing stations or support the bandwidth required for the large amount of imagery, the pan/tilt/zoom camera will be the primary method for investigating the environment near the vehicle. The movable camera will also provide more excitement for younger students. Safeguarding a camera and preventing it from being damaged is much simpler than safeguarding a rover from its environment. Additionally, camera movement provides almost immediate feedback to the operator when compared to the time lag associated with the movement of the rover to achieve the same change in viewing angle.

System Requirements

The primary and secondary mission objectives determine not only the type of operations that the rover will perform, but also the system level requirements that define exactly what the rover must be able to do. These system level requirements were then utilized to establish the subsystem requirements for the rover system. The system level requirements, and their associated specifics, are:

1. The vehicle must provide video of the moon and rover state data to Earth of sufficient quality for theme park and scientific uses.
    - Provide high resolution panoramic imagery of the lunar terrain.
    - Provide a user controllable camera for detailed examination of surface features.
    - Provide vehicle state data (velocity, acceleration, angle, etc.).
2. The vehicle must provide views of the rover while operating on the moon.
    - The rover must be capable of providing either views of itself in the terrain or views of another rover operating.
3. The vehicle must safely allow teleoperation by amateurs on Earth.
    - The rover must safeguard itself at all times against local hazards.
    - The rover must be teleoperable at a high level, i.e. generate controls based upon uplinked steering and velocity commands.
    - The rover must allow low-level, non-safeguarded control when necessary.
4. The vehicle must safely interact with the lunar environment.
    - Survive radiation, thermal, dust, and terrain environments on the lunar surface.
    - Survive radiation environment during transfer to the moon.
    - Be capable of communicating with ground stations on Earth.
5. The vehicle must follow all societal expectations with relation to launch and operations.
    - Not carry any gamma emitting sources on-board, e.g. plutonium.
    - Not disturb historical and revered sites on the moon.
6. The vehicle must operate reliably for a period of at least 2 years, to maximize the Return on Investment (ROI) for the theme park.

Rover System Concept

After considering various design configurations, a design concept was chosen. The primary system level trade-off involved satisfying the mission requirements with one rover or two. The other significant trades dealt with the power and imagery subsystems. The two main options for the power system were to utilize conventional solar cells and batteries or to use a beta-decay Krypton-85 gas source to provide heat to generate electricity through thermoelectric generation. Imagery trades to generate panoramic imagery were performed between using a ring of cameras around and on top of the rover or using a new panospheric optic which would provide a single 360° by 150° image.

The concept chosen utilizes the Kr85 power source and a ring of cameras with nighttime illumination. This will allow the rover to operate during the full lunar cycle. Two rovers will be flown to provide both off-board images of the rovers operating on the surface and increased probability of mission success through large-scale redundancy.

The locomotion subsystem consists of a six-wheeled rocker bogie, with all four corner wheels independently steered to increase terrainability. This design possesses very good terrainability combined with body averaging characteristics that reduce the amount and frequency of vibrations transmitted to the body of the rover.

Safeguarding is achieved through the use of stereo cameras during the day and a light striper at night for distances greater than 1.5 meters, an array of modulated infrared transmitter/receiver pairs for distances less than 1.5 meters, and feelers or contact sensors as the final line of defense. The communications subsystem utilizes an electronically steered phased array which scans across an angle of +/- 30°. The array will be articulated to provide a further +/- 30° of pointing, to allow a total of +/- 60°. Computing power will be provided through multiple Harris RHC-3000 processor boards.

The Kr85 power source will provide in excess of 3000 Watts thermal power. Alkali Metal Thermal to Electric Converter (AMTEC) cells will convert the heat to electricity, and will deliver 520 Watts at the beginning of the mission. The rover's thermal subsystem is designed to always reject heat to maintain interior temperatures within safe operating limits. The thermal system is mostly passive, with heat generating devices placed against radiators to control their temperatures. Small spot heaters and coolers are placed where necessary on critical components.

During theme park operations, the rovers will operate at a 50% duty cycle. This is due to communications bandwidth limitations that will allow only one high-gain antenna to be used at a time. During science and educational activities, both rovers may be used due to the smaller amount of imagery transmitted. One rover will act as the communications relay, and send both its and the other rover's communications to Earth. Inter-rover and backup communications links are implemented with omni-directional antennas.

Launch and Landing Vehicles

The Russian Proton Launch Vehicle and Phobos class lander were chosen for this mission. The main driver for this decision was cost. The launch vehicle provides a payload fairing with a usable diameter of 3.80 meters. The Phobos lander, based on the design for the Mars 96 mission, can deliver a substantial mass payload to the lunar surface. A payload interface and deployment mechanism was specified for the lander. The deployment mechanism will allow both rovers to drive off of one side of the lander.

Limitations

Due to the compromises made and the preliminary nature of this design, there are many limitations in the rover that have not yet been overcome. Lack of specification problems range from small deficiencies like the lack of contact-sensor specification to large limitations such as mass budget overruns. The rover is also limited in its operation in several areas, ranging from sensor resolution to communications bandwidth difficulties.

Rover Design

While the design team was able to specify some components of the rover system, some were left unresolved due to lack of time. Other items were not fully detailed because they are still in their design infancy and have not yet been applied to space missions. This lack of specification is reflected in the summary budgets, where appropriate growth margins were added. These margins are based both on the maturity of the design and the criticality of the component involved.

The rover system as designed exceeds its mass margin by a great deal. While this is a cause of concern, the subsystems that drive the mass of the vehicle still require finer analysis. More in-depth analysis will identify areas where the rover is overdesigned, and consequently the locomotion and structure masses will decrease. The other main mass driver, the power subsystem, is driven by the need for high temperature materials for the Kr85 pressure vessel. Further investigation into composite tanks, which would drastically lower the power subsystem mass, is required. Further advances in AMTEC cells will also increase their efficiency, which will also lower power system mass.

Rover operations will also be limited by the inherent operations scenario. As mentioned earlier, during theme park operations, the rovers will be operating on a 50% duty cycle. Communication band licensing issues preclude large amounts of bandwidth being licensed to any one concern. The imagery subsystem is limited by the amount of light available on the moon. During the middle of the lunar day, large amounts of light will reach the surface, while during the lunar night, only a very small amount of light from Earthshine will be available. This dichotomy between the two modes requires both a very wide operating range for the cameras and illumination for some of the cameras. Another limitation is the possibility of the rover becoming high-centered on an obstacle. Because the rover has a large amount of open space beneath the body, the front of the body may pass over an object when the back can not. This could be caused by sinkage of the wheels or a variety of other reasons. In this case, multiple rovers greatly reduces the risk of become stranded on an object, as one rover can help the other when needed.

Launch Vehicle

The main issue limiting the use of the Proton launch vehicle is the export controls of the United States. Due to the technical nature of the rovers, US Customs will have authority over the transportation of the rover to another country. This issue would be averted through the use of an American launcher, although that would raise the cost.

Cost

Cost was not addressed during the design of the rover system. Although some items specified during the design are off-the-shelf and catalogued, many items in the rover design are cutting edge and haven’t been designed for aerospace use before. Additionally, costs related to completely new technologies are unknown. Estimating cost for labor, management, and integration issues is a science and an art on its own, and would not have been completely beneficial to the group assembled. Therefore, while cost for componentry and launch vehicles was kept in mind, a detailed cost budget was not developed.

Chapter
1

Mission

Although twenty years have passed since the last landing, the Moon remains an unfamiliar world to most people. Only a select few have set foot on the lunar surface, and any yearning harbored by others to return and retrace footsteps made by the heroes of the Apollo Program can only been satisfied through imagination. The proposed two-year mission, starting with launch in late 1998, will attempt a 1000km traverse of historic landing sites in the Sea of Tranquility, including the first and last manned landing sites. “Telepresence”, feelings of presence and participation, will provide both an entertaining and educational experience. The cost and risk of completing this mission can find precedents in launchers and landers, rovers on the Moon and Earth, microsatellites in low-earth orbits, lunar missions, and accomplishments in the commercial sector.

1.1 Mission Objectives

The rover system delivered to the moon is designed to meet both primary and secondary objectives, selected according to commercial requirements and science objectives.

1.1.1 Primary Mission Objectives

The primary mission objectives for the system drive the vehicle design. The primary objectives of the rover system are to provide:

- imagery of the moon;
- rover state data;
- views of the rover while operating.

The first two objectives, providing data gathered on-board the rover and downlinked to Earth, must be sufficient to enable “telepresence” rides at a theme park. The objective to provide imagery of the moon is the main system driver, requiring both a panoramic imagery subsystem and a means to downlink all the imagery data to Earth.

The third objective requires the rover to either view itself from above, showing itself operating in the lunar terrain, or the ability to acquire off-board images of itself. Views of the rover taken by the lander are insufficient to satisfy this objective, as customer needs dictate views of the rover around all its operating sites.

1.1.2 Secondary Mission Objectives

The secondary mission objectives were addressed after the primary mission objectives were established. The capabilities to satisfy the secondary objectives are provided where they do not impinge on the primary objectives. These secondary mission objectives are:

- Allow teleoperation of rovers by amateurs on Earth;
- Support scientific exploration;
- Support educational outreach.

The first objective supports non-expert use of the rover. The chance to drive a rover on the moon would be a major draw for a theme park. But since theme park patrons are unskilled at robotic teleoperation, the rover must possess the ability to safeguard itself against operator error. Amateur operators would also characterize rover use by the scientific and educational communities. Scientists and students do not have the time to be thoroughly trained in the operation of the rover, and hence would also require the use of safeguarding to protect the rover.

To support scientific exploration and educational outreach, a portion of the rover operating time will be dedicated to these pursuits. Although no mechanism on the rover is provided to physically interact with the lunar surface, a great deal of exploration and education can be achieved through visual means using imagery.

1.2 Traversal Route

The mission traverse is designed to visit sites that are remembered and cherished by adults world-wide. The route is also designed to instill excitement and suspense, regarding both the uncertainty of when a site will be first visited, and whether or not the rover will discover the Soviet Lunokhod 2 vehicle.

The traverse will begin, as shown in Figure 1.1, in the Sea of Tranquility within 20km to 30km of the Apollo 11 site where the Eagle landed. This historic landing is still remembered as a fulfillment of the spirit of exploration, and is considered to be one of the greatest achievements of the American space program.

Leaving Apollo 11, the route will offer two segments, each less than 100km, to the Ranger 8 and Surveyor 5 sites; two important missions which enabled successful manned Apollo landings. These visits will keep public interest high while the rovers begin a long traverse north towards Apollo 17.

The rovers will take approximately 3 to 4 months to traverse the benign terrain between the Apollo 11 and the Apollo 17 sites. Apollo 17 was America’s last manned lunar mission and provided another high point of the space program. There, the Lunar Rover Vehicle (LRV) bounced and sped across the dusty lunar landscape.

Finally, the mission will offer a true quest to discover the landing site and trail of the Lunokhod unmanned vehicle, by again heading northward for about 200km. The Lunokhod vehicles are predecessors of this rover, as they are the only telerobotic vehicles to have operated on the Moon. Because the exact location where Lunokhod became trapped and failed is unknown, the possibility that Lunokhod’s trail will end just over the next horizon will keep interest high.

After completing its planned traverse, the rovers will continue to explore interesting sites. Even between the five planned stops, geological features of scientific and popular interest will be noted and investigated. Although the mission baseline is a 2-year mission, the continuous power source should provide ample power

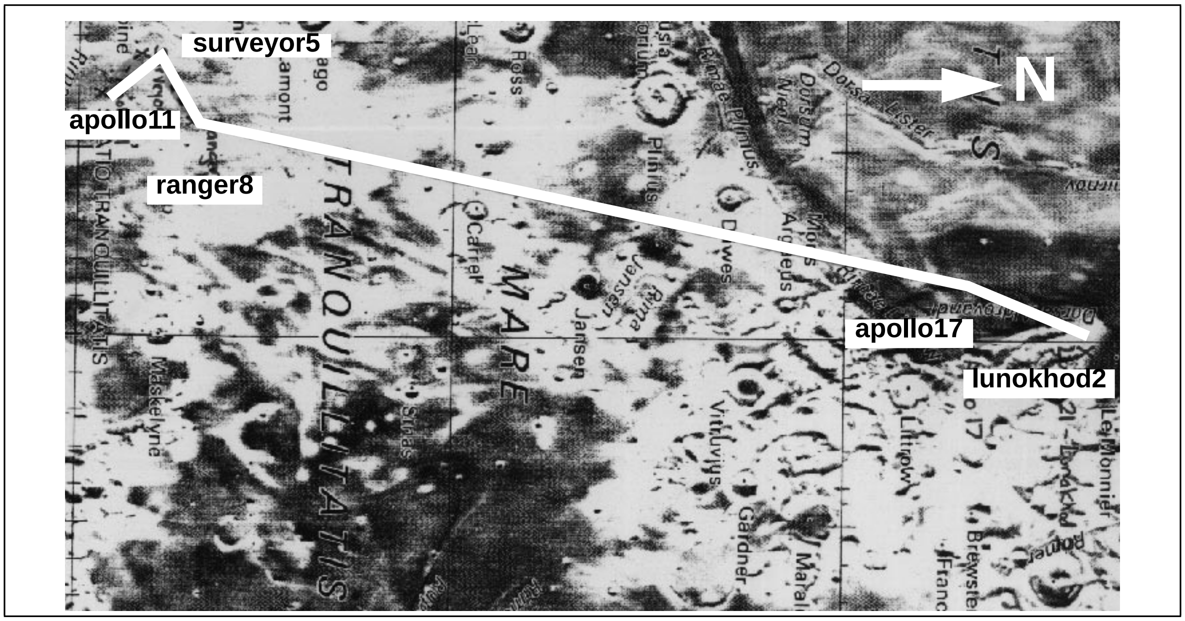

FIGURE 1.1 *Mission Traversal Route*

to operate well past the 2-year specification. Table 1.1 shows the locations of the 5 historic sites. The maximum longitude and latitude, 30.4° East, 27.0° North, will determine the geometric angle that the communications antenna must be able to rotate through to allow uninterrupted communications with ground stations.

TABLE 1.1 *Lunar coordinates of historic sites on the traversal route*

Historic Site	Longitude	Latitude
Apollo 11	24.0° East	0.8° North
Surveyor 5	22.1° East	1.5° North
Ranger 8	24.9° East	3.4° North
Apollo 17	30.2° East	19.6° North
Lunokhod 2	30.4° East	27.0° North

1.3 Operation Modes

The mission objectives allow for the definition of the mission operation modes. This scenario defines the conditions under which the rover system will achieve mission success.

The overall system design for the rovers is detailed later in this report. The rover is a semi-autonomous robotic vehicle consisting of a rocker bogie locomotion system, panoramic imagery subsystem, beta-decay constant power electrical supply, and other support electronics. The system will consist of two rovers to provide external views of the rovers while operating on the surface and to increase the probability of mission success through redundancy and possible inter-rover cooperation during operations.

Due to communications bandwidth constraints, both rovers will not be able to communicate through their high-gain antennas concurrently. This dictates a duty cycle of approximately 50% for each rover. This duty cycle can be made to coincide with the theme park ride cycle time, so that the rovers will move similar distances and remain within sight of each other.

There are basically two modes of operation for each rover, in addition to active and not active. The two modes relate to the main user, wither the theme park or science and education. The basic difference between the two modes is the type of data sent to Earth and the manner in which the rover is driven.

1.3.1 Theme Park Operations

Operations in support of a theme park is the main objective for the rover system, and, as previously mentioned, is the main system driver. There are two main modes for theme park operations:

- Trained Operator
- Amateur Operator

During both of these modes, theme park patrons will experience the rover's movements through virtual reality. This ride will operate independently of the rover mode of operation, and will utilize the video and rover state data continuously downlinked from the lunar surface. This mode requires that the rover be driven in a manner that feels "exciting."

Trained Operator

During this mode, the rover will be accepting all of its commands from a trained operator in the command center. While the rover continuously performs local safeguarding, the operator will be able to override the safeguarding if deemed necessary.

Amateur Operator

While operating in this mode, in addition to the local safeguarding performed on-board the rover, the rover's commands from the operator will be sent through ground based safeguarding to eliminate malicious commands. The speed of the rover will also be curtailed, to further decrease the risk of the rover being damaged.

1.3.2 Science and Education Operations

For both scientists and students, the two modes of operation mentioned earlier, trained and amateur operator, will be utilized. The main difference between these type of operations and theme park operations is the viewing mode. While scientists will be able to use the panoramic viewing mode associated with the theme park ride, a separate pan/tilt/zoom camera is implemented for in-depth visual exploration. This will allow scientists fine control of the imagery subsystem to examine specimens of interest on the lunar surface in detail.

A separate movable camera is also of interest for educational purposes. The pan/tilt/zoom camera will be used by students to collect data in the same manner as scientists do. The movable camera can also provide more excitement for students. The pan/tilt controls of the camera system will provide a faster response and better control of the view than control of the entire rover would provide. It will also cut down on safeguarding overhead.

This mode of operation is inherently less "exciting" than the theme park mode because scientists will drive the rover in a stop/start fashion, stopping when they wish to examine items in depth. There will also be less rover motion as the scientists debate locations to explore next. Student driving will most likely be similar in style, with fewer stops and less time spent examining objects.

Chapter
2

Design Approach and Constraints

In addition to the technical aspects of the project, the design of the roving vehicle was determined by several factors: the structure of the class, the amount of time available individually for each student and the class as a whole, and the knowledge and experience of the students.

2.1 Class Structure

The students who produced this document were enrolled in the “Mobile Robot Design” course at CMU. The purpose of the class is to introduce the students to the methodology and knowledge required in the design of a complete mobile robotic system. The course also satisfies one part of the Mobile Robot Specialized Qualifier requirement for the Ph.D. Program in the Robotics Institute. The course was taught by Dr. Red Whittaker and a graduate teaching assistant. The class consisted of ten students.

The class was broken down into ten different group. The groups consisted of:

1. Systems . . . . Andrew B. Mor
2. Structures. . . . . Tom Warren, Jesse Easudes
3. Locomotion . . . . Eric Rollins
4. Power. . . . . Alex Sharf
5. Thermal . . . . Peter Berkelman
6. Communications . . . . John Hancock
7. Sensing . . . . John Hancock
8. Computing. . . . . Jack Silberman
9. Software . . . . Martin C. Martin
10. Imagery . . . . Mei Chen

2.1.1 Time Constraints

The class met two times a week in one and a half hour sessions with the instructor, and an additional one to three hours a week without the instructor. All of the students also had additional constraints relating to course schedules and research responsibilities.

The class met for one term lasting 14 weeks. This time was consumed by learning about project and space technologies, a preliminary design, an intermediate design review, and a final design review.

2.1.2 Student Knowledge and Experience

The technical knowledge and experience brought to this class by the students was vast, however experience with the design of a complex space system was limited. While all the students had extensive course work behind them, most of that experience was theoretical in nature. Many of the students possessed practical experience in design and implementation of small subsystems, but transference of that knowledge to complex system design was not complete at the beginning of the course.

The students researched space systems in detail and how the rover requirements could be satisfied on the lunar surface. Where the knowledge required was not available within the CMU community, help was generated through industry and NASA contacts, either by means of phone calls or site visits.

2.2 Design Approach

The design methodology used for this vehicle started with determining the overall system requirements for the rovers. These requirements are detailed in Section 3.1 on page 19. It was determined that the main deliverable of the system is imagery of the moon, and the vehicle was designed to provide that as reliably and with as much availability as possible.

The design process is shown in Figure 2.1. This is a visual representation showing the methodology that was used during this design and highlights the iterative nature of the design process.

After the system level requirements were finalized, the class brainstormed to come up with multiple designs that would satisfy those requirements, with particular attention given to those problems which heavily influenced the design. The brainstorming produced similar configurations with the main differences being how the imagery and power subsystems were implemented. The class then analyzed and iterated the different configurations and determined which one best met the system level requirements. This analysis was done so as to maximize the performance and minimize the risk of the entire vehicle.

After the overall configuration was determined, technical requirements for each subsystem were established and the configuration was refined to meet those requirements until a rational design was created.

2.3 Design Constraints

The design of the rover system was impacted by many factors. The primary design drivers, after the imagery subsystem payload was accounted for, were the rover's operating environment and the lunar day/night cycle.

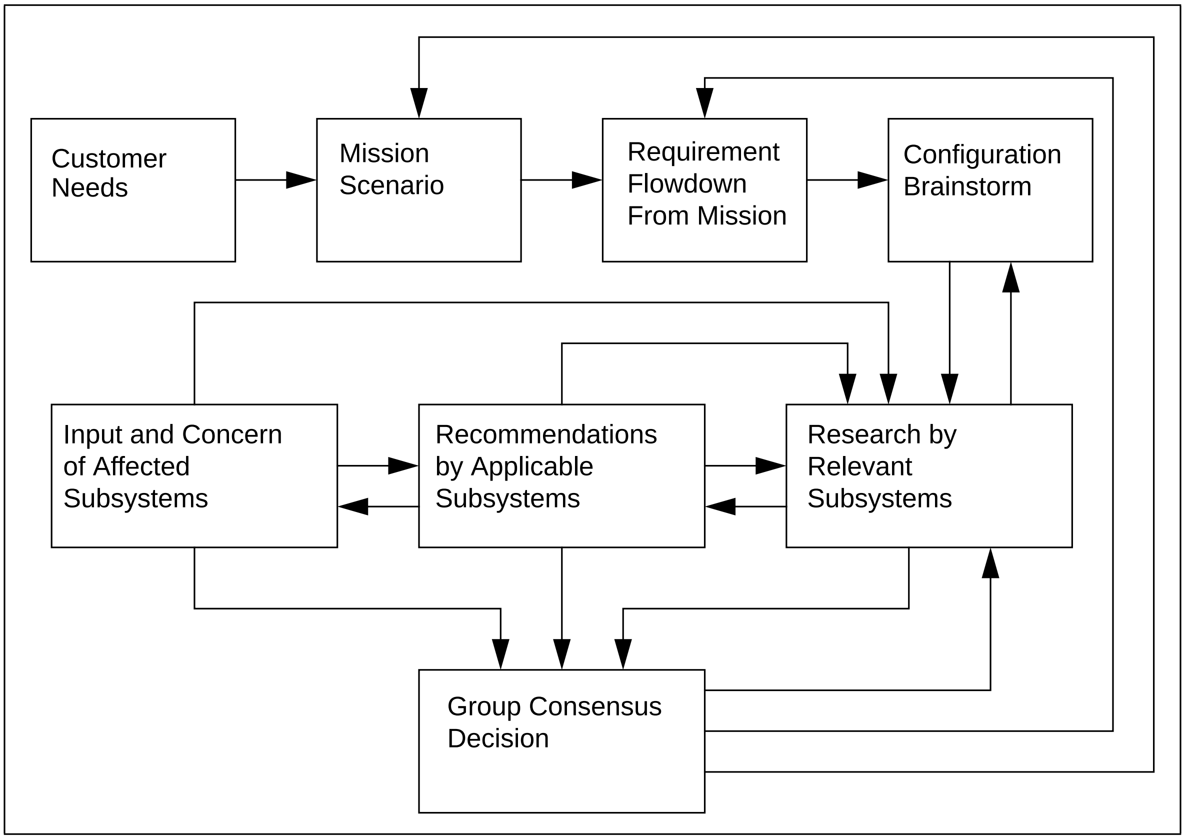

FIGURE 2.1 *Design Process*

2.3.1 Lunar Environmental Issues

The lunar environment can be characterized by 7 major categories:

1. Dust environment
2. Radiation environment
3. Vacuum environment
4. Thermal environment
5. Terrain environment
6. Micrometeorite environment
7. Sun Earth Moon Geometry

Table 2.1 summarizes these environments and their dominant effects on spacecraft on the moon.

The primary design limiting environments are the thermal, radiation, and dust environments. The vacuum and terrain environments are of secondary importance, and are also addressed. The micrometeorite environment is of such low risk that it is not addressed by this design.

TABLE 2.1 *Lunar Environment and Effects*

Environment	Effects
Dust	Surface Coating Abrasion of Mechanical Components
Radiation	Single Event Upsets Optical Coating Degradation
Vacuum	UV Degradation Outgassing
Thermal	Vehicle Heating
Terrain	Terrainability Trap Vehicle
Micrometeorite	Impact Damage
Sun Earth Moon Geometry	Long Day/Night Cycle Fixed View of Earth

Dust Environment

Due to its unusual properties, lunar dust is expected to be problematic. The particles are very fine and highly abrasive, and will erode bearings, gears, and other mechanical mechanisms not properly sealed. Lunar dust carries an electrostatic charge which enables it to cling tenaciously to all non-grounded conductive surfaces. Astronauts from manned landings reported that removing dust from their equipment was difficult.

> *The use of a whisk broom prior to ingress [to the Apollo 12 cabin] would probably not be satisfactory in solving the dust problem, because the dust tends to rub deeper into the garment rather than to brush off. [Bean et al., Apollo 12]*

The accumulation of dust on optics and radiators is also of concern. Even small quantities on the front surfaces of refractive optics will severely increase stray light scattering. Conversely, thin layering on thermal radiators is not likely to cause problems. Thicker accumulations will degrade radiator system performances and hence must be kept acceptably low for the mission's two-year duration. [1]

Dust can be lifted off the lunar surface by thruster firings of the lander, impacts by non-microscopic meteoroids, and infrequent temporary raising of dust from the surface along the terminators (the boundaries between day and night) due to charging by solar ultraviolet radiation. Although the last mechanism is not well understood, it is estimated that the dust rises no more than one-half meter above the surface.

The dominant source of suspended dust is the rover interaction with the soil. As seen in video footage of the Apollo 17 LRV, the amount of dust sprayed from the wheels was large and reached heights of over two meters. Although this is of concern and methods to limit dust suspension are being investigated, it should be noted that the velocity of the LRV was much higher than that of this rover. Since the lunar atmosphere is a hard vacuum, the lifted particles do not remain suspended in the atmosphere, but quickly return to the surface.

Thermal Environment

The thermal environment around the rover consists of direct solar flux from the sun, reflected lunar albedo flux, and infrared radiation directly from the lunar surface. During the lunar day these environs heat the rover, while during the night they provide no thermal energy at all.

The solar flux is the amount of energy that passes through a given area at a given distance from the sun. In a lunar orbit, this number varies by approximately 1% from daybreak to nightfall, and drops to zero during the lunar night. The nominal value at the Earth's distance from the sun is called the Solar Constant, and the average value is $1358 W/m^2$.

Less than 10% of the solar radiation reaching the moon is reflected back into space.[2] The amount of this albedo that impinges on the rover is dependant on the orientation of the rover and is much smaller in magnitude than direct solar radiation and IR radiation from the lunar surface.

The lunar surface acts as a grey body source at the temperature of the surface. This surface temperature varies according to latitude and the time in the lunar day/night cycle. The extremes that the rover expects to see are $+120°C$ to $-150°C$. These extremes are similar to going from super heated steam to liquid nitrogen temperatures.

Radiation Environment

During its two year mission on the moon, the rovers will encounter the harsh space ionizing radiation environment: large fluxes of low-energy solar wind particles, smaller fluxes of high-energy galactic cosmic rays (GCR), and occasional intense particle fluxes emitted by solar flares (SCR). The lunar radiation environment is summarized in Table 2.2.[2] In addition to the ionizing radiation that reaches the lunar surface, soft x-rays and ultraviolet light are also present in significant quantities.

TABLE 2.2 *Major Types of Radiation in Lunar Environment*

Type	Solar Wind	Solar Cosmic Rays	Galactic Cosmic Rays
Nuclei Energies	~0.3-3 keV/u*	~1 to > 100 MeV/u	~0.1 to > 10 GeV/u
Electron Energies	~1-100 eV	<0.1 to 1 MeV	~0.1 to >10 GeV/u
Fluxes ($protons/cm^2 sec$)	$\sim 3 \times 10^8$	$\sim 0\text{-}10^6$ †	~2-4

* eV/u = electron volts per nucleon

† Short-term SCR fluxes above 10 MeV. Flux above 10 MeV as averaged over ~1 m.y. is ~100 $protons/cm^2 sec$

The solar wind particles are the most numerous particles striking the rovers, but due to their comparative low-energy, are of less concern than galactic cosmic rays and solar flare events. Solar flares can occur several times a year, and emit a large number of particles at relatively high energies (1-100MeV). These flares can last from several hours to many days, and have the potential to bombard the rovers with high energy particles that can damage the rover's surface and structural integrity and electronic components. These energetic protons ionize optical materials and since they are massive they create defects throughout the bulk of those materials. This radiation must be considered when choosing structural materials and component placement within the rover.

GCRs occur very infrequently (~4 $protons/cm^2$-sec), but are very high energy. While the number of particles is not an issue, their high energy can cause damage to electrical components. A single particle can damage an electrical component and cause its failure through energy loss and elastic and inelastic scattering processes.

Soft x-rays and ultraviolet light affect surface coatings and optics, due to their energy levels in the solar electromagnetic spectrum. Solar ultraviolet and soft x-ray photons are sufficiently energetic to induce defect centers in optical materials, and can cause darkening throughout shallow depths.

Vacuum Environment

The lunar environment possesses a hard vacuum with 2 orders of magnitude fewer particles per unit volume than Low Earth Orbit. The hard vacuum precludes the use of many common plastics and rubbers whose strength and pliability become reduced by outgassing of their volatile components. Outgassed materials can also collect on optical and sensing surfaces, which can reduce their effectiveness. Organic, organo-metallic, and organo-silane polymers (and copolymers) which are fully reacted, and consequently have low vapor pressures, may be used if their optical and/or mechanical properties are stable over the expected fluences of solar radiation and their temperatures are maintained above “glass” phase transitions. Also, due to the relative strength of the vacuum on the moon compared to LEO, polymers approved for use in LEO may not be suitable for use on the moon.

Lunar Terrain

The terrain of the lunar surface has been defined by meteor strikes. Continual impacts of micrometeoroids have resulted in an extremely fine, loosely-compacted soil. Many of the large-scale features, such as steep crater walls and large boulders, are insurmountable obstacles to the rover. Fortunately, due to the fairly random nature of meteor strikes, these features are distributed much less regularly than geological features on Earth. Consequently, the rover should be able to traverse most stretches of lunar terrain by negotiating obstacles.

The lunar terrain is well characterized near prior landing sites and the size distributions of boulders and craters are known. Figure 2.2 shows the results of a random simulation of lunar craters and boulders created from Apollo 11 site data, a moderately rough area. Only craters larger than one-half meter (represented as circles) and boulders larger than one-quarter meter (depicted as filled rectangles) are displayed. The scale is given in the lower left corner of the plot.

The expected maximum slope that the rovers will see is approximately $25°$-$30°$. The average slope will be less than $2°$ for the overall mission.[2] The regolith, which is the material on the outer surface of the moon, has an angle of repose approaching $35°$. Around craters, the soft soil can become very deep, so wheel contact pressure must be minimized.

Earth Moon Geometry

The variations in the orientation of the Earth and Sun relative to the rover affect both the imagery and communication links. The lunar day lasts approximately twenty-eight Earth days, during which time the Sun goes from overhead, sets, rises, and returns to overhead. Therefore, the imagery system must be able to deal with sharp shadows, washed out terrain, and little ambient light.

The near side of the Moon faces the Earth at all times; reversing the perspective, from a point on the near side of the moon, the Earth is always visible, during both day and night. Although its position remains constant, the Earth would be seen to change in phase, just as the Moon does when seen from Earth. At lunar dawn and dusk, an observer on the Moon would see a half-Earth; while in the middle of the lunar day, with the Sun behind the Earth, only a crescent would be visible; and during lunar midnight, the Earth would appear to be almost full. The amount of light that reaches the moon therefore varies over the lunar day.

The exact position of the Earth in the sky depends on the position of the observer on the lunar surface. For example, to an observer at the center of the near side, the Earth would be directly overhead; while on the line dividing the near and far sides, the Earth would be visible on the horizon.

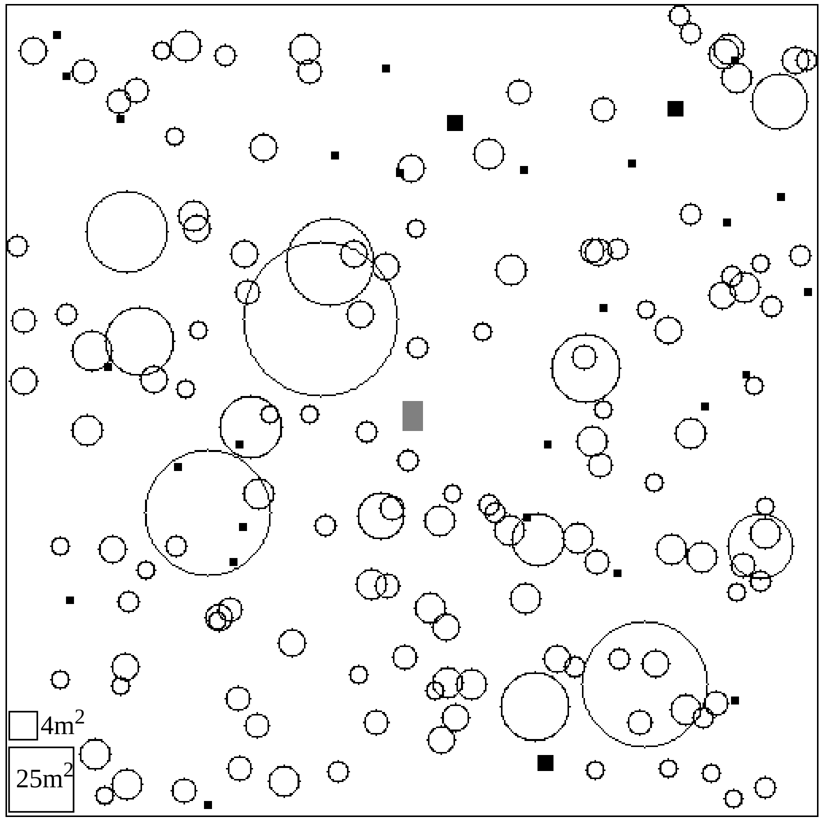

FIGURE 2.2 *Lunar terrain, simulated from data gathered by Apollo 11.*

Astronomers have defined the lunar latitude and longitude lines such that the zero degree lines intersect at the center of the near side. On the proposed route, the maximum longitude and latitude experienced would be near the Lunokhod 2 site (30.4° E, 27.0° N), as shown in Figure 1.1 on page 9. This means that the Earth will always be at least sixty degrees above the horizon.

The greatest expected angle of the rover with respect to the perpendicular from the Earth is 60°. This value is the sum of the 30° of longitude and latitude and the expected maximum slope of 30°

References

1. Katzan, Cynthia M., Edwards, Jonathan L., “Lunar Dust Transport and Potential Interactions With Power System Components”, 1991, NASA Contractor Report 4404.
2. Heiken, Grant H., Vaniman, David T., and French, Bevan M., “Lunar Sourcebook, A User’s Guide to the Moon”, 1993, Cambridge University Press.

Chapter 3

Systems Engineering

Systems Engineering covers all issues outside the realm of the other subsystems, including management issues and system wide integration. System level requirements were also generated and tracked throughout the semester, as were overall design concepts and lander integration issues.

3.1 System Level Requirements

The system level needs were established for the rovers based on the customer needs and the primary and secondary mission objectives. They are:

- The vehicle must provide video of the moon and rover state data to Earth of sufficient quality for theme park and scientific uses.
- The vehicle must provide views of the rover while operating on the moon.
- The vehicle must safely allow teleoperation by “amateurs” on Earth.
- The vehicle must safely interact with the lunar environment.
- The vehicle must operate reliably for a period of at least 2 years, to maximize the Return on Investment (ROI) for the theme park.
- The vehicle must follow all societal expectations with relation to launch and operations.

3.1.1 Imagery and State Data

The following high level requirements flow down from the first system need. The vehicle must:

1. Provide high resolution panoramic imagery of the lunar terrain.
2. Provide a user controllable camera for detailed examination of surface features.
3. Provide vehicle state data (velocity, acceleration, angle, etc.).

The requirement of high resolution panoramic imagery comes from the need to support telepresence rides in a theme park. These rides require imagery that can convince patrons that they are actually experiencing the location that they are viewing. In the case of this rover, this requires high resolution video from in front of the rover and medium resolution imagery to the sides and back. Additionally, a periodic view of the sky will also need to be downlinked to complete the panorama. The rover state data will be used to reconstruct the motion of the rover. Theme park patrons will be sitting in mock-up vehicles that will mimic the movements of the rover on the moon. In this way, the patrons will move in step with the imagery, which will increase the feeling of actually being on the moon.

The user controllable camera requirement is dictated by the science community. They require the ability to obtain multiple views of objects from varying orientations. A zoom capability is also required to examine small features in detail and larger features from a distance.

3.1.2 Views of Rover

Acquiring views of the rover operating in the lunar environment is another need dictated by the customer. In addition to theme park and scientific/educational uses, the rovers will be used for commercial marketing. This need dictates that views of the rover in the terrain be acquired. Having views of the rover in the terrain is also useful for a theme park, so that patrons can experience the rover's movements both from outside looking toward the rover and from inside the rover looking out. This need basically states that:

1. The rover must be capable of providing either views of itself in the terrain or views of another rover operating.

This requirement can be satisfied in different ways. In a multiple rover system, off-board views of the rover can be provided by another rover. In a single rover system, off-board views can be provided by a remote camera placed by the rover or by a fish-eye lens mounted above the rover looking down.

3.1.3 Teleoperation

The need for amateur operation, in addition to expert and/or autonomous operation, established the follow requirements:

1. The rover must safeguard itself at all times against local hazards.
2. The rover must be teleoperable at a high level, i.e. generate controls based upon uplinked steering and velocity commands.

Operations by trained persons dictate the additional requirement:

3. The rover must allow low-level, non-safeguarded control when necessary.

Rover safeguarding, the ability to detect hazards near the rover and take precautionary action autonomously, is a requirement for the rover due to the large distance between the moon and the Earth and the corresponding five second time delay. To achieve this requirement, the rover must be able to detect two basic hazards: obstacles that it can not surmount and drop offs which might strand it.

High level teleoperation is required for amateur drivers due to the complexity of actually controlling the vehicle. The operator will give the rover a command, such as move forward, and the rover will implement that command in the most efficient manner. This method of control hides the details of operations, so that untrained operators need only worry about where they want the rover to go.

Under some circumstances, the rover may require low-level control by the operator. This may occur if the rover gets mired in deep soil, or close to a drop off that a scientist may want to examine. In these situations, the rover must be able to provide the ability to control every function separately, to allow the user complete control of the entire vehicle.

3.1.4 Environmental Interactions

The need for the rover to safely interact with the lunar environment dictates the following requirements. The vehicle must:

1. Survive radiation, thermal, dust, and terrain environments on the lunar surface.
2. Survive radiation environment during transfer to the moon.
3. Be capable of communicating with ground stations on Earth.

The rover must able to withstand all external environments that it will encounter during its mission, including launch and transfer to the moon, as detailed in Section 2.3.1 on page 13.

3.1.5 Societal Expectations

Due to the fact that the rover is a commercial venture, the design of the rover must not invite protest. This dictates that the rover must:

1. Not carry any fissionable sources on-board, e.g. plutonium.
2. Not disturb historical and revered sites on the moon.

Aside from governmental regulations, social action organizations often take issue with the use of nuclear power sources in space missions due to the potential for damage to the Earth's environment which might develop if an accident occurred during launch or ground transport. While nuclear sources are ideal for heating and power needs, the risk of negative publicity to a commercial enterprise may force the choice of other means of generating power.

The landing sites of the manned Apollo missions were declared National Historic Sites by the United States and are not to be disturbed. The rover must circumvent these sites and take special care while operating in their vicinity.

3.2 System Functionality

In order for the rover to accomplish its specified mission, it must perform certain tasks. These tasks define the responsibilities of the different subsystems. Table 3.1 lists the top level function of each subsystem, from which the subsystem functionality and requirements are drawn.

These functions are shown graphically in Figure 3.1 on page 23. Also shown are the relevant internal and external interfaces. Mechanical interfaces are shown with solid lines, communication/data interfaces with dotted lines, and power interfaces with dashed lines. The interface between the rover and the lander module is the only interface that will be broken during the mission, when the vehicle is deployed from the lander.

3.3 Vehicle Design Concepts

During the design of this vehicle, many different designs were discussed and brainstormed. Outlined below are the main design options that the design team iterated upon.

TABLE 3.1 *Subsystem Top-Level Functions*

Subsystem	Function
Structures	Provide Environmental Protection
	Maintain Physical Integrity
	Provide Mechanical Interfaces
Power	Generate Power
	Control and Distribute Power
Thermal	Monitor Temperature
	Supply and Reject Heat
Locomotion	Generate Motion
Command, Communications, Control, and Telemetry	Computation and Control
	Command and Telemetry
	Communications
Guidance, Navigation, and Control	Determine Vehicle State
	Control Vehicle State
	Safeguard Vehicle
Imagery	Provide Imagery

3.3.1 Options

The main concepts analyzed differed mainly in two areas: the power and imagery subsystems.

Power

The main decision made regarding the power subsystem was whether to utilize solar energy or beta-decay sources as the prime source of power.

Solar energy conversion is a well known, understood, and established method of generating electric power. The primary solar-powered design arrayed the cells around the vehicle, so that it could absorb solar energy while at any angle with respect to the sun. In order to absorb enough solar radiation to supply the required power, the surface area had to be quite large, with a vehicle cross sectional area of roughly $6m^2$. This concept would have required a great deal of structural mass to support such a large vehicle. This concept is shown in Figure 3.2. The competing concept utilizing solar arrays specified articulated array panels. These arrays would track the sun, and would therefore require much less surface area to obtain the required electrical power. The main problems with this concept were that the amount of articulation could lead to reliability problems and large batteries would have been needed.

The other contending concept utilized a beta-decay source, Kr85 gas, to provide energy. While beta-decay is a nuclear source, beta particles are much less harmful to the environment and people than the gamma particles emitted by plutonium. Kr85 also has a much shorter half-life, a little over 10 years. And due to its gaseous form, Kr85 gas would disperse quickly in the event of an accident. Finally, Kr85 is an inert noble gas and doesn’t accumulate in the body. The main drawback to using Kr85 as a power source is the efficiency of

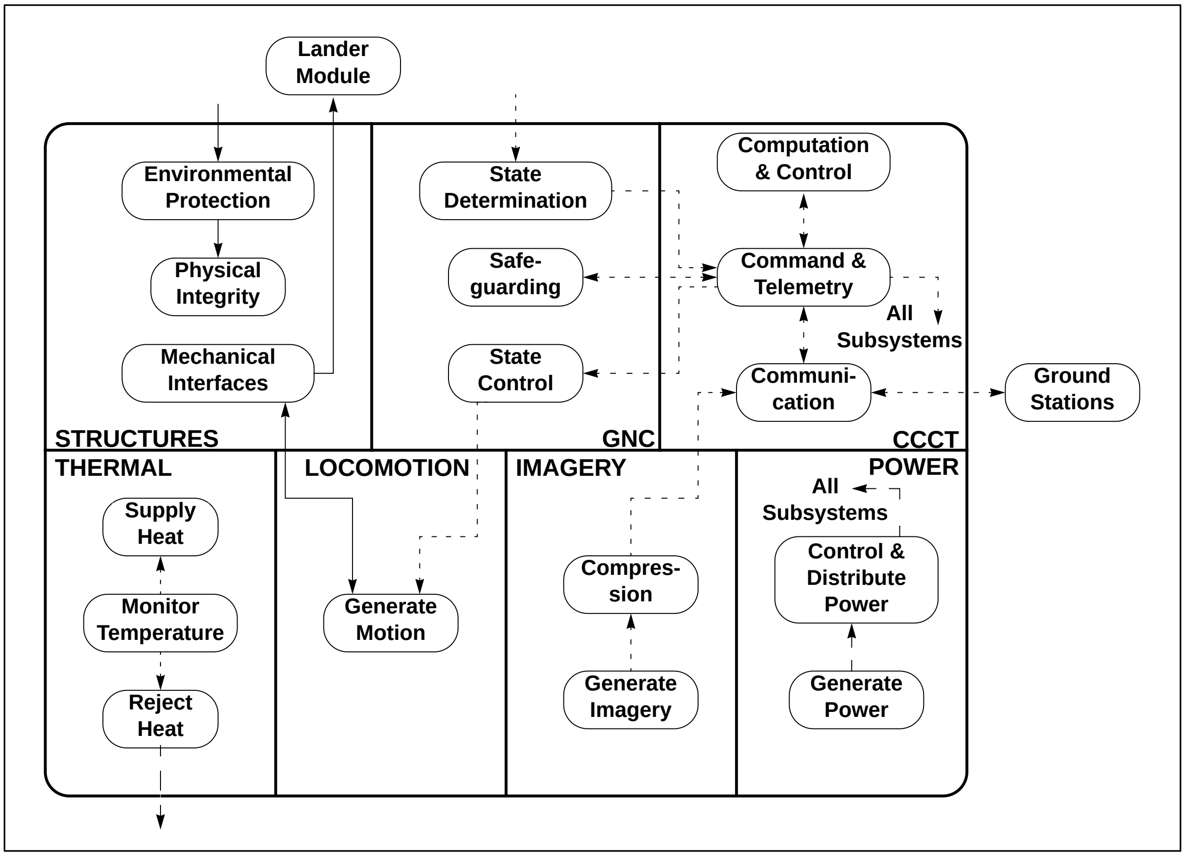

FIGURE 3.1 *System Functional Block Diagram*

thermo-electric power conversion. Established solid state converters operate at roughly 6%. An alternative thermo-electric conversion method was identified, the Alkali Metal Thermal to Electric Converter (AMTEC). While still in the design stage, this technology has already demonstrated efficiencies up to three times greater than solid state converters. AMTEC conversion also does not depend on the position of the sun in the sky, and can reject heat at high temperatures, minimizing radiator size and mass.

Utilizing a Kr85 power source for electrical power impacts the design of the rover in other ways. Because the power source is not dependant on the sun, it allows for lunar nighttime operations, which increases the customer's ROI. Also, delivering the required electrical power to the rover requires a great deal of thermal energy, which can help keep the rover warm during the cold lunar night. The original concept is shown in Figure 3.3.

Imagery

The two main concepts for imagery to provide panoramic imagery were: utilize a ring of cameras and stitching the images together or use a panospheric optic that provides a ring image of everything around it.

The panospheric camera and optic, shown in Figure 3.4, captures a 360° azimuth and over 150° of elevation on a single image. The acquired image is quite warped, but dewarping the image for viewing on a flat screen can be done in a similar manner as dewarping a fish-eye image. The system is also very simple groundside, where imagery display can be achieved by sending the warped image back through similar optics. The three major components required for panospheric imaging are a unique optic, high-resolution camera, and special-

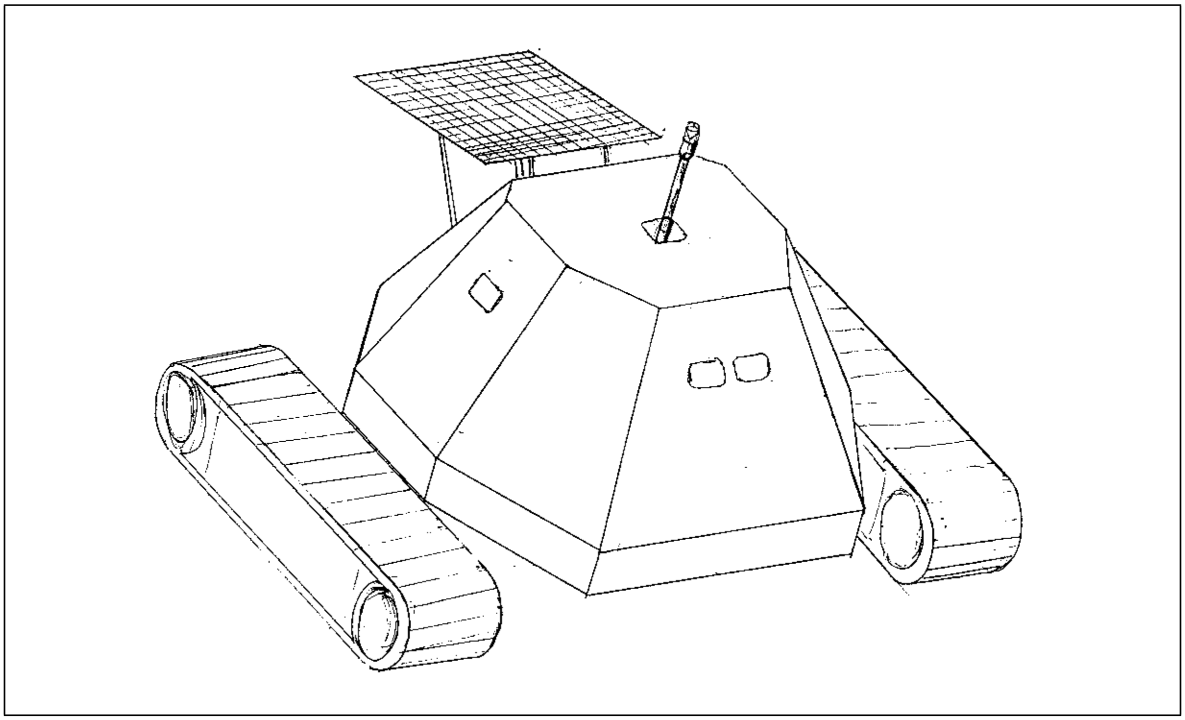

FIGURE 3.2 *Solar Array Concept*

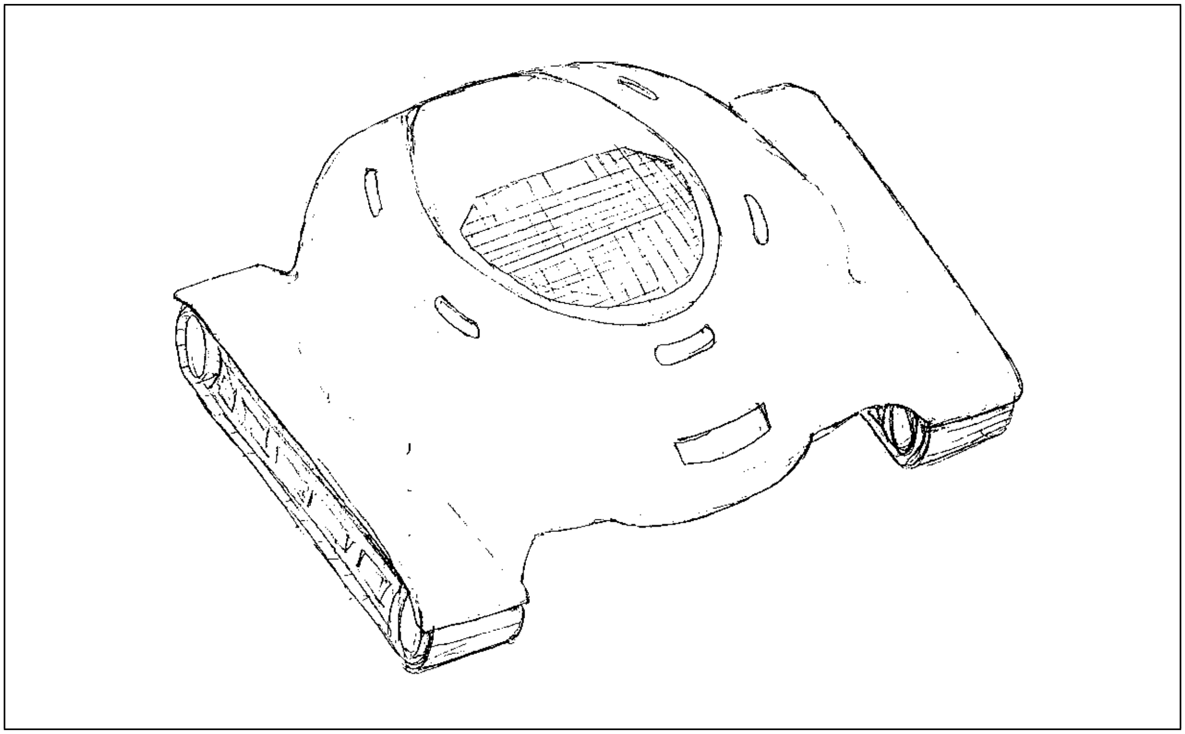

FIGURE 3.3 *Kr-85 Concept*

ized processing algorithms. No panospheric sensor is currently in existence, although design work for application to armored vehicles is underway and proof-of-concept prototypes have been demonstrated. The main advantages of this system are reliability and simplicity. With only one camera, downlinking the required imagery data is simple. The drawbacks to this type of camera system are twofold. To achieve adequate resolution in the image a 2000x2000 pixel array is required. This is a very large amount of data to send back to Earth. To obtain reasonable images of the ground near the rover for path planning, the imager must be high above the rover. If the camera is high up on the rover, then it may interfere with the communication link performance.

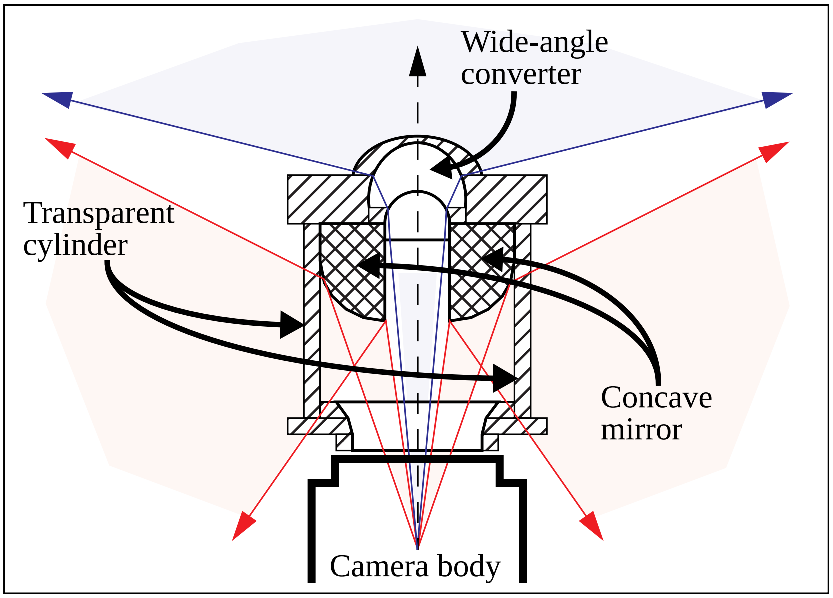

FIGURE 3.4 *Panospheric Camera and Lens*

The ring of cameras would provide a panoramic view through the use of multiple cameras with matching algorithms implemented on the ground to stitch the disparate images into one continuous 360° image. The concept analyzed utilized 6 cameras located around the periphery of the rover. Another camera was pointed skyward to capture views of the Earth and stars. The main advantage of this system is the ease of implementation into the rover system and views would not be blocked by the antenna. Suitable cameras that could be used already exist and are relatively easy to obtain. The main drawbacks are the processing required on the ground and the greater power required to utilize the multiple cameras.

3.3.2 Concept Selection

The concept that was finally accepted and iterated upon utilizes the Kr-85 power source and a ring of cameras with illumination for the imagery subsystem. Both seem feasible and it is the only one that will allow the rover to operate during the full lunar cycle. Two rovers will be flown to provide both off-board images of the rovers operating on the surface and increased probability of mission success through large-scale redundancy. The final concept is shown in Figure 3.5.

The locomotion subsystem consists of a six-wheeled rocker bogie (not shown). The four corner wheels are independently steered, to increase terrainability. All six wheels are independently driven. This design pos-

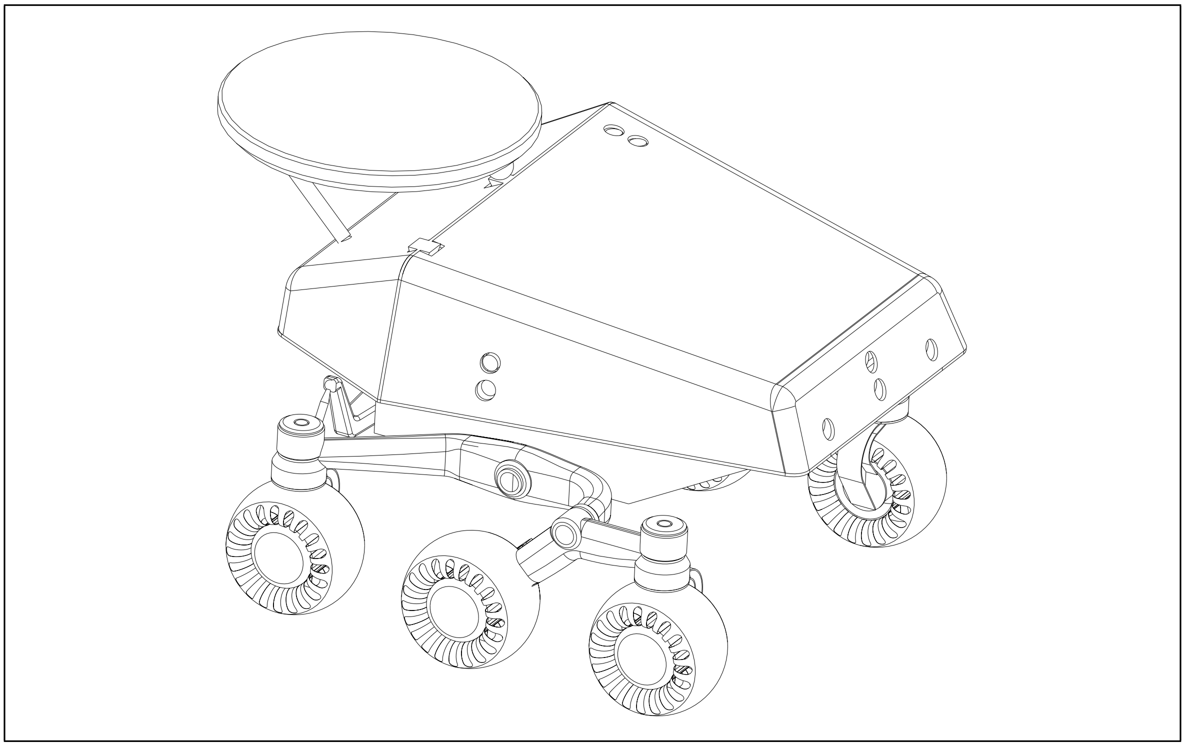

FIGURE 3.5 *Selected Rover Concept*

sesses very good terrainability and low power requirements combined with body averaging characteristics that reduce the amount and frequency of vibrations transmitted to the body of the rover. This minimizes the chances of patrons of the theme park becoming nauseous during the ride. It also provides the communication subsystem an environment with less disturbance, increasing the precision of the pointing mechanism.

Safeguarding will be achieved through the use of stereo cameras during the day and a light striper at night for distances greater than 1.5 meters and an array of modulated infrared transmitter/receiver pairs for distances from 0 to 1.5 meters. The communications subsystem utilizes an electronically steered phased array with a scan angle of +/- 30°. The array will be articulated to provide a further +/- 30° of pointing, to allow a total of +/- 60°. Computing power will be provided through multiple Harris RHC-3000 processor boards.

The Kr-85 power source will provide in excess of 3000 Watts thermal power. Therefore, the rover’s thermal subsystem will always be dumping heat to maintain interior temperatures within safe operating limits. The thermal system is mostly passive, with all heat generating devices placed against radiators to control their temperatures. Small spot heaters and coolers are placed where necessary on critical components.

A view of the different rover components is shown in Figure 3.6.

The basic operating scenario for the vehicles will be to have one rover operating while the second rover is idle. This restriction, as mentioned before, is set by the allowable communication’s bandwidth, and is not required by the rover design. Therefore, when necessary, both vehicles can operate at the same time with limited bandwidth. Communication’s downlink will be provided by only one of the rovers, with inter-rover communication achieved through omni-directional antennas. This will allow the rover’s to “help” each other while moving or if stuck.

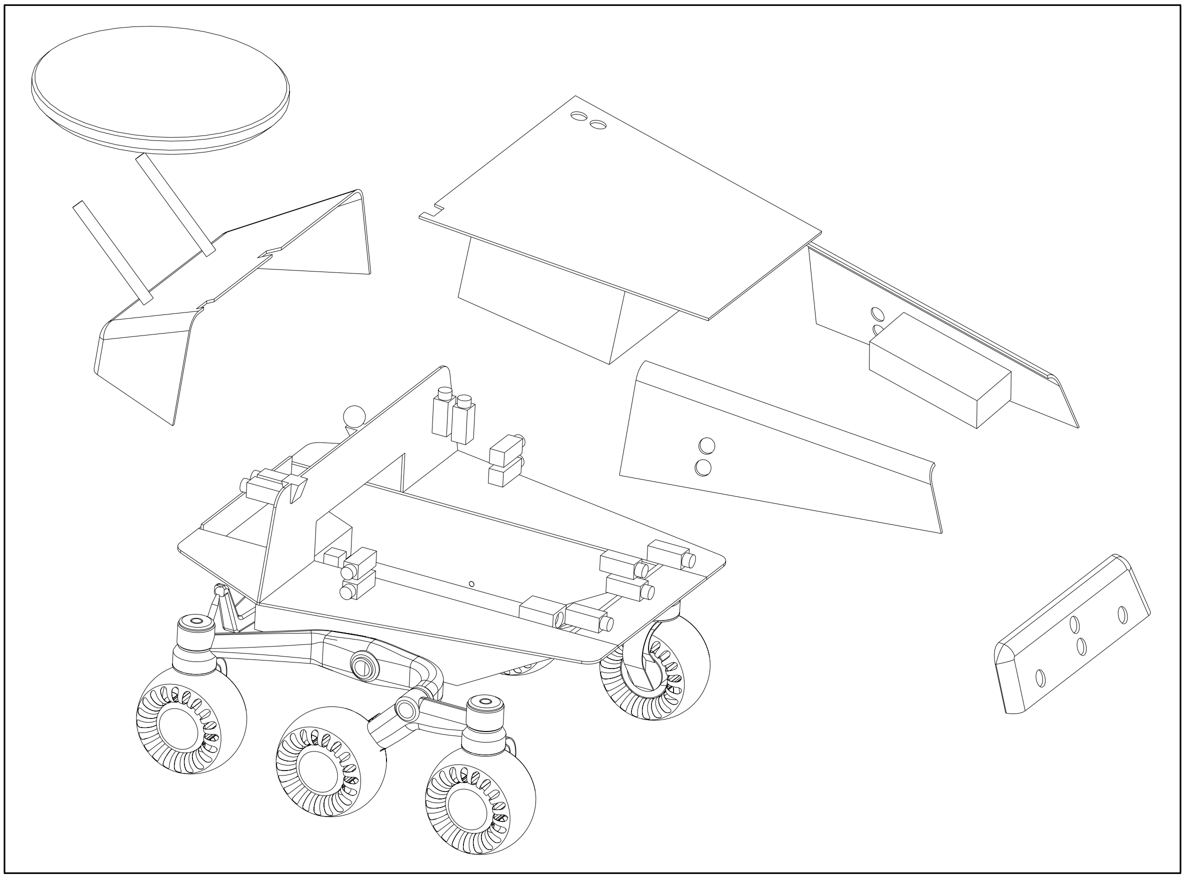

FIGURE 3.6 *Exploded View of Rover, Showing Different Subsystems*

3.4 Vehicle Design Constraints

Several hard requirements were placed on the overall rover system for various reasons. The constraints fell into two main categories: size and mass. Both of these constraints are established mainly by the landing vehicle. The launcher/lander also impose additional constraints based on the launch environment.

3.4.1 Launch Vehicle

Although this design group could have investigated the possibility of using different launch vehicles, it was determined that the Russian Proton C Launch Vehicle would be used. This decision was based on the cost and its large payload capacity as well as the availability of a lunar lander design. In addition to size constraints that are dictated solely by the payload volume available above the lander, the loads felt by the rover in the launch vehicle will exceed any loads applied to the rover while operating on the moon. These loads are detailed in Table 3.2. The launch vehicle is shown in Figure 3.7.

3.4.2 Landing Vehicle

The Russian Phobos lander was chosen for similar reasons as the Proton Launch Vehicle. The design is baselined for the joint NASA/Russian Mars 96 mission, and should not be difficult to adapt for a lunar mission. The

TABLE 3.2 *Launch Vehicle Characteristics-Proton C*

Property	Value
Mass to LEO, 51.6° inclination	22,000 kg
Max. Axial Acceleration	+6 gravities
Max. Lateral Acceleration	+/- 3 g
Frequency Spectrum	unknown
Max Shock	2500 g @ 1500-5000 Hz
Cleanliness	Class 100,000

lander can deliver a total payload, including adaptor, of 600kg to the moon. The lander loads are lower than the launch loads, and are not design drivers. The lander can deliver the payload to within approximately 4.5 km of the designated landing location. The lander characteristics are detailed in Table 3.3. The lander is shown in Figure 3.7 and Figure 3.8.

TABLE 3.3 *Lander Characteristics-Phobos Lander*

Property	Value
Mass to Lunar Surface	600 kg
Max. Landing Position Error	4.3 km
Max. Landing Velocity	2 m/s vertical 1.2 m/s horizontal
Payload Center of Gravity Height	< 1 m
Deployment Ramp Angle	30°

As mentioned, the lander design can deliver 600 kg to the lunar surface.

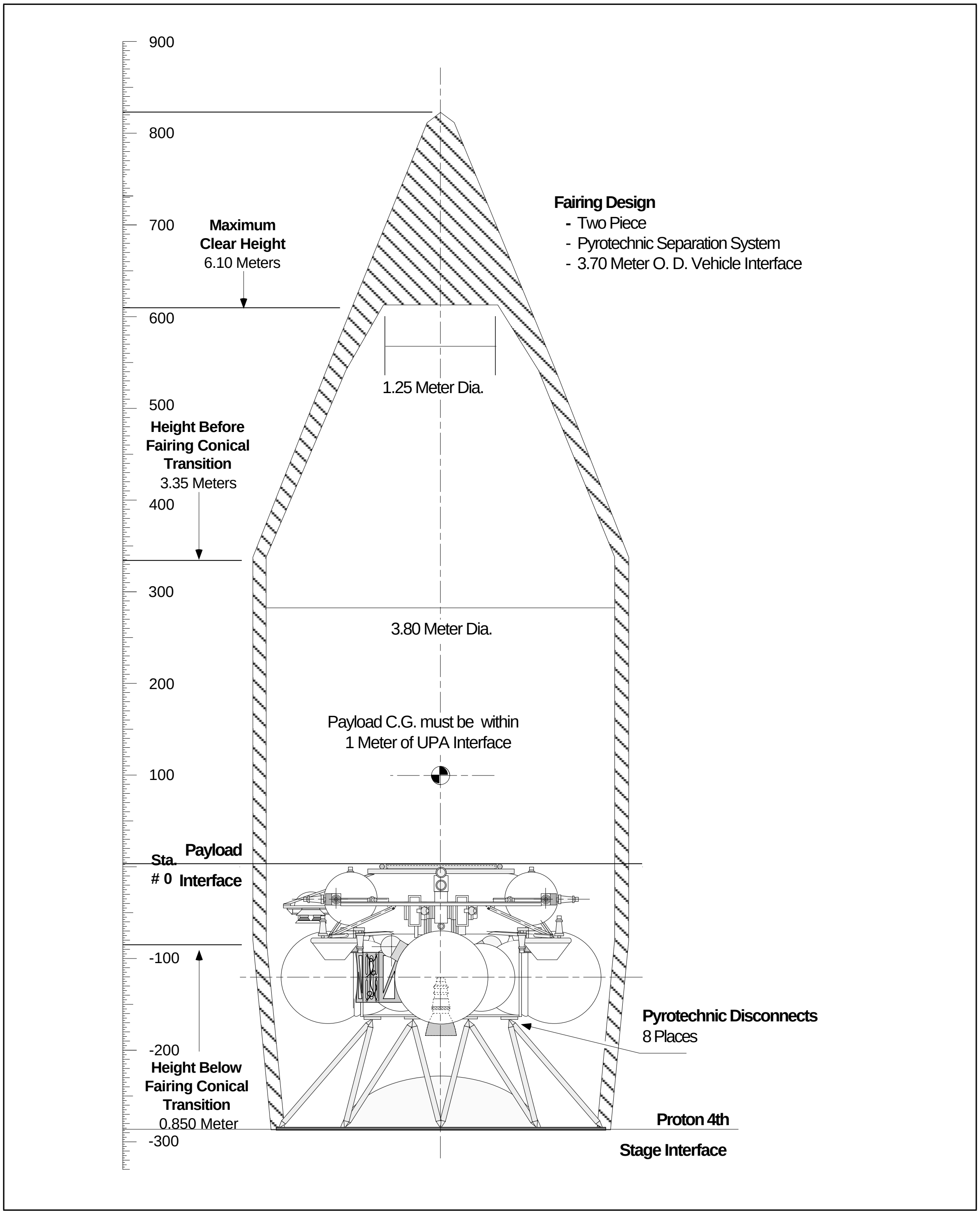

FIGURE 3.7 *Proton Launch Vehicle With Phobos Lander-Cross Section*

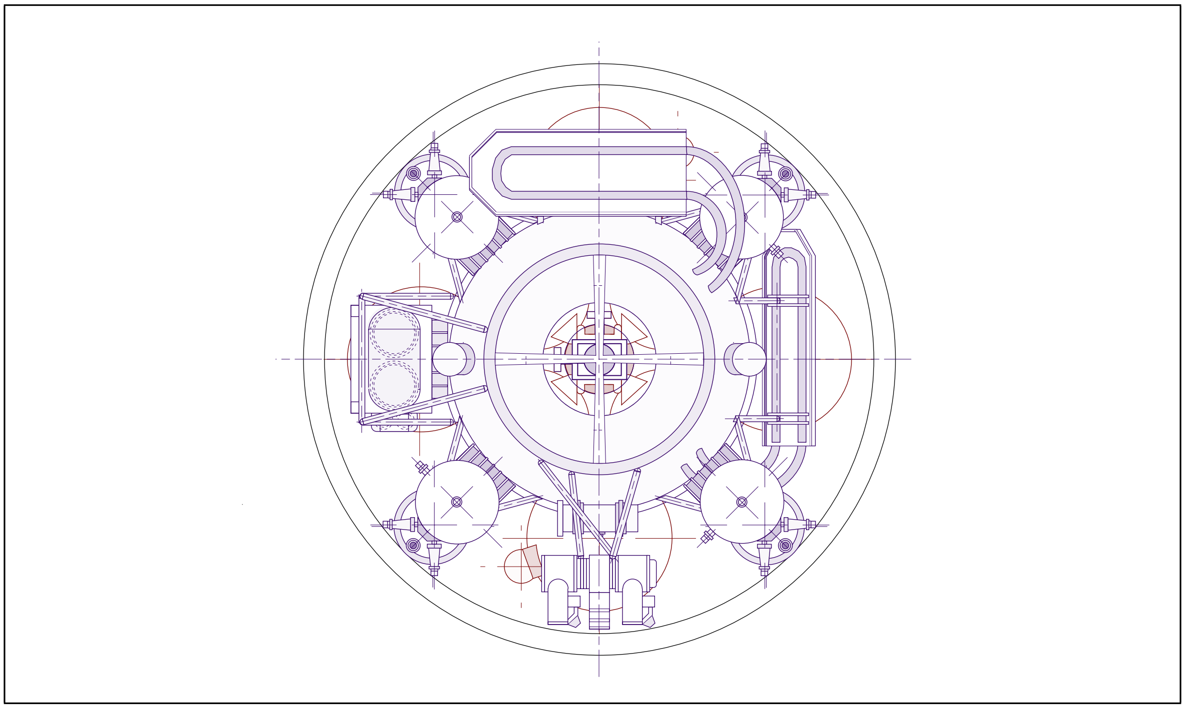

FIGURE 3.8 *Proton Launch Vehicle With Phobos Lander-Top View*

Chapter 4

Structures

The structure of the lunar rover mechanically supports all other systems, attaches the rover to the lander, and provides interfaces between the body and the locomotion subsystem. This chapter describes the structural design of the rover along with the failure modes and open issues.

4.1 Requirements

The design must satisfy all strength and stiffness requirements of the rover and its interfaces with the lander. The launch vehicle is the most obvious source of structural requirements, dictating the rover weight, geometry, rigidity and strength. Rovers should be able to sustain the launch loads and fit in the lander. The main structural requirements are:

- Protection from environment: The structure should be able to survive the lunar environment (extreme temperatures, vacuum and radiation) for at least 2 years.
- Interfaces with locomotion and lander.
- Accessibility to components inside: All the components inside the body should be accessible for pre-launch testing and replacement.
- Support rover components: The structure should support all components inside the body.
- Unobstructed view for cameras and sensors: Cameras and sensors require specific fields of view. The design should provide mounting location so that they are not obstructed by each other, other components or the structure itself.
- Low C.G.: The center of gravity should be as low as possible for stability purposes.
- Visually appealing: The rover should be visually appealing.

4.2 Structure Design

The structure consists of

- Lower Shell
- Upper Shell
- Structure for interface with lander and chassis

Figure 4.1 and Figure 4.2 show the structure of the rover.

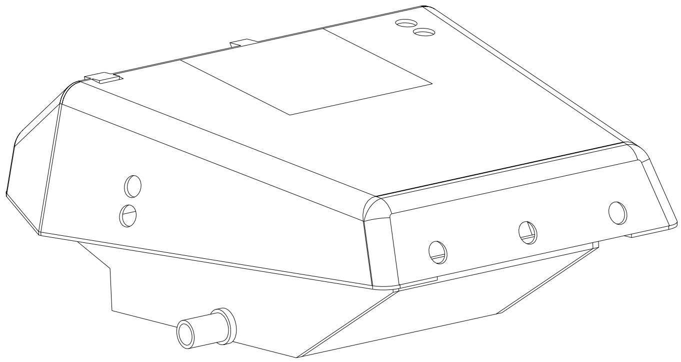

FIGURE 4.1 *Rover Structure*

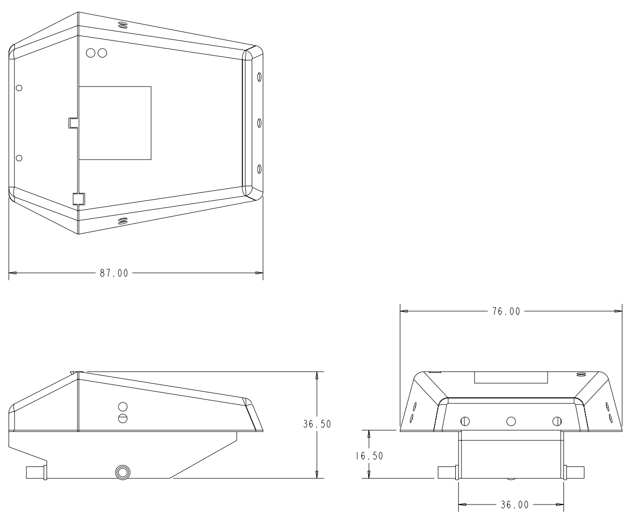

FIGURE 4.2 *3-View of Rover Structure*

The lower shell is the main structural component and consist of 1 inch Al honeycomb (Al core and Al face sheets) panels. Honeycomb (or sandwich structures) has exceptional strength to weight ratios and is extensively used in aerospace industry. Sandwich structures consist of a lightweight shear-resistant core bonded to outer face sheets (Figure 4.3). A sandwich panel acts like an I-beam. The faces correspond to the top and bottom flanges of the beam and resist in-plane bending, tension and compression. The core acts like the I-beam's web and reacts to shear and out-of-plane compression, while providing support for the face panels. Though face sheets and cores can be of nearly any metallic or composite material, Aluminium honeycomb is chosen due to availability and low cost.

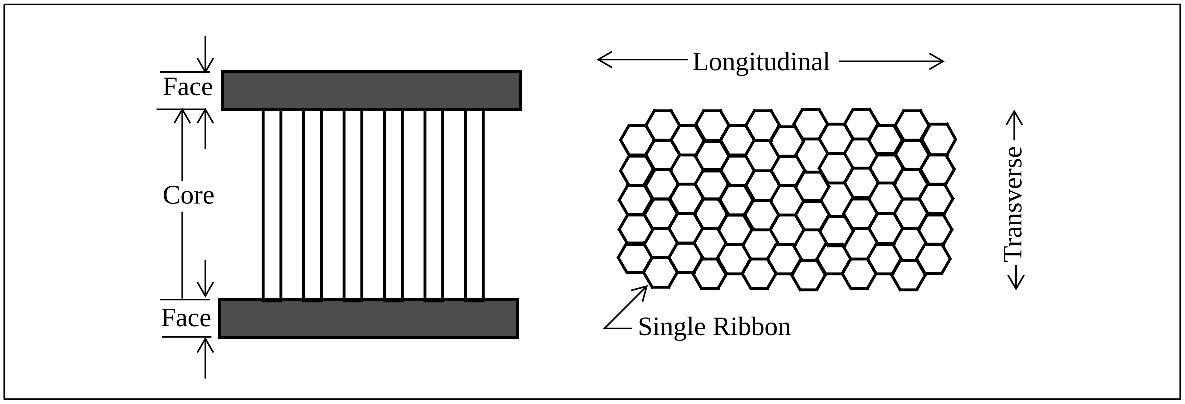

FIGURE 4.3 *Details of Sandwich Construction*

The upper shell is made of 0.5 inch honeycomb (Al core and Kevlar face sheets) panels. The upper shell is not a structural member and therefore may be thinner. Kevlar face sheets are selected because they are easy form and can provide an appealing facade to the rover. Coefficient of thermal expansion of Kevlar is similar to Aluminium and hence irregular thermal expansion should not be a problem.

The body is connected to the locomotion subsystem at three points using load bearing pins. The same pins are used for the interface with the lander. After landing the pins will be separated form the lander using pyro charges.

4.3 Design Features

An exploded view of the structural design is shown in Figure 4.4. The main features of this design are:

- Easy accessibility: All components inside can be easily accessed by taking the side panels off.
- Visually appealing: Upper shell is not structural and can be shaped to improve visual appeal.
- Easy manufacturability: Lower shell is made of flat sandwiched panels and is easy to manufacture using proven techniques.
- Low C.G.: Heavier components like power system and electronics are mounted on bottom of the lower shell, thus keeping the C.G. low (25 cm from center of pin; overall C.G. 0.7 m from ground)
- Efficient radiation: The structure provides enough area for both thermal radiators to be located on the top of the rover.

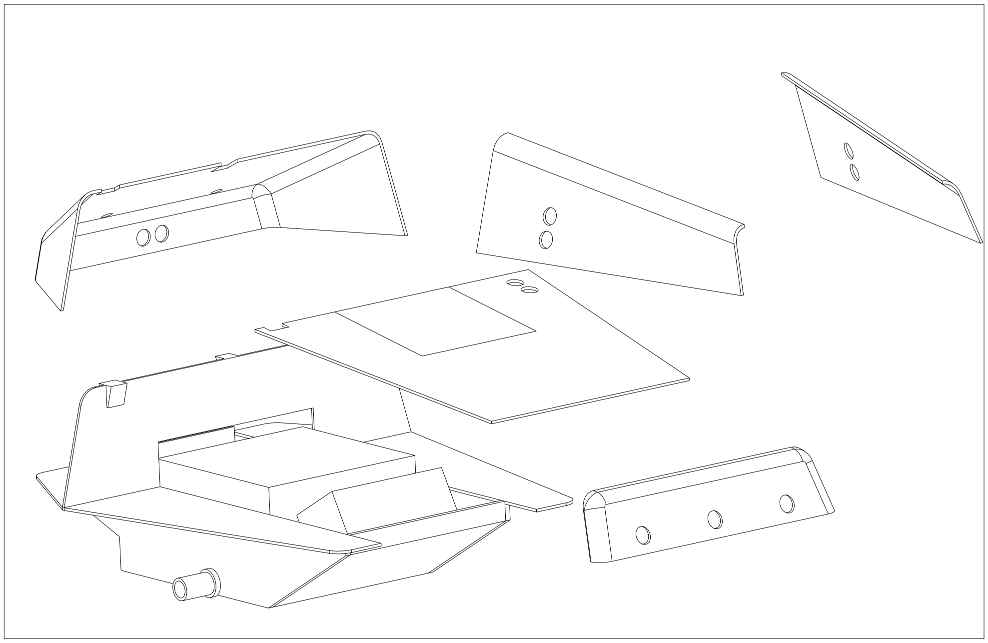

FIGURE 4.4 *Exploded View of Rover*

4.4 Failure Modes and Reliability

Table 4.1 shows the potential failure modes for the structure.

TABLE 4.1 *Failure Modes*

Component	Failure Mode	Effect	Prevention and/or Response	Criticality
Rover-Lander Interface	Failure of separation device (pyro charge, etc.)	Rover would not be able to separate from lander: Mission Failure	Redundant pyro-charge Extensive testing before launch	1
Rover-Chassis Interface	Mechanical failure of interface pins	Chassis would be separated from the body: Mission Failure	Appropriate factor of safety Extensive testing before launch	1
Irregular Thermal Expansion	Upper shell and lower shell may have irregular thermal expansion	Components may be directly exposed to the lunar environment	Choose materials with similar coefficient of thermal expansion (ex: Aluminum and Kevlar)	2

4.5 Open Issues and Future Work

- Detailed analysis (finite element) with different loading conditions
- Communication interfaces during launch
- Address failure modes
- Decrease mass (better composites)
- Micro-meteorite protection
- Radiation shielding

4.6 Summary Budget

Table 4.2 shows the mass budget for the structural components of the lunar rover.

TABLE 4.2 *Mass Budget*

Component		Unit Mass [kg]	# of Units	Total Mass [kg]
Upper Shell	Wingbase	2.22	2	2.45
	Hood	2.06	1	2.06
	Shell_Rear	4.25	1	4.25
	Shell_Sides	3.21	1	3.21
	Shell_Nose	1.15	1	1.15
Lower Body	Side	6.74	2	13.48
	Front	0.73	1	0.73
	Bottom	9.59	1	9.59
	Front_Angle	6.01	1	6.01
	Rear	2.7	1	2.7
	Rear_Angle	3.21	1	3.21
Interface	Rocker bogie Pins	2.27	3	6.8
Fasteners		25% of body mass		13.91
Total				**69.55**

Chapter
5

Locomotion Subsystem

The configuration and design of the locomotion system for the lunar rover must be responsive to the requirements of a two year, one thousand kilometer traverse across the lunar landscape. For much of this journey, the terrain will be benign and will not tax the structural or functional capabilities of the rover. The most interesting areas of the moon outside of the Apollo sites, however, are also the most challenging for the locomotion system. In the vicinity of craters, for example, the rover will find deep lunar soil, steep slopes, and relatively large obstacles to avoid or conquer. These are the occasions which truly determine the performance that the rover must show to successfully complete its mission.

5.1 Requirements

From the terrain and overall mission requirements, five general requirements have been identified as targets for the design of the locomotion system of the rover:

1. maintain stability
2. limit excursions of the rover body
3. enable terrainability
4. develop mechanical robustness
5. limit penalties on the system as a whole

This design examination begins with a presentation of examples of rover vehicles which provide precendences from which the design of the rover is drawn. Form giving analyses such as an examination of wheel sinkage are presented here, but most of the design and its references to these requirements are presented in a qualitative manner with a detailed analysis to be completed during future studies and development of the rover.

Requirement #1 drives the dimensioning of the wheels, particularly the wheel diameter. A worst case terrain situation has been identified to be a slope of 35° with a 25 cm obstacle. This provided a target for much of the analyses performed. The analyses will describe design spaces from which useful sets of parameters can be chosen.

Requirements #2 and #3 are discussed as they relate to the relevant rovers. These requirements drive the geometry of many of the locomotion system's elements. Appropriate adjustment and detailing of some of these dimensions is left to future work.

Requirements #4 and #5 are defined to drive the compatibility of the locomotion system with the mission and with the rest of the rover subsystems. The development of mechanical robustness calls for a design which is mechanically simple and reliable. Limiting penalties on the rover is defined to minimize the needs of the locomotion system's mass, volume, and power.

The locomotion system is divided into five design elements: chassis and suspension, steering, driving, wheel, and safety designs. These elements are chosen from several examples of relevant precedences including the Soviet rovers Lunakhod I and Marsakhod, the Apollo 16 LRV, and JPL's Rocky 4. These examples and the development of rationale for the rover choices are presented below. Following these qualitative choices is a presentation of the design and the quantification of selected parameters.

5.2 Locomotion Configuration

5.2.1 Chassis and Suspension

Relevant Examples

Lunakhod I

The primary elements of the Lunakhod chassis are four aluminum alloy wheel modules, each with two arms pivoting around curved I-beams onto which drive units are mounted. The main instrument compartment serves as a base to which these modules are mounted. Terrain following is accomplished through a suspension system using elastic torsion members.

LRV

The LRV chassis is constructed of 2024 aluminum alloy tubing connected to joints by welding in a "strut and node" arrangement. Aluminum (2219-T81,T87) arms connect the wheel units to the frame and provide suspension through Cr-Mo-V heat treated steel torsion bars and steel viscous dampers.

Marsakhod

The Marsakhod chassis is made up of three actively articulated sections onto which the wheel modules are directly attached. These articulations can be controlled to cause the wheels to directly follow the ground.

Rocky 4

Rocky 4 includes an aluminum alloy body with a passive linkage system made of square aluminum alloy tubing. Wheel and mounting fixtures are welded. This "rocker-bogie" suspension system contains no elastic elements except for the wheels.

Lunar Rover

Description

The MRD 95 rover employs the same "rocker-bogie" suspension system that is seen on Rocky 4. The rocker and bogie links will be made from thin walled aluminum alloy tubing welded to aluminum housings for pivots and actuators. These sections will be designed to take advantage of the high strength to weight ratios typical of tubular structures.

Rationale

The key to the success of any wheeled locomotion system is that adequate traction is always maintained. The Lunakhod and LRV each use an elastic suspension system to accomplish the task of keeping the wheels on the ground to ensure traction. But since the force provided by these elastic suspension members changes as their deflection changes, a characteristic of such systems is the uneven amount of normal force imparted to the ground by each of the wheels. Since traction is directly related to this normal force, the traction of these systems is also uneven and unpredictable on uneven terrain.

The Marsakhod rover does a better job of properly distributing the normal force throughout the wheels to guarantee traction through active articulated body motion. This system can in fact distribute weight unevenly if that is what the situation requires. Because of its articulated body, however, this system would be difficult to implement because much of the current design relies on the idea of central environmental control. The Marsakhod system also becomes difficult to implement at the higher speeds expected of this rover.

The rocker-bogie suspension implemented on Rocky 4 is the best candidate for the lunar rover. The primary reason this type of suspension is appropriate is its characteristic of creating a nearly equal normal force at each wheel, regardless of position. For example, with a typical elastic suspension, a leading wheel perched on a rock would cause a reduced normal force at the center wheels and thus reduced traction from those wheels. This can decrease the obstacle climbing capabilities of the rover. Since the obstacles that the rover is expected to encounter and surmount are fairly large - on the order of the size of the wheels - this loss of capability is not acceptable.

Also particularly importantly to the lunar rover design is the “body averaging” kinematics of the rocker-bogie suspension system. In equalizing the forces at the six wheels of Rocky 4, the suspension system also minimizes the excursions of the body. In short, the vertical displacement of the geometric center of the vehicle is the average of the vertical displacements of the wheels. for example, if two wheels move up seven centimeters, two move down three centimeters, and one moves up four centimeters, the body moves a total of 2 cm. Similar effects occur for pitch and roll. With the communications requirements playing a major part in the design, this averaging is particularly important since whatever “smoothing” of the terrain the locomotion system can do is that much less that the communication system must account for.

Adjusting the relative sizes of these links and thus the spacing between wheels can profoundly affect this averaging motion. Because this can imply a change in wheelbase as well, these sizes can also affect other aspects of the rover’s terrainability. Presented here is a system with equal length links which may be adjusted in the future to more exactly accommodate the lunar terrain.

5.2.2 Steering

Relevant Examples

Lunakhod I

Lunakhod I is an eight wheeled, skid steered rover with the ability to point turn.

LRV

The steering system of the LRV functions much the same way as a regular automobile, times two. It includes Ackerman steering at the front *and* the rear and is steered by two steering actuators (one for the front two wheels, one for the rear two) working trough a six bar linkage.

Marsakhod

Marsakhod can employ skid steering of its six wheels, angle its body sections to change heading, or actually use its body articulation actuators to “walk” without the help of its wheel motors.

Rocky 4

Four of the six of Rocky 4’s wheels are explicitly and individually steered while the middle two are fixed in a forward direction. This enables Rocky 4 to accomplish point turns with no slippage.

Lunar Rover

Description

A four wheeled explicit steering system is chosen for this rover, with the four corner wheels explicitly steered about their vertical centers and the middle two wheels fixed in a forward position. This steering system is much like the Rocky 4 system and is consistent with the reasoning behind the selection of this type of suspension system. The most compelling argument for the chassis and suspension system design choice is its characteristic of passively maintaining traction on all of the wheels. This philosophy is extended to the steering system in that the four-wheeled explicitly steered vehicle maintains the best traction. The result is a vehicle with the best possible performance.

Rationale

The Ackerman steering system of the LRV is appropriate for the relatively high speeds at which the vehicle travels. But these speeds were only practical because the astronauts were right on board steering the vehicle, and thus they were able to react quickly to any trouble that might be in the path of the rover. When the rover did get stuck at one point, the astronauts were able to get out of the rover, move it to a better location, and resume their traverse. The lunar rover is teleoperated and does not have the response time advantage of on-board high-level navigation (humans) that the LRV does. It would also be unable to rescue itself from a trapped position as the LRV was. These considerations enforce different requirements on smaller, slower system.

To combat the difficulty of getting into dangerous situations, the rover must be more maneuverable than the LRV. Even with its double Ackerman steering, the turning radius of the LRV is approximately equal to the length of the machine. If a differential “skid” steering system is employed on the lunar rover, this radius is essentially zero length - the space required to turn is only the cylinder circumscribed by the rotation of the machine about its geometric center. Stuck without the help of an astronaut’s hand, this ability is an important escape characteristic.

Additional advantages of a pure skid-steering system, the same used on Lunakhod, include the relative small number of parts as compared other systems. Since steering is accomplished entirely from control of the velocity of the driving systems, the “steering system has *no* moving parts and actually *no* additional “parts” at all.

Two problems arise, however, in the practical implementation of the pure skid-steering system. The first is the inefficiencies associated with driving wheels in a direction which is not tangent to their motion. From this, two logical choices for this configuration arise: to steer two of the corner wheels, or to steer all four of the corner wheels. The torque requirements placed on the wheel actuators is more than three times as high for a skid steered vehicle as it is for a vehicle with two explicitly steered wheels. And this requirement drops significantly again if four wheels are explicitly steered. In fact, on level ground, the forces on the locomotion system in a properly oriented point turn are approximately equal to slow, straight driving.

The second problem is the loss of traction that occurs during a point turn. As discussed previously, it is traction which ensures the success of a wheeled system, but inherent in the skid-steering system is the breaking of traction whenever a turn of any kind is executed. If the rover is placed on a slope, this traction loss will translate into the rover sliding down the hill during a turn. The more traction is lost, the less able the rover is to retain its position during a turn. This loss of traction leaves a purely skid-steered vehicle with a sloped turning ability of almost half that of a two wheel steered rover. An additional penalty is the power loss associated with pure skid steering due to these inefficiencies.

5.2.3 Drive

Relevant Examples

Lunakhod I

The lunakhod chassis and suspension connect to the wheel through a three stage planetary gear set driven by a brushed d-c motor. This in-line (series) reducer has an 85% efficiency and is made of self-lubricating materials including steel alloys. An electrodynamic retarder provides braking force through single titanium disk.

LRV

The LRV drive system includes four 184 W d-c series wound motors located at each of the four wheels. These actuators connect to the wheel through a harmonic drive reducer and are slowed with drum brakes.

Marsakhod

The Marsakhod drive system includes components similar to those in the Lunakhod rover, located at each of its six wheels.

Lunar Rover

Description

The rover will use the same type of in-line reduction drive system located at each of its six wheels as is shown on each of the previous examples. The LRV shows that harmonic drive can be compatible with the lunar requirements. Coupled with a brushless d-c motor, this compact package is the best choice for the lunar rover.

Rationale

Despite the repeated precedence of distributed drive systems shown on the above examples, a centralized drive system was first considered. This type of system, however, was determined to be inappropriate because a point failure had the possibility of disabling two, three, or even all of the wheels, crippling or immobilizing the rover. Mechanically distributing this torque to the wheels through the links of the suspension also presents difficulties in that this distribution tends to rotate the links about their pivots when large torques oppose the rotation of the wheels. The already difficult problem of sealing against the abrasive lunar dust is also magnified in the need for a greater number of seals. These difficulties are reduced or solved by placing the motors directly at the sites where they are needed - the wheels. One difficulty with placing the motors at the wheels is the need for distributing the temperature regulation system as well. As shown on the Lunakhod, coatings can work effectively at the lunar daytime temperatures. Additional systems such as localized heaters might be required for operation during the lunar night.

5.2.4 Wheel

Relevant Examples

Lunakhod I

The Lunakhod wheels consist of three rims, each connected to the hub by sixteen spokes. Wire mesh forms the tires of the vehicle with sixteen grousers aiding in traction. Wheel diameter is 0.51 m, wheel width is 0.20 m, and grouser height is approximately 0.02 m.

LRV

Zinc plated piano wire is woven to form an elastic mesh for the tires of the LRV. At a smaller diameter inside these tires is a titanium bump stop which is connected to a rigid aluminum alloy hub. Titanium grousers are arranged in a chevron pattern around the circumference of the tire to aid in traction and provide a coverage of approximately 50%. Wheel diameter is 0.82 m, wheel width is 0.23 m, and grouser height is approximately 0.01 m.

Marsakhod

Thin titanium sheet metal is formed into the rigid shape of a cylinder joined with a cone. This shape lifts the vehicle in stiff soil, reducing tire-print size and increasing driving efficiency, but sinks to provide expanded tire-print area for support in soft soils. Wheel diameter is 0.35 m, wheel width is 0.40 m, and grouser height is approximately 0.03 m.

Rocky 4

Rocky 4’s wheels are made of stainless steel in a structurally elastic shape which is soft in radial deflection but stiff in the tangential and axial directions. Sixty-four rows of ten lugs replace the grousers seen on the other examples, increasing flat driving efficiency while retaining obstacle climbing ability. The wheel dimensions are a 0.13 m diameter and a width of 0.07 m.

Lunar Rover

Description

An elastic mesh wheel of titanium alloy or plated steel alloy will be used as the “tire” of the rover. This mesh will be stiff enough to retain most of the stability of the Marsakhod or Lunakhod non-elastic wheels, but will provide some of the shock absorption and conformability useful for the LRV and Rocky 4. This mesh is attached to an aluminum alloy hub which is connected to the reduction unit and motor, with the single seal of the entire wheel assembly formed between the hub and the motor housing. Also connected to this mesh tire are several grousers providing an effective ground coverage of 2/3.

Rationale

A question inherent in the above examples is whether or not elasticity should be included in the system at any point. Elastic suspension elements have been ruled out of the suspension design for reasons relating to traction as discussed previously. For the excursions which the suspension is designed to accommodate, the useful range an appropriately sized elastic mechanism is likely to have is much smaller than the range of the link suspension itself. But both the LRV and Rocky 4 have elastic elements included incorporated in the design of the wheels. For LRV this serves the purpose of damping the vibrations of a higher velocity ride. For Rocky 4, the elastic wheels ensure that a point contact is never relied on to lift the vehicle over an obstacle - the wheel deforms slightly to grip more of a corner before attempting to lift the body over. This can also act as a shock absorber to cushion an impact to an object which does not gently lift the suspension up as intended.

The dimensions of the wheels themselves must be determined to be effective for several different criteria for the lunar rover. These criteria include obstacle crossing, ditch crossing, and stability margins. These and other criteria are the subjects of future research on the design rationale for this rover. What can be taken as a minimum for this study, however is the size wheel necessary to create the necessary ground pressure and limit sinkage to an appropriate depth to ensure the mobility of the rover. Analyses in the following section determine this size. The appropriate height and frequency of grousers is left to future analyses.

5.3 Locomotion Design and Analysis

5.3.1 Locomotion Subsystem

The locomotion system design for the MRD 95 rover is shown below.

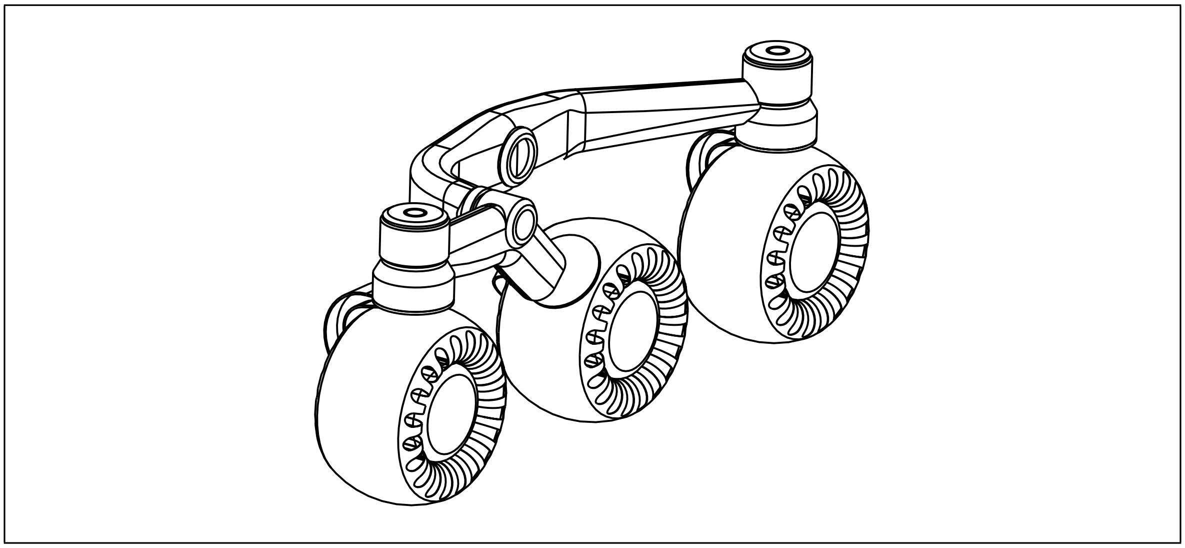

FIGURE 5.1 *Locomotion Subsystem*

Sizing of Elements

Several elements of the locomotion system have been identified for preliminary analysis to ensure overall functionality of the locomotion system and appropriate interfacing with other rover systems. Such elements include gross wheel sizing, actuator sizing, and geometric clearances. With these elements sized appropriately, a first cut at the locomotion design can be completed. Several other parameters describing geometries and requirements internal to the locomotion system can be calculated after this first cut to improve rover performance with little effect on the overall design or on other rover systems.

Tire Diameter and Width

Two factors affect the first-order sizing of the wheels. The first of these factors is the stability of the rover on maximum terrain. The wheelbase is assumed to completely fill the length of the machine, thus, the larger the wheel diameter, the smaller the wheelbase. For this design, static stability is determined for the worst case slope condition and a maximum acceleration vector is added as a transformation to a dynamic case. This is shown below with all of the weight of the rover being supported by the rear wheels - the condition at the threshold of stability. With this threshold considered as the point where the center of gravity of the machine crosses above the rear wheels' point of contact, the following relations describe the margins for tipover:

$$\phi + \theta = \operatorname{atan}\left(L - \left(2\left(D/2\right)\right)/2h\right) \quad \textbf{(Equation 5.1)}$$

Where the variables refer to the figure above. From geometry:

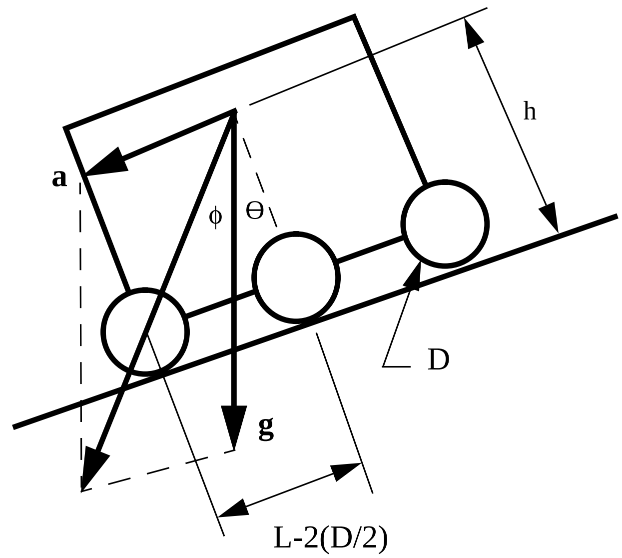

FIGURE 5.2 *Rover Stability*

$$\sin\phi / \sin((\phi + \theta) - 90) = -a/g \qquad \textbf{(Equation 5.2)}$$

Combining these two equations and assuming h to be 0.75 m, L=2.0 m, and g = 9.81/6 m/s^2 yields the following function:

$$a = -1.635 \sin(\beta - \theta) / \sin(\beta - 90) \qquad \textbf{(Equation 5.3)}$$

$$\beta = \operatorname{atan}((2 - D)/1.5) \qquad \textbf{(Equation 5.4)}$$

Figure 5.3 shows the angle slope which is safely traversable at a range of accelerations given a range of possible wheel diameters. This assumes the height of the center of gravity to be 0.75 m from the ground, a reasonable value considering the low location of most of the heavier components of the rover.

If a safety margin of 5° is added to the slope, this shows the rover accelerating to full speed in 4 seconds (0.25 m/s^2) to be stable at an angle of approximately 33° with a wheel diameter of 0.50 m.

The second design factor contributing to the sizing of the wheels is the ground pressure necessary for adequate functioning of the rover. After an examination of Lunakhod I's performance on the lunar soil, the Soviet designers determined that 3 kPa would provide the needed support for lunar vehicles (in some situations Lunakhod I sunk as much as 0.20 m at two to three times this value) and should be used as a design target for future lunar missions. This ground pressure, however, is dependant on sinkage of the wheels into the lunar soil. Bekker's model for sinkage in soft soils yields the following relations.

$$z = [3Wt/(3-n)(Kc + K\varphi Wc)\sqrt{D}]^{2/(2n+1)} \qquad \textbf{(Equation 5.5)}$$

where: W = load per wheel = (250kg)(9.81m/s^2)(1/6<g>)(1/2 <wheels>); Kc = cohesive modulus lunar soil deformation =0.14 N/cm^2; K_{psi} = frictional modulus of soil deformation = 0.82N/cm^2; n = exponent of soil deformation = 1; c = coverage of wheel = 2/3. This reduces the expression to:

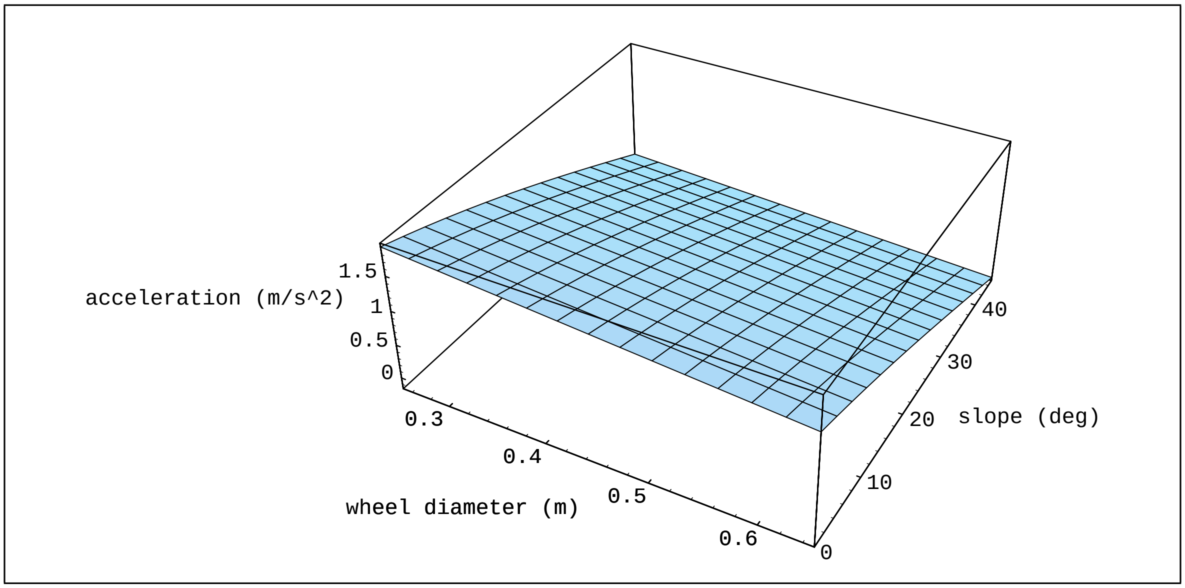

FIGURE 5.3 *Rover Acceleration Possible as a Function of Wheel Diameter and Slope*

$$z = [936.4/D(0.14 + 55W)^2]^{1/3} \qquad \textbf{(Equation 5.6)}$$

Included in these calculations is the assumption that the rover is supported by only two of its six wheels (the case at the tipover threshold described previously) and that the wheels provide only 2/3 coverage (therefore the effective width of the wheel is taken as 2/3 the true width). Figure 5.4 shows the relation between wheel width, diameter, and sinkage.

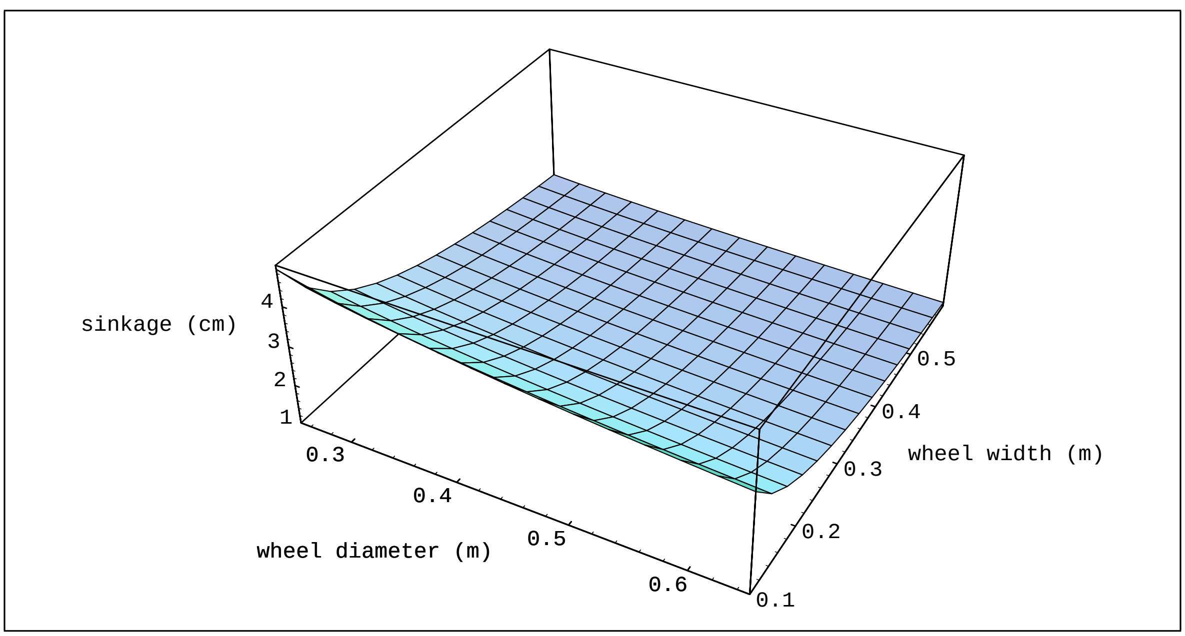

FIGURE 5.4 *Wheel Sinkage as a Function of Diameter and Width*

Again choosing a diameter of 0.50 m and a width of 0.30 m, Bekker's model predicts a sinkage of approximately 2 cm.

Checking the ground pressure provided by such a configuration is accomplished through the following relations based on Agekin's wheel model where pressure is determined as a function of width, diameter, and sinkage. A schematic of a wheel is shown in Figure 5.5.

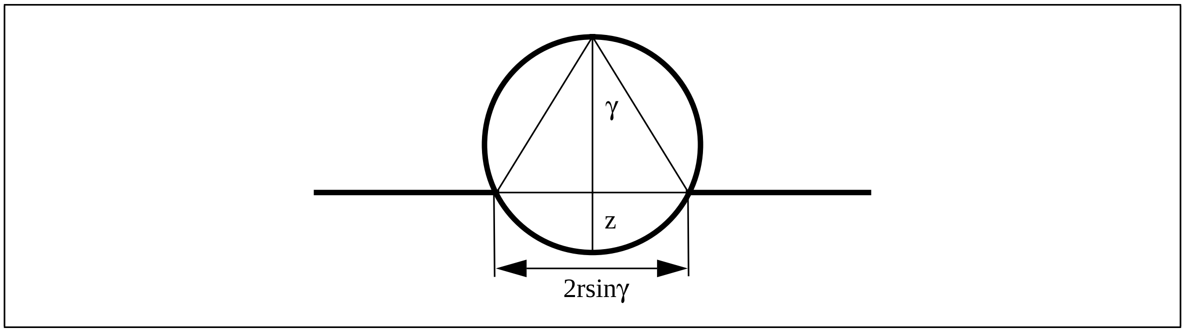

FIGURE 5.5 *Wheel Sinkage*

$$Pr = Wt/WcD\sin\gamma \quad \textbf{(Equation 5.7)}$$

where:

$$\gamma = \operatorname{acos}(1-(2z/D)) \quad \textbf{(Equation 5.8)}$$

When combined with the sinkage value of 2 cm, these equations become:

$$Pr = (0.408/m)/WcD\sin(\operatorname{acos}(1-(0.04/D))) \quad \textbf{(Equation 5.9)}$$

where m is the number of wheels considered as support. Assuming a best case of even support by all six wheels, Figure 5.6 was generated.

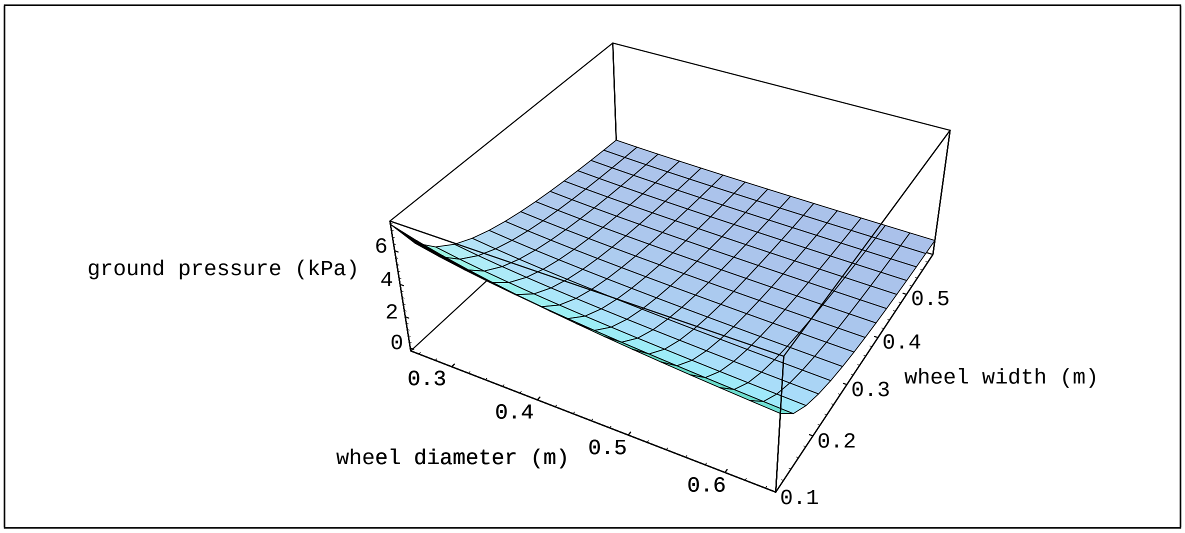

FIGURE 5.6 *Ground Pressure as a Function of Wheel Diameter and Width (Rover Supported by All 6 Wheels)*

Assuming a worst case of support by only the two rear wheels, as in the case of climbing a slope close to tipover, Figure 5.7 was generated.

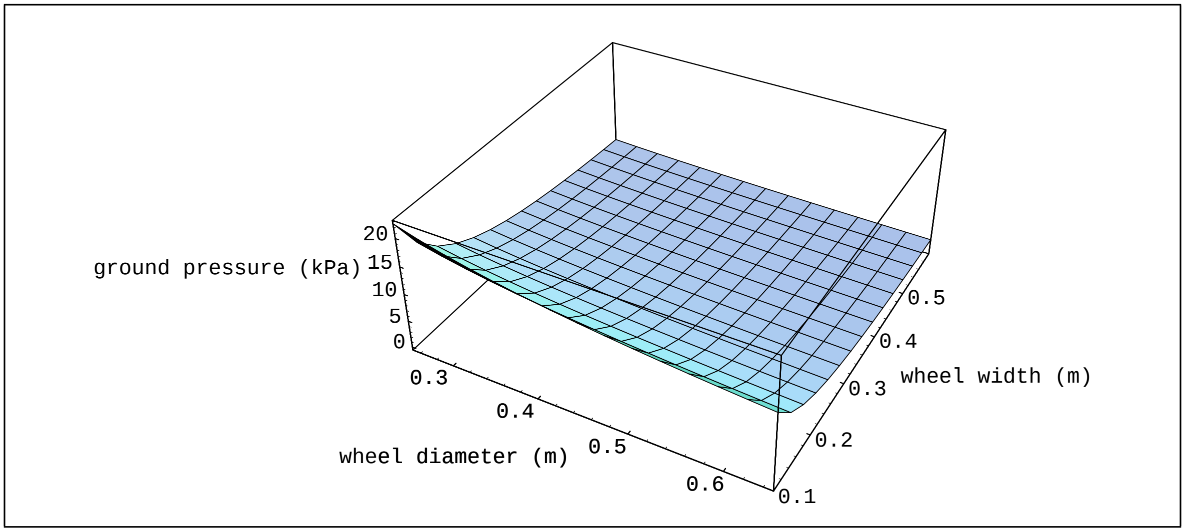

FIGURE 5.7 *Ground Pressure as a Function of Wheel Diameter and Width (Rover Supported by 2 Wheels)*

For the 0.50 m wheel, a width of 0.30 m provides much better than the suggested 3 kPa ground pressure for flat driving and sinks to about 6 kPa on the steep slope. Since much of the rover's traverse will take place on more gentle slopes, the dexterity lost by the relatively high ground pressure at the highest slopes is unlikely to greatly affect the mission. And the rover can still expect moderate performance at these pressures.

Many other terrainability factors affect the sizing of the wheels for the rover which are beyond the scope of this report. Those presented here show conflicting directions for the sizing of the wheels - stability drives the diameter toward a minimum while ground pressure gains from maximization. What has been shown here represents a design space from which a viable solution can be chosen. For the lunar rover, this solution includes a wheel diameter of 0.50 m and a wheel width of 0.30 m, allowing an acceleration time to top speed of 4 s (0.25 m/s^2) on a slope of 33° with sinkage of approximately 2 cm.

Actuators and Power Draw

The examples of the Soviet and American rovers and JPL's rocker bogie machine show that useful actuator - reducer units can be designed for mission requirements similar to those for the lunar rover in a physical space which do not define the design of the wheels or other locomotion elements. What the sizing of the actuators does affect, however, is the power budget for the locomotion system. A slope and acceleration of 33° and 0.25 m/s^2 is used to size these actuators. Since the design of the rover includes four steering actuators, all wheels can be properly oriented in directions tangent to the vehicle's motion so turning does not require the power that a skid steered system does. Aside from a slight change in soil losses, the power draw for turning will be approximately equal to that required for straight driving. Thus the following relations show the requirements the actuators place on the power system. Referring again to Figure 5.2 on page 44 the torque required from the rover's locomotion is found to be:

$$T = 0.5DM(a + g'\sin\theta) \quad \textbf{(Equation 5.10)}$$

which at a top speed of 1 m/s and lunar gravity g' of 9.81/6 gives:

$$Power = 39.8a + 64.9\sin\theta \qquad \textbf{(Equation 5.11)}$$

Figure 5.8 shows the relationships between power draw, angle of slope, and acceleration. It includes an overall efficiency factor of 50% and an additional 20% allotted for the four steering actuators.

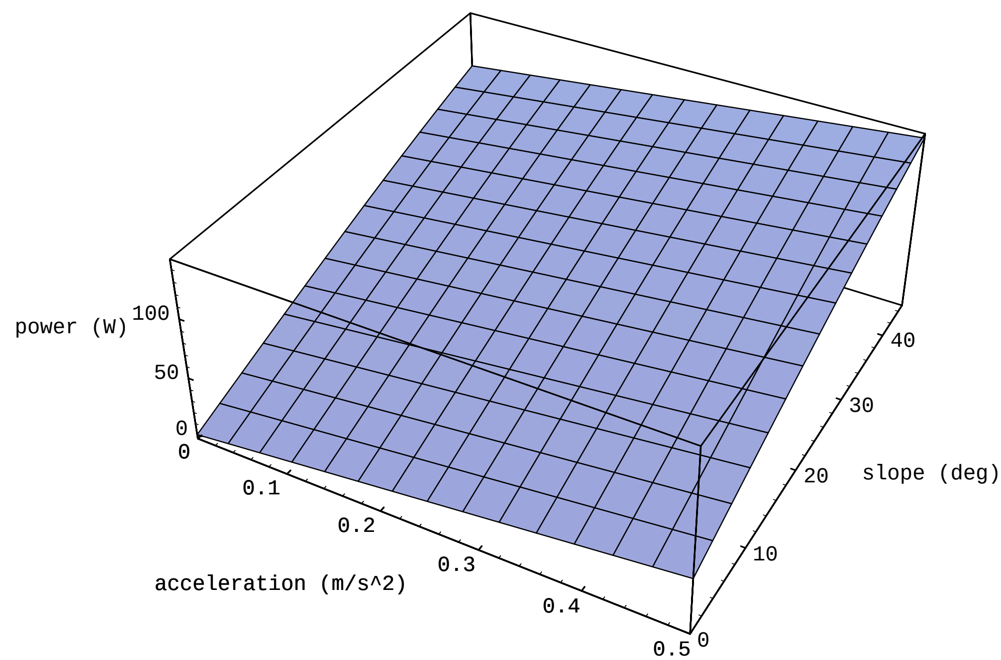

FIGURE 5.8 *Power Required as a Function of Acceleration and Slope*

For example, an acceleration of 0.25 m/s^2 up a 33° slope gives a power draw of approximately 100 W.

Locomotion System Mass

The design shown has been calculated through solid modeling to have a total mass of 75 kg. The linkages are constructed of thin-walled aluminum alloy tubing welded to bearing housings at pivot points and actuator housings at the steering and driving actuators. Actuator-reducer systems have been specified at 5 kg for driving and 3 kg for steering, values consistent with previous lunar missions. An appropriate budget for bearings has also been specified. An approximation for wheels has also been shown and is consistent with a scaled version of the wheels used on Apollo's LRV, the closest match to the wheel design of the rover.

Clearances

Calculating system width clearance from the specification of wheel width shown before and an additional allowance for the width of the linkages (0.20 m per side) gives a space approximately 0.80 m wide underneath the body. Body height clearance is specified as equal to the wheel diameter. With the diameter and sinkage calculated previously, the rover will have the ability to pass over an obstacle nearly equal to the height (diameter) of the wheels.

5.3.2 Mass Power and Volume Budgets

Mass

Table 5.1 shows the physical breakdown of the mass contributions of each of the locomotion subsystem parts.

TABLE 5.1 *Mass Budget*

Component	#	Part Mass [kg]	Total Mass [kg]
Large link	2	5.5	11.0
Small link	2	3.4	6.8
Averaging link	1	1.8	1.8
Wheel housing	6	2.6	15.6
Fender	6	0.2	1.2
Wheel	6	0.6	3.6
Steering actuator	4	1.4	5.6
Driving actuator	6	3.4	20.4
Reducer	10	0.9	9.0
			75.0

Power

Previously power draw was shown as a function of acceleration and slope angle. For calculating the power budget for the locomotion system, the acceleration is set fixed at zero to give the requirements at a constant velocity. Given wheels of the designed dimensions, Table 5.2 shows the power draws that will occur at the slope angles shown.

TABLE 5.2 *Power Draw*

Slope Angle [deg]	Power Draw [W]
5	13.6
10	27.1
15	40.4
20	53.4
25	65.9
30	78.0
35	89.5
40	100.3
45	110.3

Volume

To allow for excursion of the linkage system during obstacle climbing, clearance above the links must be included as part of the locomotion system volume. A target obstacle size of 0.25 m has been identified as sufficient for most of the lunar terrain in the analyses of the December Edition of the LRI Configuration Group's report. Combining obstacle height, linkage kinematics, body motion, and sinkage yields a necessary volume of $1m^3$ - approximately twice the overall volume of the locomotion system in its resting state.

5.3.3 Safety

Relevant Examples

Lunakhod I

Emergency explosive disconnecting bolts allow free spinning of the wheels if the drive system is damaged and not functional.

LRV

Emergency disconnects are manually operated by the astronauts.

Lunar Rover

In addition to the emergency disconnect at the drivers in the case of a drive motor failure, the rover will have two additional safety elements built in to the design of the locomotion system. The first is a specialized disconnect for the four actuators which steer the corner wheels. If one of these actuators was to fail at an angle which was not consistent with the direction of travel of the rover, this sideways wheel would greatly affect the performance of the rover, especially the power draw. Therefore the emergency disconnect on the steering actuator will also include a “pin” which locks the wheel in the forward direction in the case the emergency disconnect is activated. This will ensure that the disabled wheel will at least be turned in the primary traveling direction.

The second possible safety element is an additional actuator to help the rover in the case of high centering. If an actuator is placed at some point on the averaging linkage of the rover, this actuator could move the rocker-bogie systems into a position to improve traction enabling escape from the situation. During normal operation this actuator would be idle.

Chapter

6

Power System

6.1 Requirements

- The rover power system must deliver 520 watts of electrical power.
- Continuous power, including that for night operations, must be provided over full mission duration.
- The generated power must be distributed throughout the rover to all subsystems.
- Peak power needs of various scenarios must also be addressed.
- Power must not be generated by fissionable sources.

6.2 Interfaces

Figure 6.1 shows a subsystem block diagram for the power subsystem. The diagram also shows the flow of energy throughout the system. All items in the drawing are at least singly redundant.

The basic design of the subsystem utilizes a beta-decay gas to provide a large amount of heat. This heat will be converted to electricity, which will then be distributed throughout the rover. No batteries are utilized in this design.

6.3 Power Source

A Krypton-85 heat source and Alkali Metal Thermal to Electric Converters (AMTEC) are specified for the rover design to enable operations throughout the lunar night, but without the regulatory and environmental concerns attendant with plutonium. A developmental Kr85 power source design has simplified the envisioned rover by providing numerous technical benefits in conjunction with social and environmental advantages over other continuous power sources. One benefit of a Kr85 based power system over a standard system consisting of solar cells and batteries is the ability to operate continuously during the lunar day and night without the need

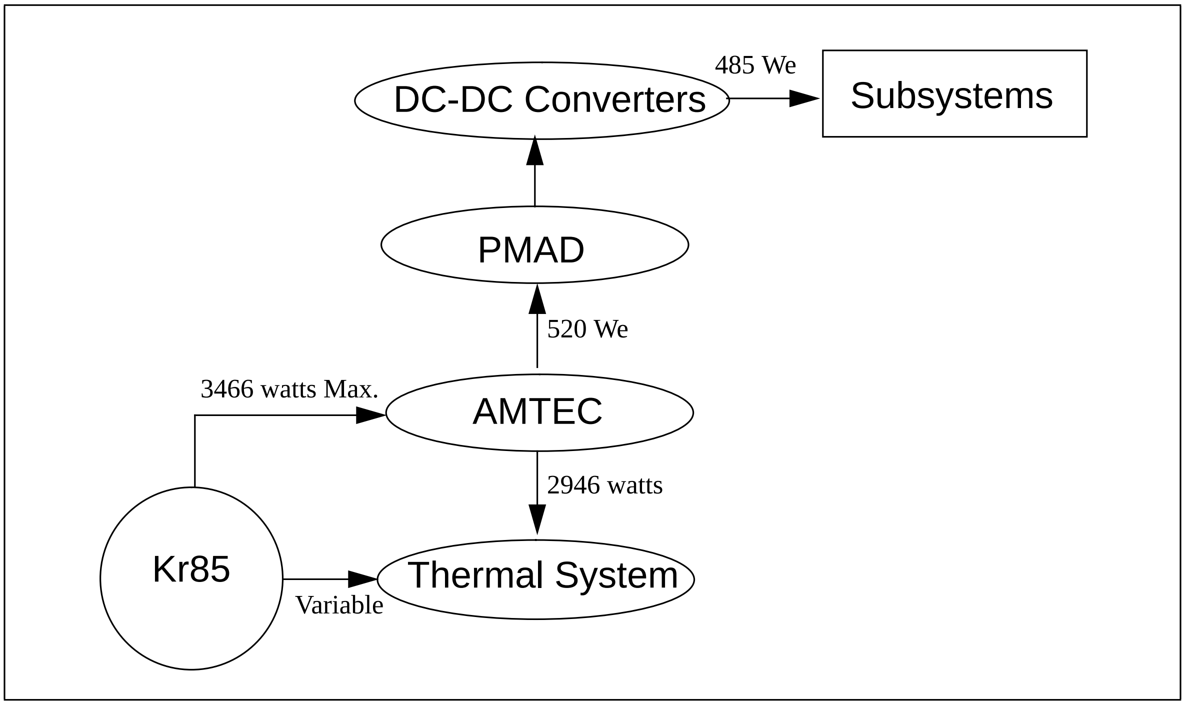

FIGURE 6.1 *System Functionality*

for battery backup. This simplifies both the power and thermal systems. Early designs suggest that power densities of a Kr85 device will be technically viable and programmatically appropriate for this mission.

6.3.1 Process

Krypton-85 is a gas isotope that emits beta particles at high energy (~ 0.7MeV) with a 10.7 year half-life. The energy of the beta particles is converted to heat in a containment vessel. The heat passes through the vessel wall to a thermoelectric converter and is partially converted to usable electrical energy. The remaining heat is rejected to space through a dedicated radiator on the surface of the rover. Over the two year mission duration the total power output from the device decreases approximately 13% because of the radioactive decay.

6.3.2 Gas

Due to its gaseous nature, krypton is relatively benign to health and handling concerns compared to metal isotopes, gamma emitters, and conventional fissionable sources such as plutonium. Krypton-85 gas is a waste product of nuclear fuel reprocessing commonly vented to the atmosphere which can be isolated by centrifuge or laser separation. Procured krypton gas for this system is expected to be only 33% pure which would generate an estimated 512 watts of heat for every kilogram of contained gas.

6.3.3 Operating Parameters

The krypton gas will be contained at a pressure of 100 atmospheres (1470 psi) and a temperature of 1000K (1340^{o}F). Based on the power budget described in Section 6.9.1 on page 57, 3500W of heat will be conducted through three krypton pressure vessels to thermoelectric conversion cells. Based on a cell efficiency of 15%, 520 watts of electrical power will be provided at the beginning of the mission for each rover.

6.3.4 Vessel

Although benign as an isotope, a krypton battery introduces safety concerns relating to high temperature, high pressure vessels that do not apply to plutonium. To contain pressurized krypton gas at high temperatures, exotic nickel-based alloys must be used. Tank walls must be sufficient to contain Kr85 for a two year life time at 1000K. Since structural integrity of these high temperature alloyed vessels exponentially decreases with lifetime of operation, additional factors of safety must be included. Tank walls must also be thick enough to absorb most of the energy of the emitted beta particles to increase efficiency and block radiative emissions and reduce radiation effects around the vessels. The presently specified tank material is Astroloy with an end of mission yield strength of 40ksi. This alloy will require a wall thickness of 1.3cm for each of the three 23cm diameter pressure vessels. An overall safety factor of three is included in the vessel design.

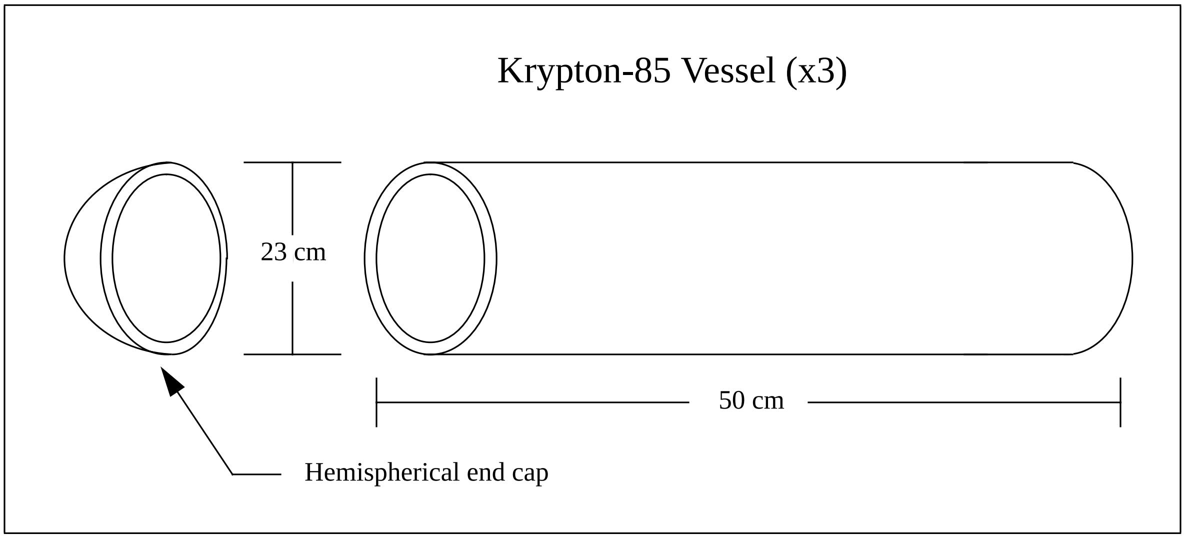

FIGURE 6.2 *Krypton Vessel*

6.3.5 Explored Options

Other core power sources that were considered include: radioisotopes such as plutonium, other previously unimplemented beta decay sources, and photovoltaic conversion.

6.4 Thermoelectric Generation

Use of the emerging AMTEC (Alkali Metal Thermal to Electric Conversion) technology provides significant quantities of electrical power not previously possible with traditional conversion systems. The high temperature of the pressurized Kr85 vessel wall is ideal for driving AMTEC converters, and the relatively high cold side temperatures minimizes radiator area. The AMTEC technology is expected to reach conversion efficiencies of 20-25% by 1996.

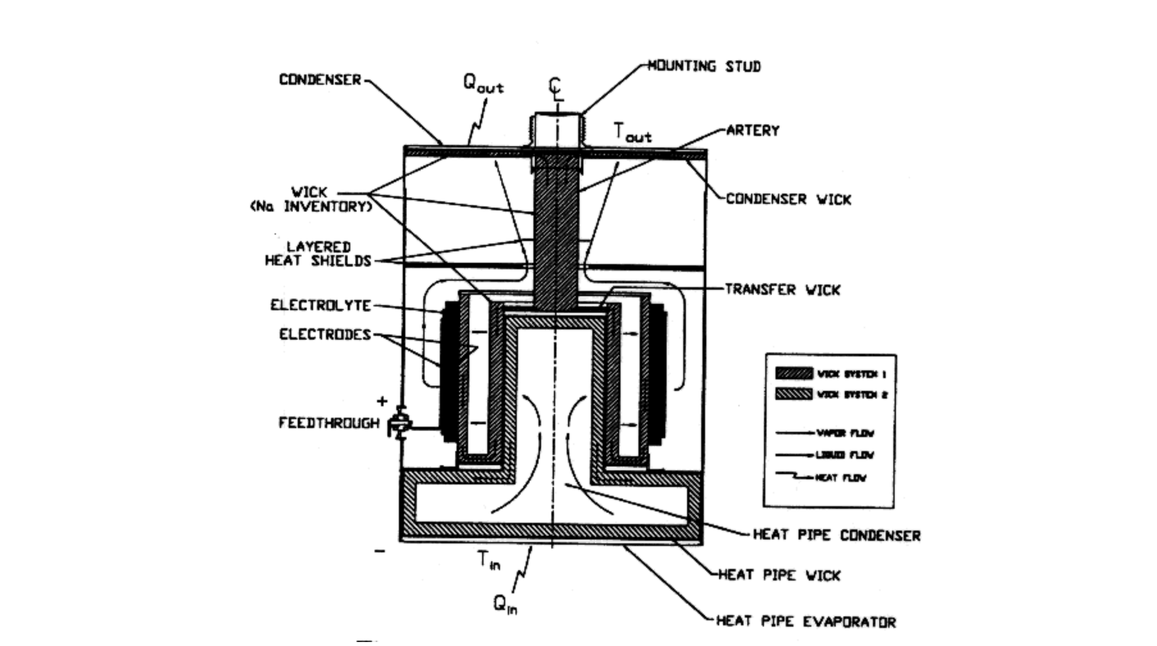

FIGURE 6.3 *Expanded Schematic of AMTEC Cell*

6.4.1 Process

"The AMTEC cell is a thermally regenerative concentration cell utilizing sodium as the working fluid and sodium beta-alumina solid electrolyte (BASE) as the ion selective membrane through which a nearly isothermal expansion of sodium can generate high current/low voltage power at high efficiency... The conversion of thermal to electric energy occurs by using heat to produce and maintain a sodium concentration gradient across a BASE membrane... The liquid sodium in the heat pipe evaporator, evaporates and flows as a vapor to the heat pipe condenser inside the BASE. The vapor condenses and deposits its latent heat, picked up in the evaporator, inside the BASE tube. Then the sodium liquid returns to the heat pipe evaporator through the heat pipe wick. In the power loop, sodium liquid fills the wicks on the condenser, in the artery, on the outside of the heat pipe condenser and the inside of the BASE tube. The heat delivered by the heat pipe loop keeps the entire BASE tube region hot and raises the vapor pressure of the sodium inside the BASE... The condenser is kept at a low temperature. The sodium vapor pressure (and concentration) in the region of the condenser and the outside of the BASE tube is therefore much lower than inside the BASE tube. This pressure, or concentration gradient produces and electrochemical potential difference across the BASE tube wall... When current is drawn through the electrodes and current collectors on both sides of the BASE, energy is extracted from the cell in the form of electrical power."[1]

6.4.2 Test Data

Currently, AMTEC conversion cells have operated reliably over a two year lifetime demonstrating efficiencies of 18%. Cell power densities are currently on the order of 30 W/kg, and are expected to reach 40 W/kg in the near future. In addition, shock, vibration, and projectile tests have been preformed. The primary failure mode of the tested cells have been from oxidation, which is not a concern during the majority of the mission duration.

6.4.3 Operating Parameters

For the power system design, a baseline of 15% conversion efficiency is applied pending further AMTEC test data. Although we expect to operate the AMTEC cells at 1000K at the BASE evaporator end and 700K at the condenser end, the cell can operate within 970K-1270K at the evaporator and 370K-770K at the condenser. With an output of 8 watts electric (W_e) per cell, 65 cells minimum will be necessary.

6.4.4 Explored Options

Several other conversion technologies were examined for feasibility of use in the rover design.

- Standard RTG's including Silicon-Germanium and Bismuth-Telluride
- Stirling Engines

The first option was unsatisfactory due to their low conversion ratios, on the order of 6%. The second option raises concerns regarding vibration and long term reliability.

6.5 Power Management and Distribution

Many reliable power management systems have flown previously. Due to the simplicity of our power source and our minimal provisionary power needs, we plan to adapt a previously flown system. Full redundancy is necessary in this component.

6.6 Assembly

The krypton pressure vessels rest in an aerogel and MLI insulation block. AMTEC cells are directly mounted to conductive spacers on the curved surface of the pressure vessels. An aerogel insulation block is lowered onto the AMTEC cells to allow unidirectional heat flow. Finally the power system's radiator is directly mounted to the cold side of the conversion cells to complete the assembly of the power system. Figure 6.4 shows how the different components will fit together. The krypton vessels are not pressurized until shortly before launch for safety and performance needs.

6.7 Failure Modes

The failure modes for the power subsystem range from minor, non-critical, to many mission critical modes. Because the rover is so dependant on the power system working effectively, margins were introduced into the design process as mentioned earlier. The mission critical failure modes are mentioned below.

The effect of failure in an AMTEC cell is simply a loss of electrical power to the rest of the system. The loss of a few cells results in a less aggressive mission: either reduced terrainability, video or safeguarding. If a large number fail, the loss of electrical power would end the mission.

The failure of a single Kr85 pressure vessel would result in a less aggressive mission, whereas the failure of two devices would force a greatly reduced mission (e.g. never transmitting video while moving) which could not fulfill the mission requirements. Failure of all three devices would end the mission.

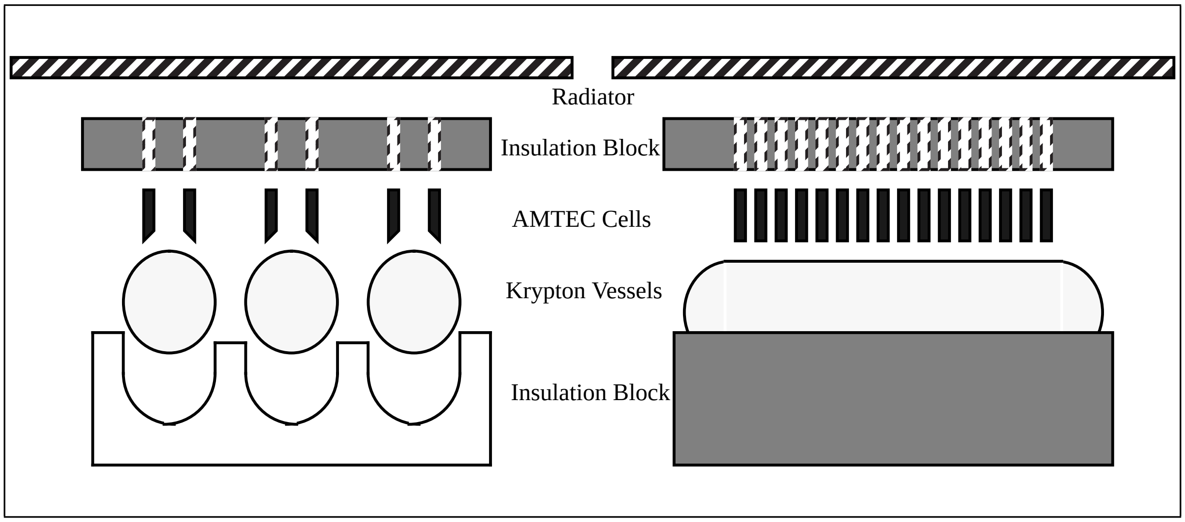

FIGURE 6.4 *Power Source Assembly*

Failure of the Power Management System would end the mission, therefore completely redundant Power Management Systems are specified.

TABLE 6.1 *Power System Failure Modes*

Component	Failure Mode	Effect	Prevention and/or Response	Criticality
AMTEC Cell	Single Failure	No visible effect	Backup Cells	2
	Multiple Failure	Reduced power output	Backup Cells	1
Krypton Vessel	Single Vessel Leak / Rupture	Ground safety risk, Minor decreased output power, Possible thermal risk	Multiple Vessels	2
	Multiple Vessel Leak / Rupture	Ground safety risk, Major decreased output power, possible thermal risk	Large Safety Factor	1
Power Management System	Failure	Redundant system utilized	Redundant System Utilized	2
	Dual Failure	Total subsystem power loss	Redundant and Reliable Components	1
DC -DC Converters	Single Failure	Redundant system utilized	Redundant system utilized	2
	Dual Failure	Single subsystem power loss	None	1
Insulation	Tear / Breakage	Thermal risk to adjacent system, System heat and power loss	Insulation	2

6.8 Open Issues

- The primary concern with the power system is amount of mass that is currently specified. The possibility of utilizing composites in the design of the pressure vessel to lessen the mass is being explored.
- The AMTEC technology has moderately robust constraints. Optimization of their incorporation into the rover design is underway.
- A complete thermal analysis of the power system is necessary to insure proper operation.

6.9 Summary Budgets

6.9.1 Power

The controlled rover will typically operate in one of five different power modes, shown in Table 6.2. First of which is the "Full Operation Mode" in which the rover operates with average locomotion power and full video panorama transmitted during the lunar day, or single camera transmission with active illumination at night. The second operation mode is "Hard Terrain Mode" in which the rover operates at peak locomotion draw with single camera transmission only. Third is "Full Operation / Limited Video Mode" where the rover operates with average locomotion and single camera transmission. The "Scientific Mode" encompasses a stopped rover which is transmitting either the full panorama, the pan/tilt camera, or single camera with active illumination. Finally, the fifth mode is "Idle". Here the rover is stopped with no video transmission. Figure 6.5 shows the power draw of rover operations that include percentages for contingency growth. Enough power is supplied to cover rover operations.

TABLE 6.2 *Rover Power Budget at Beginning of Mission*

	Full Operation Mode	**Hard Terrain Mode**	**Full Operation Limited Video**	**Scientific Mode**	**Idle**
Locomotion	75	150	75	0	0
Thermal Control	15	15	15	15	15
Power Management	35	35	35	35	35
Communications	90	30	30	90	30
Computing	60	60	60	20	20
Imagery	45	11	11	45	0
Compression	60	15	15	60	0
GNC	35	35	35	0	0
Total	415	351	276	265	100

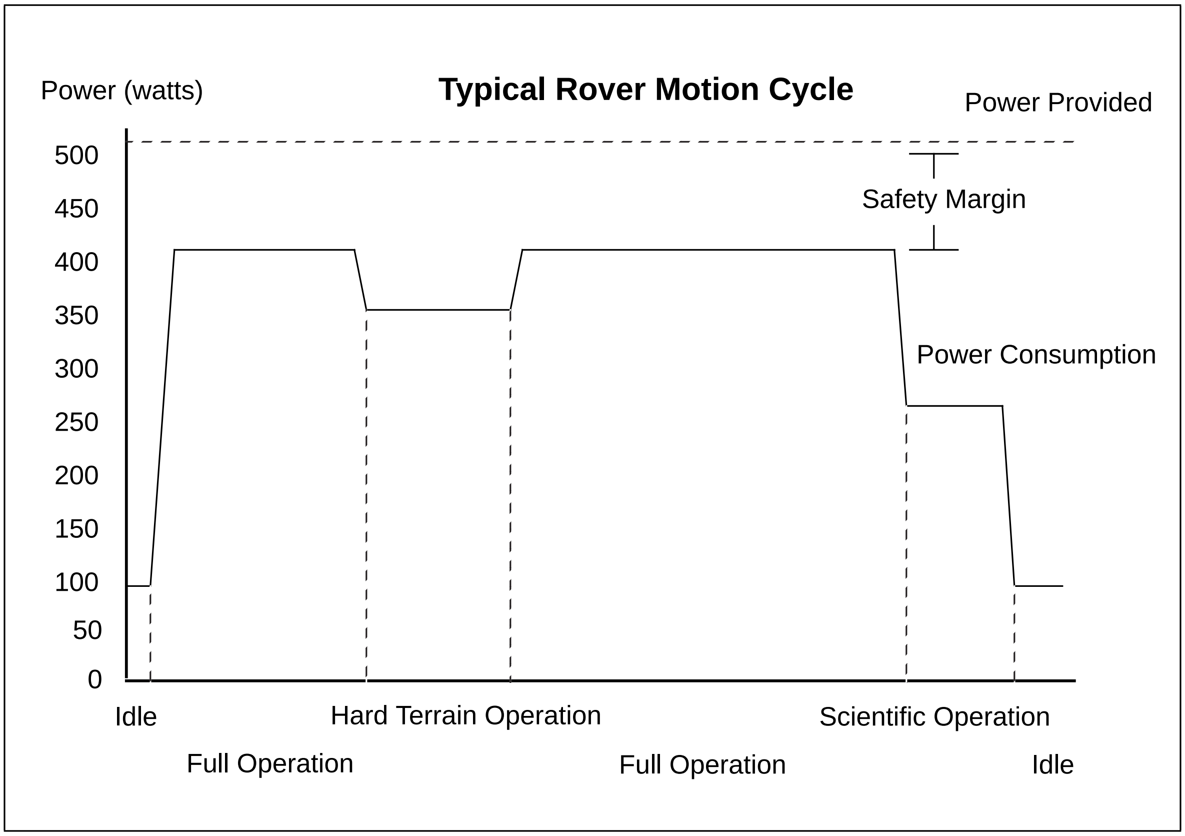

FIGURE 6.5 *Rover Power Draw Scenario*

6.9.2 Mass and Volume

Although the system contains more than 40% of the rover mass (see Table 11.2 on page 116), it is designed to mount directly to the back of a 0.5 m^2 radiator with a depth of less than 0.5 m (including insulation).

TABLE 6.3 *Mass Budget*

	Mass (kg)
Krypton Container	79.0
Krypton Gas	6.6
AMTEC Cells	17.3
PMAD	4.5
Insulation	1.0
Cabling and Connectors	10.0
Total	118.4

References

1. Ivanenok, Joseph F. III, and Sievers, Robert K., “Radioisotope Powered AMTEC Systems” *IEEE AES Systems Magazine p.29-35*, November1994

Chapter
7

Thermal Regulation

Thermal regulation is necessary for a lunar rover due to the extremes of heat and cold experienced on the lunar surface during the lunar day and night. Since the moon has no significant atmosphere for heat transfer by convection, the equilibrium temperatures on the rover are determined by the intensity of thermal radiation absorbed and emitted from the outer rover surfaces and by heat conduction between the components of the rover. The principles of thermal design and analysis are therefore similar to those used for space satellites.

The requirements of rover thermal regulation are first presented, then heat transfer phenomena for the lunar surface are reviewed, with an explanation of materials and components. The thermal regulation subsystem for the lunar rover is then presented in design, analysis, robustness, and budgeting, concluding with recommendations for further work.

7.1 Requirements

A thermal regulation design must keep all materials and components within their functional temperature limits during all modes of operation and environmental conditions. The worst-case hot scenario occurs during the peak of the lunar day with all heat-producing electrical systems operating at maximum power. The worst-case cold condition occurs during the coldest point of the lunar night while the rover is in an off-duty cycle and not moving, navigating, or transmitting data.

7.1.1 Component Temperature Constraints

The electronic components impose the most stringent temperature requirements for our design, and must be kept within temperature bounds of -40 to 50 ^{o}C. CCD chips for video cameras should be kept below 30 ^{o}C to avoid degradation of image quality due to dark current. The “cold” side of the AMTEC thermoelectric generators must be kept at a temperature of 370-770K for generation of electrical power.

7.1.2 Environmental Conditions

Ambient thermal conditions vary over a wide range between the lunar day and night cycle. The thermal regulation system of the rover must be sufficiently robust to withstand these extreme temperature differences.

- Minimum surface temperature of -180 ^{o}C during lunar night
- Maximum surface temperature of 130 ^{o}C during lunar day
- Incident solar radiation of up to 1358 Watts/m^2 during lunar day

7.1.3 Internal Dissipation

The two main internal heat sources on the lunar rover are the Kr85 heat source for thermoelectric generation and the computing and electronics enclosure. The Kr85 heat source is specified to generate 3500 Watts of heat at all times. The electrical components in the rover enclosure dissipate 200-300 Watts of heat and up to 100 Watts will be dissipated in the locomotion actuators.

7.2 Heat Transfer

Using the conservation of energy principle, the equilibrium temperatures of the lunar rover components can be calculated from the heat flow in and out of any selected control volume. At equilibrium, the temperature is constant and the heat flow into the volume must equal the heat flow out.

There are three modes of heat transfer which are relevant to the thermal design of a lunar rover: conduction through solid structures, radiation and absorption between exposed surfaces and space, and convection between surfaces and fluids.

7.2.1 Conduction

Heat conduction through a uniform solid is governed by its conductivity, surface area, and its temperature gradient in the direction of heat transfer. The rate of heat conduction is governed by the equation given below:

$$q = ka\frac{\Delta T}{\Delta x} \qquad \textbf{(Equation 7.1)}$$

where q is the conduction heat flow in Watts, a the surface area, k is the thermal conductivity of the material, Δx is the thickness, and ΔT is the difference in temperature across the material. Typical material conductivities can range from 389 W/m/K for copper to 0.02-0.03 W/m/K for various polymer foams.

7.2.2 Radiation and Absorption

For diffuse or Lambertian surfaces, heat emitted into space is modelled as proportional to that radiated by a perfect radiator or blackbody. The emitted energy is a function absolute temperature to the fourth power:

$$q = A\varepsilon\sigma\left(T_s^4 - T_a^4\right) \qquad \textbf{(Equation 7.2)}$$

where ε is the surface emissivity of the material, $\sigma = 5.67x10^{-8}$ W/m^2/K^4 is the Stefan-Boltzmann constant, A the surface area, and T_s and T_a are the absolute temperature of the surface and the ambient environment respectively. The vacuum of space is equivalent to an ambient temperature of 3K.

The absorbed energy is given by the product of the incident energy G, the surface area a, and the material absorptivity constant for the material α. The incident heat energy for objects in Earth orbit directly exposed to solar radiation is 1358 Watts/m^2.

$$q = GA\alpha \quad \textbf{(Equation 7.3)}$$

The equilibrium temperature of a planar surface exposed to solar flux can be calculated by setting the absorbed energy equal to the emitted energy and solving for temperature T.

The radiative and absorptive parameters of materials are generally a function of the wavelength of the incident radiation and may also depend on surface finish and coating thickness. For wavelengths from mid-infrared through solar radiation, this function is lumped into an experimentally determined single constant.

7.2.3 Convection

Due to the lack of atmosphere, there is no convective heat transfer between the lunar rover and its environment. The phenomenon of convection is used however in circulating fluid thermal regulation systems and is the principal means of heat transfer which occurs in heat pipes as described below.

7.3 Components

During the history of space travel, specialized materials and components have been developed for thermal regulation in the extreme conditions of space. The specialized materials used in the lunar rover are heat pipes, where very high thermal conductivity is needed to transport heat effectively, aerogel and multilayer reflective insulation to prevent leakage of heat energy across thermal gradients, and thermal coatings to effectively radiate internal heat and minimize solar heating.

7.3.1 Heat Pipes

Heat pipes are closed metal containers containing liquid and a capillary wicking material on the inside surface. Heat applied at any point along the heat pipe causes the liquid near that area to vaporize and quickly diffuse the heat energy to the interior of the pipe while drawing additional liquid to that point by capillary action. The heat energy is then transferred to the cold side of the pipe. This phenomenon results in a very high effective thermal conductance for the heat pipe. Heat pipes can be fabricated in a variety of shapes to provide even temperatures for various components and enclosures. A schematic of a heat pipe is shown in Figure 7.1. The capacity of heat pipes is generally measured as the product of heat energy carried and the distance it travels: A typical heat pipe of 1.27cm in diameter has a capacity of 5080 Watt-cm.

Variable conductance heat pipes have also been developed for space applications where the capacity of the pipe is a function of the difference in temperatures between the hot and cold ends. Variable conductance heat pipes [VCHP] are therefore very effective for keeping components within a tight temperature range despite large variations in heat load.

7.3.2 Surface Coatings

Paints and coatings with desirable emittance and absorptance parameters can be used for effective thermal regulation by radiative effects. Generally, high emittance is desirable so that internally generated heat can be radiated effectively and low absorptivity is desirable to minimize the effects of variations in solar heating.

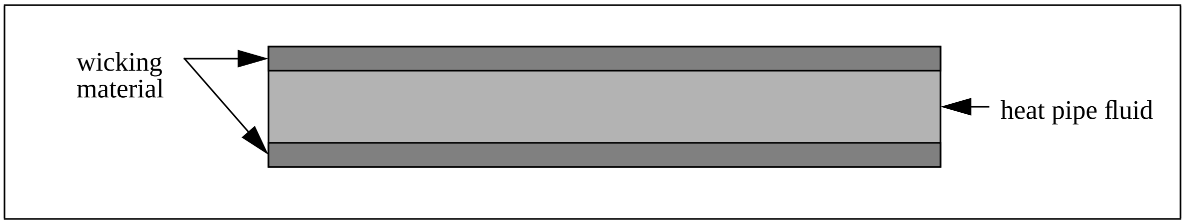

FIGURE 7.1 *Heat Pipe Functional Schematic*

White paints, epoxies, and ceramic coatings are effective for thermal radiators when exposed to solar radiation due to the combination of a low solar absorptivity below 0.2 and a thermal emissivity above 0.8. There are also materials with a similar ratio of emissivity to absorptivity such as metallized teflon and optical solar reflector [OSR] surfaces, which have greater cost and weight.

7.3.3 Insulation

Multilayer reflective insulation and aerogels are highly effective insulating materials suitable for space applications. Since the two operate by different principles, they can be used in a complementary fashion. Since multilayer insulation is most effective for large, featureless, flat, smooth surfaces, the lunar rover insulating strategy is to use multilayer insulation for flat panels, and aerogel behind the panels at all seams, corners, and other surface features.

Multilayer Reflective Insulation

This insulation is made of thin layers of metallic foils separated by insulating oxides or fabric in vacuum. Conductive heat transfer is practically eliminated; heat transfer across this material is primarily by thermal radiation from one layer to the next. The performance of this insulation type depends heavily on the details of its configuration. Seams, attaching points, and folds are all paths for heat leakage through the insulation. The effective emittance ε of multilayer insulation blankets typically ranges from 0.002 to 0.02 depending on the area insulated and any other configuration factors that add heat leakage paths.

Aerogels

Aerogels are extremely lightweight insulating materials made by evacuating the fluid components from regular gel materials without collapsing the solid support structure of the gel. Aerogels have been fabricated with densities as low as 5 kg/m^3 and thermal conductivities of 0.02 W/m/K in vacuum at room temperature.

The development of carbon aerogels increases the insulating capability of aerogels. These carbon aerogels are opaque and greatly reduce radiative heat transfer and can also insulate effectively while withstanding temperatures up to 1000 K.

7.4 Preliminary Analysis and Design

The lunar rover configuration that was chosen has enabled the design of a simple, passive thermal regulation system with a single operating mode. The availability of the on-board Kr85 heat source delivering a perpetual source of heat during the mission lifetime makes lunar night survival and operation possible with little difficulty. A single closed enclosure results in a tendency towards overall temperature equalization. No active circulation of coolant fluids or mechanical actuation of moving parts is necessary for this thermal system configuration. Figure 7.2 shows the general layout of thermal control components in the rover.

The general design for the thermal regulation system for the lunar rover calls for separate radiators for the Kr85 heat source and the electronics enclosure, a high-emittance/low-absorptance surface paint for all exposed rover surfaces, and panels of multilayer insulation and aerogel to isolate the underside of the rover from heat transfer with the lunar surface.

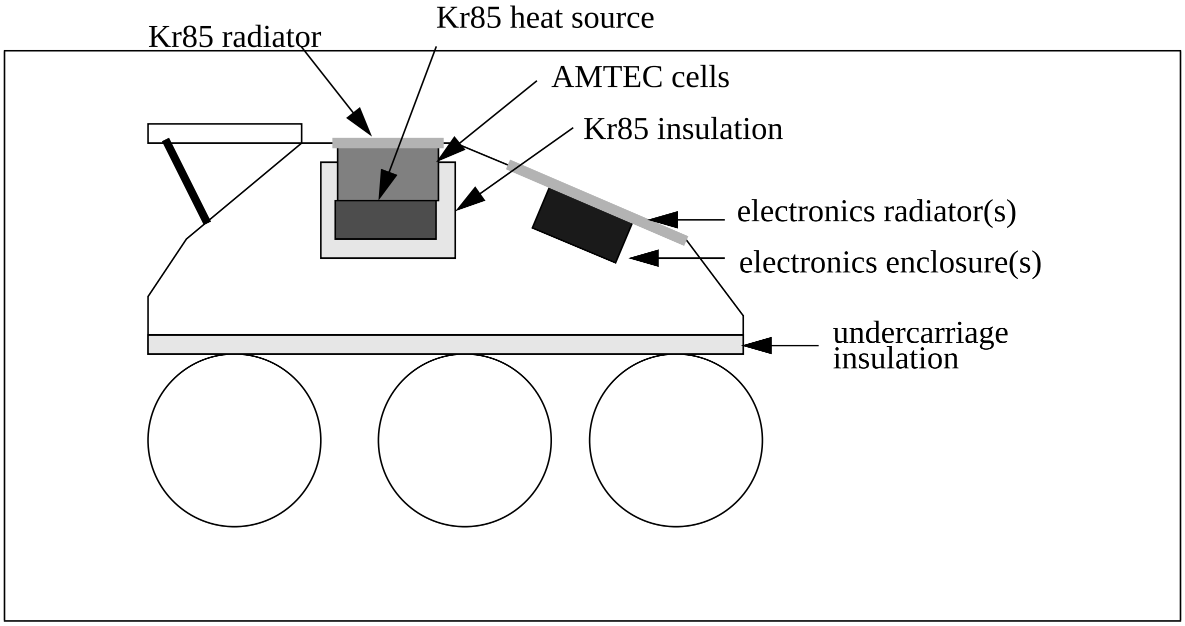

FIGURE 7.2 *Structural Elements of Thermal Subsystem*

7.4.1 Thermal Coating

A coating with excellent radiative and material properties for space missions, YB-71, is available from IIT Research Institute. This coating is a modification of ones used on the Apollo missions and is composed of Zn_2TiO_4 pigment and a potassium silicate binder. Its emissivity is 0.92 and its absorptivity is 0.12. It has been tested for ultraviolet degradation, hard vacuum, and temperatures up to 1000 ^oC. The application thickness should be at least 30 microns thick to withstand damage from micrometeorites.

7.4.2 Radiators

The Kr85 heat source requires its own separate radiator to prevent overheating the rover enclosure. Since the heat output side of the heat source can range from 500-800K for efficient thermoelectric generation, the size and temperature of the radiator is not critical. A thin metal plate radiator of $0.4m^2$ operating at 700K is sufficient to dissipate the 3000 Watts of waste heat.

The radiators for the electronics enclosure must dissipate 250 Watts on average from the electronics enclosure while keeping the components within their acceptable temperature limits. A $1.5m^2$ radiator coupled to the electronics enclosure would result in a daytime temperature of 9 ^oC and a nighttime temperature of -35.3 ^oC. Since this nighttime operating temperature is near the lower end of the electronics operating range, a pair of variable conductance heat pipes are added to the design to supply up to an extra 200 Watts of heat from the Kr85 heat source to the electronics enclosure when the electronics temperature drops below 10 ^oC.

Heat pipes are used on the electronics radiator to evenly dissipate heat over a larger area. Graphite fiber panels also provide higher thermal conductivity with lower mass.

The parameters of the two radiators are summarized in Table 7.1.

TABLE 7.1 *Radiator Parameters*

Radiator	Material	Area	Operating Temperature	Heat Dissipated	Mass
Kr Heat Source	Aluminum	0.4 m^2	427 ^oC (700K)	3000 W	1.12 kg
Electronics	Graphite Panels and Heat Pipes	1.5 m^2	10-25 ^oC	350 W	4 kg

7.4.3 Body Insulation

Thermal insulation is needed on the lunar rover to protect the internal components from the excessive heat of the Kr85 heat source and to isolate the undercarriage of the rover from heat transfer. Multilayer insulation will be used on all flat surfaces to be insulated while carbon aerogels will be used at all the heat leakage points of the multilayer insulation such as panel seams, junctions, corners, and support points.

The most stringent requirement for insulation is to isolate the components in the rover enclosure from the Kr85 heat source at 1000K. In order to minimize mass, a sandwich of 2 cm of aerogel with 25 layer MLI blankets on both sides will be used here. This insulation method results in limiting heat leakage from the Kr85 source to 100W with only 1.5 kg of material.

Carbon aerogels of densities of 60 to 500 kg/m^3 have been tested for conductivity and strength at one atmosphere and in vacuum. Conductivity and strength were both found to be approximately proportional to density. A carbon aerogel of 80 kg/m^3 with thermal conductivity in vacuum of 0.02 W/m/K at 300 K and 0.075 W/m/K at 1000 K was chosen as an effective yet structurally robust insulating material.

Twenty-five layer insulation with aluminum sheets and nylon fibers separating them is estimated to have an effective emittance of 0.005 when used in panels on the order of one square meter in area.

Heat leakage paths and amount of heat transferred is shown in Table 7.2.

TABLE 7.2 *Heat Leakage Paths*

Interface	Insulation	Area	Mass	Conducted Heat to Inner Enclosure
Kr Heat Source and Enclosure	25 layer MLI - 2 cm aerogel- 25 layer MLI sandwich	1 m^2	1.5 kg	100 W
Undercarriage and Lunar Surface, Night	25 layer MLI with aerogel at seams	4 m^2	0.6 kg	-6 W
Undercarriage and Lunar Surface, Day				23 W

The additional heat leaked into the rover enclosure from the lunar surface and the heat source has been accounted for in the design of the electronics enclosure.

Aerogel insulation without MLI must be used on the phased array communications antenna to keep the electronics within -40 to 40 ^{o}C bounds as metallic layers may interfere with the radio communications.

7.4.4 Thermoelectric cooling

Active 2 Watt thermoelectric cooling units are used to draw heat off of each camera CCD.

7.4.5 Thermocouple sensing

Thermocouple junctions will be placed at various points inside the rover enclosure to constantly monitor local temperatures so that operation parameters of the rover can be adjusted accordingly.

7.5 Heat Flow Schematic

Figure 7.3 shows all major heat transfer paths in the lunar rover thermal regulation design. The only two heat sources are the sun and the Kr85 heat source; all the heat is eventually radiated into space, some of it being converted to electrical power and back into heat beforehand.

7.6 Failure Modes

Table 7.3 describes the different failure modes for the thermal subsystem. The subsystem is very robust due to the lack of active components or moving parts.

Gradual physical degradation of the thermal regulation materials and components may occur due to temperature cycling, micrometeorite bombardment, or physical stresses, resulting in larger temperature excursions than specified in the design. The effect would be minor unless some materials are severely damaged and performance of the main radiator or the Kr85 insulation is significantly reduced. Dust accumulation may also become a problem, if large amounts of dust are deposited on the radiators. If the operating temperatures exceed the bounds of operation for other subsystems, the mission could be critically threatened.

7.7 Mass and Power Budget

The only electrical power needed is for thermoelectric cooling of camera imaging CCD’s. Aerogels, multilayer insulation, and composite heat pipes and radiators enable very lightweight design. Table 7.4 details the power and mass requirements for this subsystem.

7.8 Future Work

More detailed modeling and analysis will be necessary as the design of the Kr85 heat source is refined. Some analysis of thermal transients should be done as well to find the rate of heating and cooling. Uneven heating may also be significant due to shadowing and solar flux from the side.

Experimental results are also needed before prototyping the actual rover. This can be done with a small physical model and heat source in a vacuum chamber.

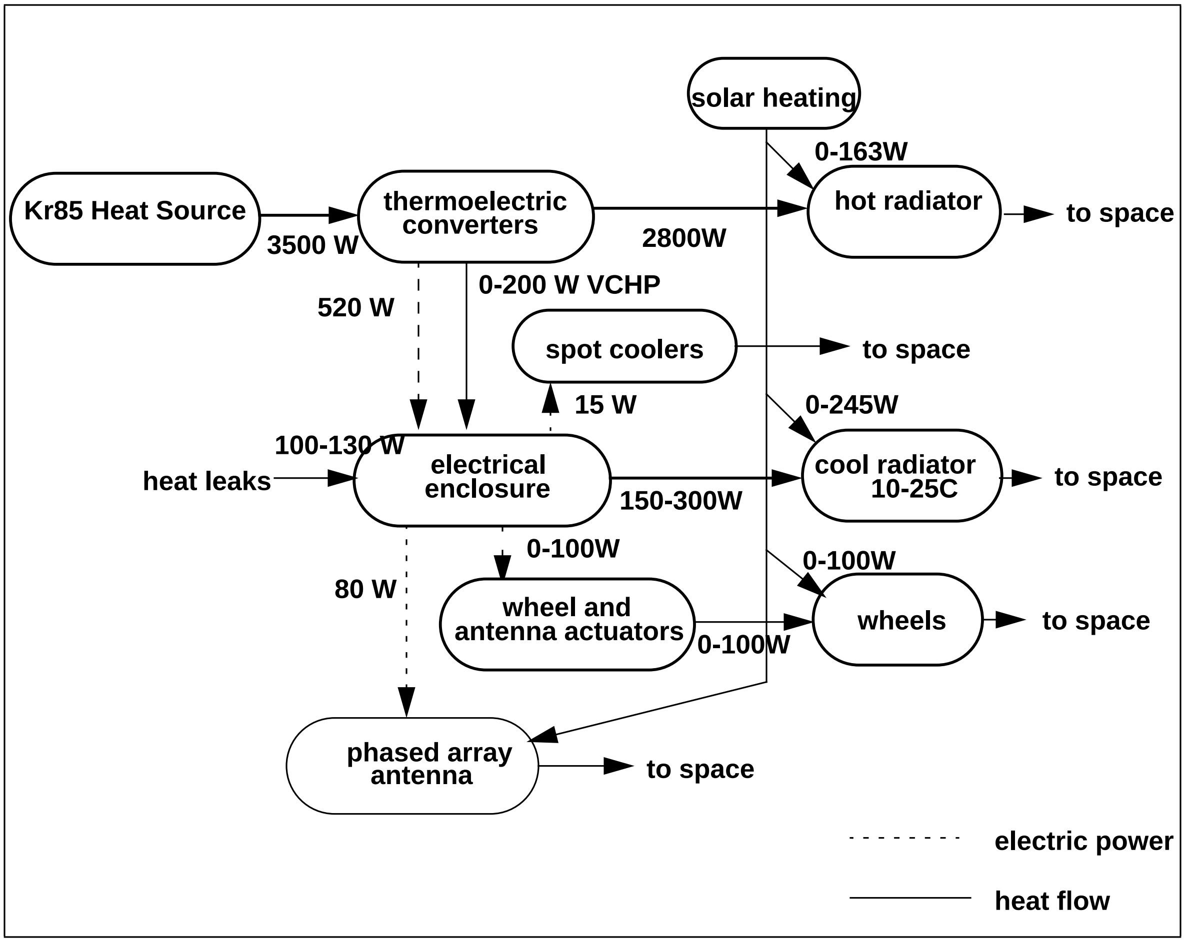

FIGURE 7.3 *Heat Flow in Lunar Rover*

TABLE 7.3 *Failure Modes*

Component	Failure Mode	Effect	Prevention and/or Response	Criticality
Thermoelectric Cooler	Bad connection or short-circuit	Greater image noise	Good Wiring Connections	3
Thermal Coatings	Dust coverage	negligible on insulated surfaces, great temperature increase on radiator surfaces	radiators above maximum height of dust	1
	Gradual Material Deterioration	slight to drastic temperature increase	application thickness, material selection	2/1
Exterior Insulation	Physical degradation, Panel Damage in Collision	slight to drastic temperature increase	low mechanical stress, no collisions	2/1
Heat Source Insulation	Material Deterioration	slight to drastic temperature increase	low mechanical stress, heat resistant materials	2/1
Radiator Heat Pipes	Leakage/Rupture	slight loss of radiator efficiency and <10 ^{o}C rise in enclosure temperature	structural support	2
VCHP	Leakage/Rupture	enclosure temperature drop to -35 ^{o}C during lunar night	structural support	2

TABLE 7.4 *Summary Budget*

Component	#	Total Mass [kg]	Average Power [Watts]	Standby Power [Watts]
Kr85 Heat Source Radiator	0.4 m^2	1.2	-	-
Electronics Enclosure Radiator	1.5 m^2	4	-	-
Kr85 Heat Source Insulation	1 m^2	1.5	-	-
Body Insulation Panels	4 m^2	0.6	-	-
Thermoelectric cooling for CCD arrays	6	0.5	15	15
Total		7.8	15	15

References

1. Larson, Wiley J and Wertz, James R., “Space Mission Analysis and Design”, Kluwer Academic Publishers, 1992.
2. Guyer, Eric C. ed., “Handbook of Applied Thermal Design”, McGraw Hill 1989.
3. Bock, V., Nilsson, O. et al.,”Thermal Properties of Carbon Aerogels”, Int. Symp. on Aerogels, Berkeley CA 1994

Chapter
8

Guidance, Navigation, and Control

The GNC subsystem is responsible for determining and controlling the rover's position and heading on the moon. In addition it provides two of the customer needs: attitude and acceleration data for a theme park ride and a safe method for amateur teleoperation. Position and attitude determination is performed by a star tracker, an Inertial Measurement Unit (IMU) and inclinometers. GNC is additionally responsible for controlling rover motion and safeguarding the rover. Safeguarding is implemented using stereo cameras, a light striper, and an array of infrared sensors.

8.1 Requirements

- Allow teleoperation by skilled and unskilled operators.
- Safeguard rover from dangerous terrain.
- Support autonomous operations.
- Attitude determination sufficient for both theme park ride and safeguarding/navigation.
- Approximate position determination sufficient for finding points of interest on the moon.
- Allow full speed (1 m/s) operation as often as possible.
- Avoid trenches, craters, and cliffs that may endanger the rover.
- Minimize the number of times near range and contact sensors are used.

8.2 Interfaces

Figure 8.1 shows the navigation system and its interface to the other components of the rover.

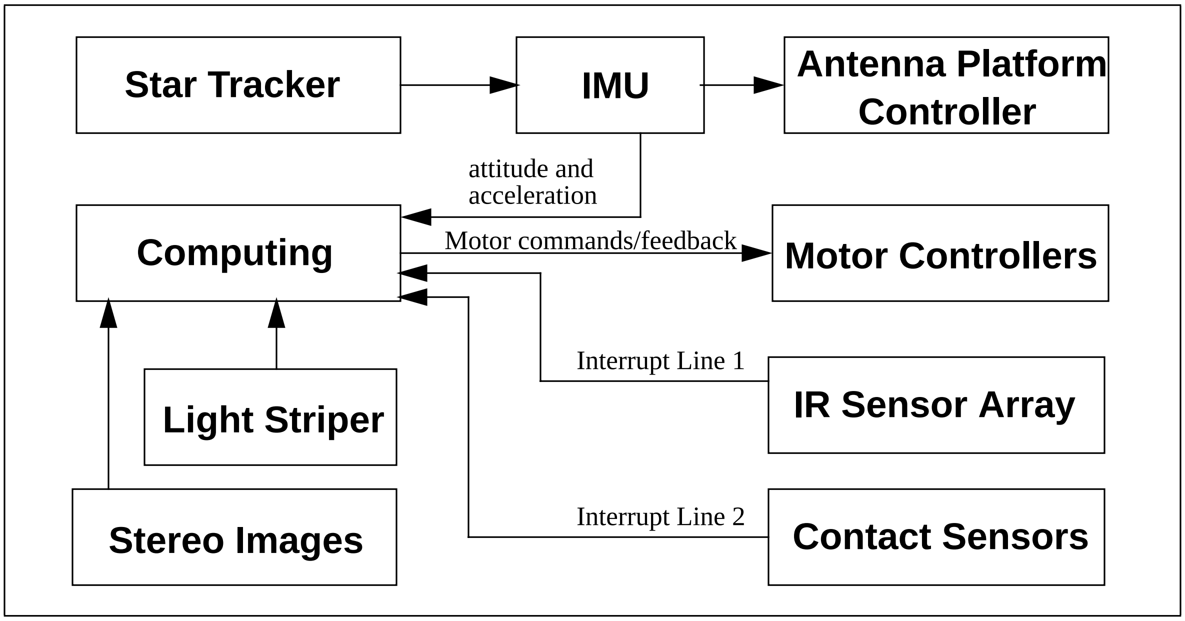

FIGURE 8.1 *Navigation System and Interfaces*

8.3 Control Modes

The rover will have several different modes of operation:

- Idle mode
- Amateur Operator
- Trained Operator
- Scientific/Educational Mode
- Autonomous Mode

Since bandwidth limitations require that only one rover transmit at a time, each rover will be "idle" approximately 50% of the time. During this "idle" time, the rover may put most of its systems on standby power. However, the rover is able to take some high quality still images for future transmission, map the nearby area with its sensors, perform more computer housekeeping chores and status checks, or go into the autonomous mode so that the transmitting rover can view an active rather than passive rover.

It is expected that amateur operators will drive the rover a large portion of the time. Since the amateur operator will be confronted with unfamiliar environs, unfamiliar controls, and significant control delays, a suite of sensors will be used to safeguard the rover. During this "amateur mode", the rover will accept commands from the amateur operator. Based on its onboard sensing, the rover will filter the commands by finding safe paths or steering arcs and following the arc closest to that designated by the amateur operator. Since the rover will likely reject some commands provided by the amateur, it is very important that the operator feel that she has control over the rover. Otherwise, the operator may leave disappointed that the rover didn't seem to do what she commanded. To achieve this, the rover will transmit the safe steering arcs to Earth and these will be displayed on the operator's console so that she will be more likely to pick one of these directions and will also understand what the rover is doing. Should an error occur, a trained operator will take over and will be able to switch to the trained operator mode.

"Trained operator mode" will be very similar to the amateur mode, with the rover still transmitting the safe steering arcs to the operator's console. However, the trained operator will have the option of overriding the safeguarding so that the vehicle will obey the operator completely. The trained operator will also be able to demand raw sensor data and will have access to the other cameras on the rover (the belly camera and the sky camera). A trained operator will also have the option of switching the rover to autonomous mode.

The scientific and educational operations are explained in Chapter 1.

8.4 Attitude and Position Determination

Accurate attitude sensing on the rover is required for two reasons. The first is to maintain the integrity of the communications link with Earth. The second is to provide the data for a motion platform ride at an amusement park on Earth.

Drift of the primary antenna's beam center away from Earth results in a corresponding gain loss. To keep the bit error rate at acceptable levels, a drop in gain requires an increase in power or a decrease in the transmitted data rate. Since the image data sent back to Earth is the primary deliverable of our product, it is unacceptable to reduce our data rates in order to simplify the antenna pointing problem. Limited on-board power also makes it unacceptable to feed more power to the antenna than 80W. Thus, for high bandwidth communication to Earth the beam center must deviate less than 0.5 degrees.

A motion platform ride on Earth also requires accurate attitude determination. If the sensed attitude greatly differs from the true attitude, riders on Earth may feel motion sickness when presented with the conflicting imagery. Although the accuracy necessary to reduce motion sickness of riders on Earth is not known, it is likely that the requirements are somewhat less stringent than those presented by the antenna pointing problem.

Two star trackers and two IMUs will be placed on the rover body. The second unit of each is for redundancy purposes. In normal roving operation, a star tracker will obtain a fix approximately every 10 minutes. This will be sent to the IMU where it will update its current values. A ten minute fix period is used because the IMU data should not drift significantly over that period of time. Attitude data is read from the IMU continuously and is fed to the antenna pointing controller and is also relayed to Earth.

Precise position determination on the moon is a difficult problem. Fortunately, it is not generally needed for rover operations. However, in order to find points of interest on the moon such as the Apollo sites, it may be sometimes necessary to determine the rover's position with a precision on the order of 100 meters. A rough position can be determined using the star tracker and a gravity vector sensor (inclinometer) to estimate current latitude and longitude. However, these measurements will most likely be accurate only to 0.5 degrees. An error of 0.5 degrees corresponds to 15 km on the moon. This is clearly not precise enough to locate the lunar points of interest. Therefore, more precise estimates will be made on Earth by using the lunar map database acquired by the Clementine satellite and by video images provided by the rover. Although humans can perform the task of estimating map position based on vision, there has also been some research in automating this process [8].

8.5 Safeguarding Options

For the rover to survive a two-year mission, the body must be protected from damaging impacts. It is also necessary to prevent the rover from entering a location from which it is physically unable to leave. Protection of the rover from physical harm is referred to as "safeguarding." Although a skilled teleoperator might be able to drive the rover collision-free over a long period of time, even skilled operators make mistakes. Video imagery provides the operator with a limited view. In unfamiliar territory an operator may not be able to sense depth well enough with only a single camera to safely guide the rover. In addition, it is expected that the rover will be driven by unskilled operators at theme parks. Communication dropouts might further endanger the rover if navigation depends solely on operator input for its safety. A combination of unskilled operators, unfamiliar territory, transmission delays or dropouts, and unfamiliar controls demands onboard sensing and intelligence for the rover. A suite of sensors was designed for safeguarding the rover. The safeguarding system is broken into 3 separate systems -- near-range (0 to 1.5 m), far-range (1.5 to 8 m), and contact sensing.

8.5.1 Contact Sensing

Contact sensing is the last line of defense. Contact sensing is necessary in case the near-range or far-range sensors fail to detect an obstacle, resulting in a rover collision. A collision can damage the structure, internal components, and drive mechanisms. Although it is best to avoid collision, damage to the rover can be minimized by being able to sense a collision and immediately halting the rover, thereby lessening the impact forces transmitted to the body.

8.5.2 Near-Range Sensing

Although an exceptional ability to sense and lessen the forces transmitted to the rover upon collision might make active sensing of the surrounding environment unnecessary, the many collisions the rover might sustain over the course of two years would eventually cause serious deterioration or breakage of contact sensors. Active sensing was deemed necessary. Three different technologies were considered for fulfilling the proximity sensing needs: capacitive, radar, and infrared.

Capacitive Sensors

Capacitive proximity sensors operate by measuring the electrical capacitance between a plate and its surrounding environment. When an object draws near, changes in the geometry and dielectric characteristics in the sensing region cause the capacitance to change. The sensing range is typically on the order of a few inches, though the capacitive sensors developed at Sandia National Labs have ranges of up to 40 cm.[6] Because the sensing region is approximately hemispherical in shape, capacitive sensors are good at providing detection over a fairly large area with a single sensor, but provide no direction information unless an array is used. Capacitive sensors tend to be heavier and consume more power than infrared emitter/detector pairs.

Radar

Radar sensors can operate over short or long ranges, and were considered for proximity sensing. An electromagnetic wave is emitted and if sufficient energy is reflected from a target, to the receiving antenna, receiver output changes to indicate object detection.

Infrared

There are several kinds of infrared (IR) proximity sensors: breakbeam, reflective, and diffuse. The first two types require control over the environment and so are impractical for our use. Infrared emitter/detector pairs function similarly to radar sensors but use optical rather than RF energy. The IR sensors have a few advantages over radar sensors. IR sensors have a tighter beamwidth (on the order of 2-3^{o}) which provides better directional information, and the components are very small. IR sensors achieve more reliable detection than radar sensors because of fewer specular reflections. The Rayleigh criterion states that a surface reflects incident energy specularly (rather than diffusely) if:

$$h < \frac{\lambda}{8\sin\alpha} \quad \textbf{(Equation 8.1)}$$

where h is the amplitude of the surface corrugation, λ is the wavelength, and α is the angle between the surface and the ray. Since IR has a shorter wavelength than radar it reflects diffusely off of more surfaces. Specular reflections cause problems for radar unless the sensor beam is nearly perpendicular to the object because the energy tends to reflect off of obstacles and away from the detector, rendering the obstacle invisible to the sensor.

8.5.3 Far-Range Sensing

Although the near-range and contact sensing might adequately protect the rover from colliding with obstacles, the virtual reality ride that would result from relying solely on these two sensing modes would likely be unsatisfactory. The ride would be full of stops and starts since near-range detection would automatically halt the vehicle. Far-range sensing will allow the rover to sense obstacles ahead of time so that it can steer clear of dangerous situations by choosing steering arcs that maximize clearance around the vehicle. The objective of the far-range sensing is to keep all obstacles over 25cm in height out of the rover's near-range sensing area where the obstacles pose a danger to the rover and requires an automatic halt.

There are numerous technologies available for providing sensing at this distance. Stereo vision, optical flow techniques, laser rangefinders, laser light stripers, depth from defocus, and a new scannerless rangefinder developed at Sandia were all considered for far-range sensing. For a comparative summary of the far-range sensors, see Table 8.1.

Stereo Vision

Stereo vision computes depth by measuring the disparity between points in two images of a scene taken from different perspectives. By triangulation, a depth estimate is computed. Stereo has two advantages over other methods of building dense depth maps. First, its components are highly reliable since it requires no moving parts. Second, it captures the entire frame at once so that all the pixels in the depth map are calculated from the same perspective. It is easily parallelizable and it is a well understood technology. There is a lot of experience in using stereo for mobile robots. Stereo does have the disadvantage that it is necessary to precisely match points which requires searching in the second image for the corresponding pixel for each pixel in the first image. This requires a lot of computational power (on the order of 50 MIPS). Since stereo is based on triangulation it also can suffer from occlusion effects. Like any of the passive vision-based methods, it will be unable to obtain depth information from textureless areas, and it will be unable to operate during the lunar night because of the low illumination level. However, stereo should operate well during the lunar day and has been chosen as the daytime far-range sensing method.

Laser Light Striper

There are many variations on laser light stripers. All of them, however, employ a camera and an active illumination source. By knowing the distance between the camera and the light source and by finding the light stripe in the image, triangulation can be used to find the depth of a "line" of points in the image. The simplest method sweeps a single laser line across the scene while a camera takes a series of images. This method, however, is quite slow since if T is the time it takes to sense and digitize an image, then the scanning of N stripes takes $N \cdot T$. Improvements can be made by assigning gray codes to the stripes and scanning the collection of stripes in sets. The information can then be acquired in $T \log N$. Using differently colored stripes can speed up the mapping process. However, a computational sensor has been developed in which each sensor element records a stripe detection time-stamp as a single laser line is swept across the scene at high speed. Depth maps can be produced in 1 millisecond. However, current VLSI technology limits the total number of cells to 28x32.[3]

Light striping can suffer from occlusion effects as with any method based on triangulation, and it is impractical for day operations because the active illumination would have to compete with the very strong incident solar radiation. However, as a sensor for night operations it is the best option available.

Laser Rangefinder

Laser rangefinders operate by sweeping a laser beam across a scene and measuring the time of flight (directly or by phase differencing) for a laser beam to reach a point in a scene and return to the detector. Multiplying the time by the speed of light gives very accurate depth measurements. There is quite a bit of field experience in using laser rangefinders for mobile robot navigation. There are many advantages to laser rangefinders: they provide highly accurate depth information over a wide field of view (sometimes a full 360^o). Since they only illuminate a single point at a time, they can operate reliably during both day and night with a low-power laser diode. However, the 2-DOF scanning mechanisms necessary to obtain a 3-D map with a laser rangefinder are prone to mechanical problems. Because the laser itself is not scanned, but rather the beam is reflected off of dual rotating mirrors, errors in the mechanisms amplify the error in beam deflection by a factor of 2. The alignment of the mechanisms could suffer greatly over the course of 2 years of operation in rugged terrain. In addition, the mirror surfaces degrade over time. Pits can form in the mirror surface which effectively leave blank spots in the constructed depth images. Over 2 years, serious degradation of the mirror surfaces is not expected, but the mechanical problems often associated with laser rangefinders prevented us from choosing this technology for our rover.

Depth from Defocus

Depth from defocus works by taking two images of the same scene at different camera focal settings. The level of blurriness of each image is computed by measuring the frequency composition via a Fourier transform. By comparing the blurriness of the two images and using an accurate model of the camera optics, it is possible to estimate the distance to each point in the images. Since the two images are taken from the same perspective (either serially or simultaneously through the use of a beam splitter), matching (as in stereo vision) is unnecessary. Since matching is computationally expensive, this can result in some computational savings although not much since the Fourier transforms are quite expensive as well. The major benefit of not needing matching is increased accuracy and reliability of results. Ordinary depth from defocus methods do suffer in image areas with no texture (as in stereo). A new method implemented at Columbia uses an active illumination pattern on the scene to impose a texture on the scene, resulting in unprecedented accuracy from depth of defocus.[5] However, the method has only been used on objects at very short range (less than a meter) and since it requires illumination of the entire scene at once, it requires more power than other active perception methods. The high power requirements and its relative immaturity were the deciding factors in not using depth from defocus on the rover.

Sandia Scannerless Rangefinder

Sandia National Labs has recently developed a scannerless rangefinder that can produce high density depth maps at high rates. The range imager works by using either a high-power laser diode or an array of LEDs to completely illuminate the scene. The phase shift of the reflected light from the target relative to the AM carrier phase of the transmitted light is measured to compute the range to the target. The gain of the image intensifier within the receiver is modulated at the same frequency as the transmitter. The light reaching the CCD is dependent on the phase of the return signal and its intensity (dependent upon the reflectivity of the target). To normalize reflectivity variations the intensity of the return beam is sampled twice, one with the receiver modulation gain disabled and once with the modulation on. Thus, the range associated with each pixel is essentially measured simultaneously across the entire scene. Although this system has the advantages of providing highly accurate depth estimates at fast rates, the system employs many components, and is more massive and power-consuming than the other sensors. In addition, the Sandia rangefinder is relatively new technology and hence we have decided against using it on the rover.

TABLE 8.1 *Comparison of Far-Range Sensors*

	Stereo	Laser Rangefinder	Light Striper	Depth from Defocus	Sandia Scannerless
Day Ops.	Yes	Yes	Unlikely	No	Unlikely
Night Ops.	No	Yes	Yes	Yes	Yes
Power	10 W	10 to 15 W	15 W(night)	High	High
Computing Power Needed	High (50 MIPs)	Low	Low to Medium	Medium	Medium to High
Mass Est.	2-3 kg	4-5 kg	2-3kg	2-3 kg	10-15 kg
Update Rate, Limitation	1 Hz computing-limited	1-2 Hz scanner-limited	Depends... image acquisition limited	30 Hz, computing and camera limited	4 Hz, computing limited
Maturity/ Previous Exp.	High	Medium	Medium	Low	Low
Reliability of Results	Medium	High	High	High	High
Reliability of Components	High	Medium	High	High	Unknown

8.6 Safeguarding Design

8.6.1 Near-Range Sensing

The rover will have an array of infrared emitter-detector pairs (see Figure 8.2), spaced approximately every 10 cm along the front. In order to save power, the sensors will be multiplexed and the array will be scanned so that only one emitter-detector pair will be active at a time. The scanning rate will be at least 10 Hz so that obstacles can not slip past a sensor while its inactive. Additionally, the emitter and detector will be amplitude modulated in the 40-80 kHz range. Modulation of the signal should allow the sensor to effectively subtract or “ignore” the ambient infrared energy on the moon. The sensors should have a range of approximately 1.5 meters and will be mounted at the base of the chassis (approximately 1 m off the ground) and will be inclined 35 degrees downward from horizontal. The drawing in Figure 8.3 shows this setup. It will provide detection of obstacles larger than 30 cm at a distance of 1 meter. The gain should be tuned either through experimentation or software control so that ground reflections do not trigger the IR sensors. The output will be connected to a computer interrupt that upon obstacle detection should immediately cut current to the wheel motors to stop the rover.

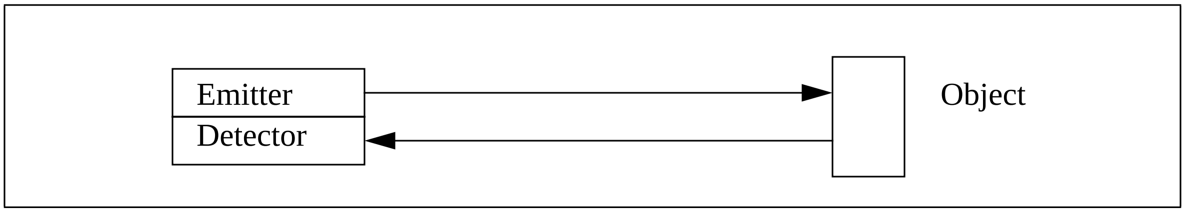

FIGURE 8.2 *Infrared Emitter-Detector Pair.Infrared light reflect diffusely off of object.*

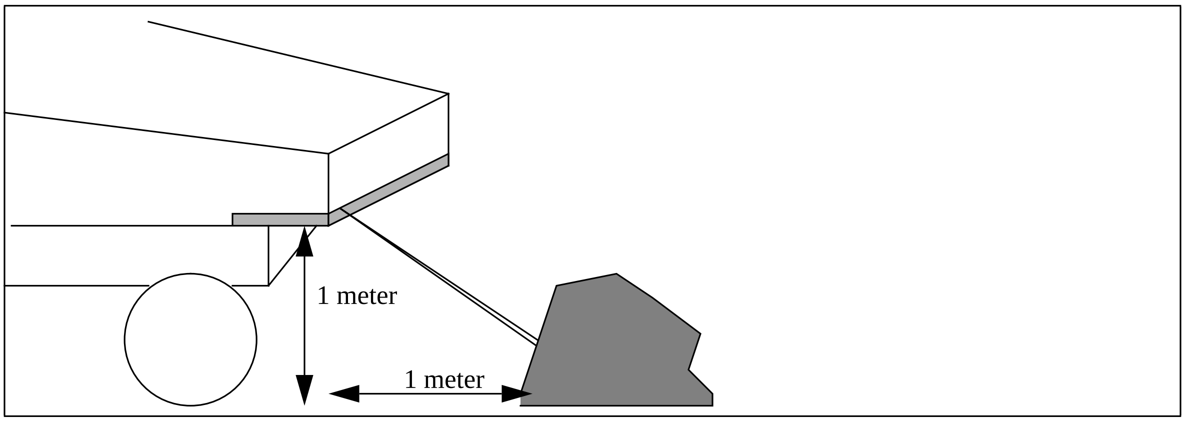

FIGURE 8.3 *Location of Infrared Array. Light gray area shows location of IR array. Active emitter-detector pair senses an obstacle.*

8.6.2 Far-Range Sensing

Based on the trade-offs discussed above, the rover will be equipped with stereo for lunar day operations and a laser light striper for night operations. The stereo system will use the imagery subsystem's front central camera as well as two additional "wing" cameras, one on each side. Normal operation will consist of using the central camera plus either of the wing cameras. The configuration gives the rover an ability to "blink" left or right while also providing redundancy in case of camera failure. In choosing a baseline for the system, there is a trade-off between the depth resolution and the ease of matching points in the scene. A larger baseline (baseline = 2d) will result in larger image disparities allowing for greater depth resolution, but will also decrease the area of overlap of the cameras and will increase occlusion effects which make stereo matching difficult. By choosing a required depth resolution at a certain distance it is possible to calculate the desired baseline. Figure 8.4 shows the basic paramets of the stereo equation. Given the focal length of our cameras (f = 7.5 mm) and the size of the sensor (8.8 mm), and choosing a depth resolution of 25 cm per pixel of disparity at 5 meters distance from the rover requires a baseline of approximately 37 cm. A baseline of 40 cm between the central and wing cameras was chosen. Since the rover has 50 cm ground clearance and can climb obstacles of 25 cm or less, this should give reliable detection at an adequate resolution for safeguarding the rover. This layout is shown in Figure 8.5. If it is found that higher reliability or higher resolution is needed for some reason, the camera configuration gives the operators the option of using the two outer cameras as the stereo pair or using all three for trinocular stereo at the cost of slower update rates given the necessary increase in computation.

This could be quite useful in especially rocky areas where the vehicle would be traveling more slowly and better detection would be helpful.

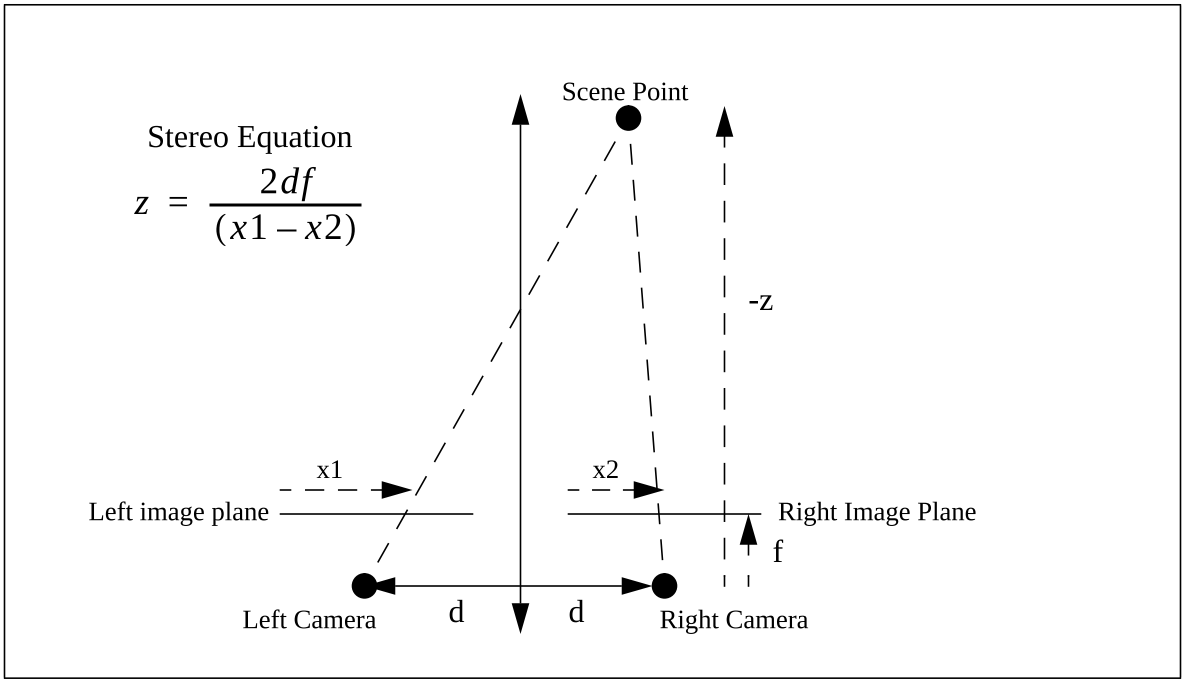

FIGURE 8.4 *Basic Stereo Diagram*

The camera for the light striper will be mounted on top of the rover, just above the front central imagery camera. The laser for the light striper will be mounted on a 1 DOF actuator below the front central camera, just under the body. Depending on how the system is implemented the light striper can be scanned in either azimuth or elevation using a vertical or horizontal laser stripe, respectively. From an actuator point of view, an azimuthal scan is probably preferable.

8.7 Navigation

Navigation must allow full speed (1 m/s) operation as much of the time as possible, and avoid trenches, craters and cliffs that may endanger the rover. Such “negative obstacles” are difficult to detect directly with a sensor even on Earth. Also, as the near range sensors can not be assumed to be 100% reliable, we want to minimize the number of times we utilize them for rover safety.

8.7.1 Prototype

Navigation software has been developed on the Ratler test vehicle, which uses a trinocular stereo head mounted on a motion-averaging mast (see Figure 8.6). The positioning system employs encoders, inclinometers, a compass, and a turn-rate sensor to maintain the position and orientation of the rover as it traverses. The system has operated successfully during long-duration field exercises in the face of significant sensor noise. The approach is to apply aggressive filtering to readings from a suite of simple sensors.

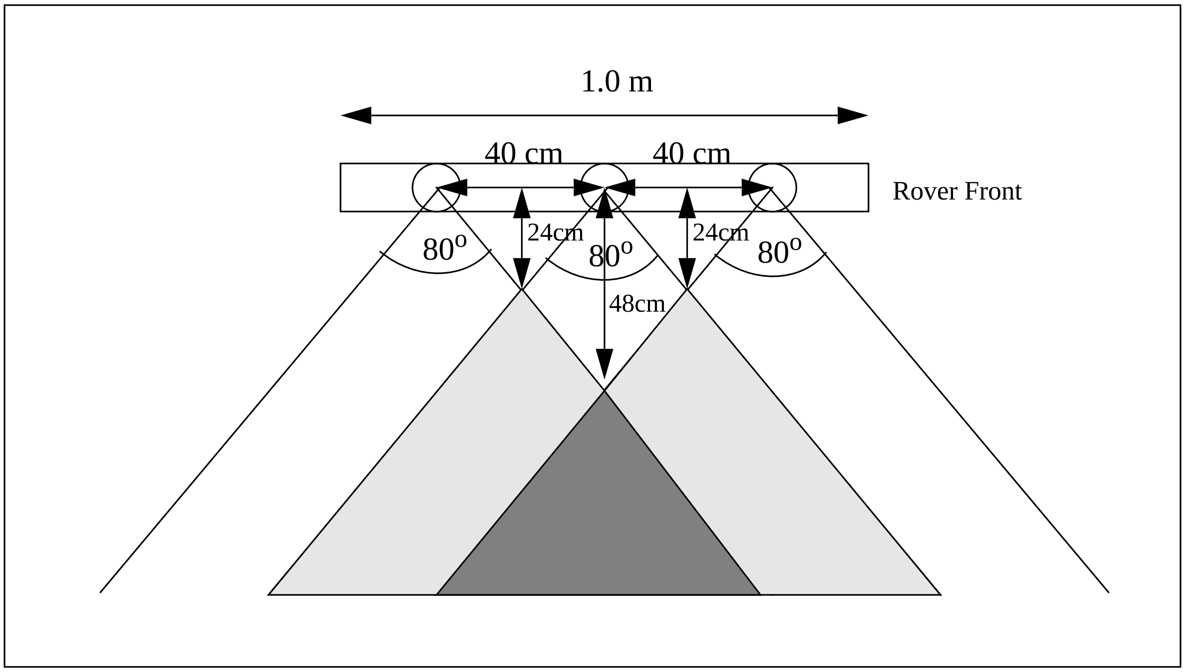

FIGURE 8.5 *Overhead view of Stereo Cameras. Light and dark shading shows overlap of outer and inner camera views. Darker shading shows overlap of two wing camera views*

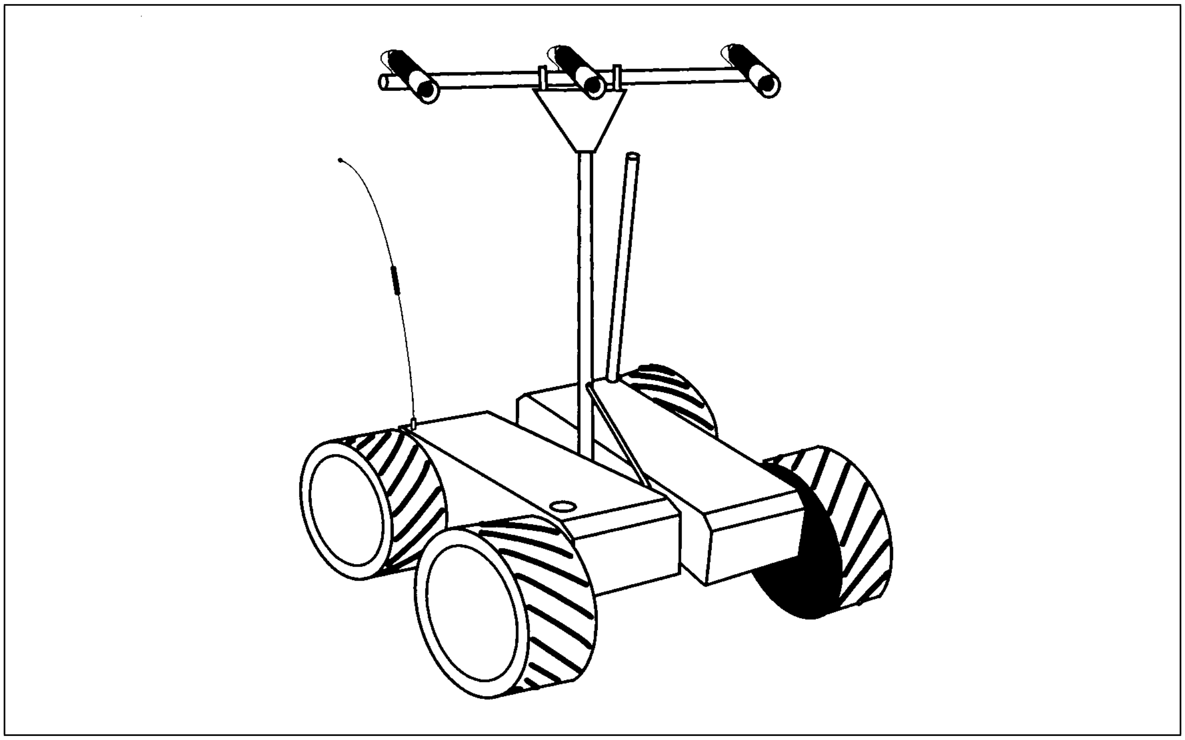

FIGURE 8.6 *The Ratler test vehicle uses a trinocular stereo head mounted on a motion-averaging mast*

The system uses two Sparc 10's (approx. 50 MIPS each) for navigation. One is dedicated to stereo, the other does sensor filtering, path planning and displays the user interface. The stereo matching takes an average of about 0.7 seconds for one triple of images.

Mapping

The mapping system consists of a stereo module that derives terrain information from trinocular images. The hardware consists of three auto-iris 8 mm lenses, CCD cameras mounted on a motion-averaging mast, and on-board frame grabbers and processors. The mapping software takes as input a stereo triple and outputs arrays of the three coordinates X, Y, and Z of the image pixels. Imaging requirements constrain the location of cameras:

- *Lookahead distance:* The cameras must see far enough ahead that, traveling at full speed, the software has time to recognize obstacles and steer around them. At a maximum speed of 0.7 m/s for the Ratler, the cameras must see at least 1.5m from the front wheels.
- *Width of field of view:* The cameras must see at least 3 vehicle widths at all distances beyond the lookahead distance, so that the rover can maneuver around obstacles one vehicle width in size.
- *Resolution:* An obstacle 20 cm tall must subtend at least 6 pixels in order to be reliably detected.

Given these requirements and others, a complicated trade-off analysis was performed. After extensive simulation and experimentation, a camera height of 1.5m, a baseline of 0.9m, and a tilt angle of 25 degrees down were chosen for the Ratler.

Images are first rectified in software to bring the epipolar line of any point in one image to be along the horizontal line with the same y coordinate in the other images. The best disparity is then computed by finding the maximum over horizontal offset of the normalized correlation over a rectangular window.

Area based stereo, although well established, is known to produce a potentially large number of false matches due to lack of texture, occlusions, and repetitive patterns. In order to achieve the level of reliability required for navigation, four types of filtering are used. The first two types use thresholds on (respectively) the standard deviation of the distribution of intensity in the neighborhood of a pixel, and on the best correlation for a pixel. These classical filters eliminate the low-textured areas and part of the occluded areas.

The third filter is designed to eliminate ambiguous matches. It uses a threshold on the relative difference between the global maximum of correlation and the second best peak in correlation. This test is effective in discarding pixels at occlusion boundaries and ambiguous matches due to repetitive patterns. The last filter is a median filter on the disparity map.

To reduce the computer time needed to process the stereo, the planner computes the interval of distances for which the stereo matching will add information to the map already built. Experience with the Ratler confirms that only a small fraction of the image needs to be processed once the navigation system is in a steady state. Further reduction of the computation time may be achieved by evaluating the correlation at a subsampled set of pixels, but using the full resolution for calculating the correlation at a given pixel. The combination of selective windowing and partial subsampling allows us to achieve both the computational speed and the precision required for continuous motion at low speeds without using special purpose hardware (only a Sparc 10).

Mapping Performance

The longest stereo run took place over 6 hours of intermittent operation (interrupted by rain and battery recharges) as Ratler traversed 1,078 m over the rough terrain of a slag heap. During this trial, the stereo module processed at least 3,000 image triples, and computed at least 1.5 million three dimensional points. The only failures observed were due to transient effects caused by disconnection of video cables, and by abrupt lighting changes that overwhelm the auto-iris lenses.

Positioning

The raw data from the sensors is biased and noisy and sometimes corrupt. Performing a spectral analysis of the data suggested using a low pass filter such as the Butterworth or Bessel filters. These were implemented, and while extremely effective in suppressing the noise, they also introduced a 2-3 cycle delay between the filtered value and the signal. The solution was to use a Kalman filter with a sensor model that heavily weights the previous reading if the turn-rate sensor indicates that the robot is accelerating. The resulting improvement is dramatic.

8.7.2 Navigation and Positioning for the Lunar Rover

The techniques involved in and lessons learned from camera placement on the Ratler can be used on the rover. Ratler's stereo based navigation can be used directly by the lunar rover. The only issue is parallelizing the algorithms. The stereo matching algorithm above, and all improvements except the selective windowing are applied to pixels independently, and hence are trivially parallelizable. The rectification is also trivially parallelizable. The selective windowing algorithm is fast and could be done by a single processor (leaving the others idle) without significant degradation. Although some sensors may be different, the Kalman filter with turn-rate based models should work well for whatever sensors are finally chosen.

The Ratler has used two Sparc 10s (50 + 50 MIPS) to run at 0.3 m/s, whereas we want to run at 1 m/s. However, the planning computer was spending some of it's time running the user interface, and the maximum speed of the current setup has never been fully explored. Several improvements to both the stereo matching and path planning algorithms have been envisioned which would allow the rover to run at 1 m/s with 50 MIPS for stereo and 20-25 for path planning.

8.8 Failure Modes

Unlike some of the other subsystems, collapse of the safeguarding system does not render the rover inoperable. However, it would severely limit rover velocities and rover control by amateur teleoperators. Having several layers to the safeguarding system makes the system more robust to failure by any one component. There is some redundancy at each level. Three cameras usable for stereo provides some redundancy: failure of any one camera does not eliminate stereo vision. If a second camera should fail and render stereo inoperable, it is still possible to operate the rover with almost full functionality. The loss of the ability to see far ahead will simply make panic halts more frequent and careful operation more desirable.

In the current design, there is no redundant laser light striper. It was felt that it was not worth the extra mass and complexity required to carry a redundant device, since light stripers are quite reliable. Moreover, loss of the light striper simply makes panic halts more frequent but does not seriously jeopardize the safety of the vehicle.

The near-range sensing offers component redundancy as well. Failure of one or two IR modules is insignificant. In the very unlikely case that the multiplexing and modulation circuitry should fail, rendering the IR sensors inoperable, the maximum speed of the rover could be decreased giving the far-range sensors ample opportunity to build a reliable map of the area ahead of the vehicle. Performance of the rover would not be significantly compromised.

Finally, if contact-sensing should fail (such as a broken switch) collisions should still be detectable by other means. Sudden increases in wheel motor currents or a discrepancy between the wheel speed and a ground speed radar could indicate a collision.

Since redundant components are included in the design for both the IMU and star tracker, a single failure of either will not affect the mission. Failure of both IMUs would force the star tracker to provide fixes as fast as possible. In this situation, antenna pointing would suffer and some bandwidth might have to be eliminated or sent through the other rover. If the second star tracker fails, the rover will not be able to point the antenna in the right location and the rover would be forced to transmit its data stream through the omni-link to the other rover. The other rover would then relay this data to earth. Because of the redundant communication paths, failure of both IMUs or star trackers does not result in a failed mission.

The short term responses to various navigation failure modes are to slow down, switch in backup computers, and to rely more heavily on the near-range and touch sensors for collision avoidance. In the longer term, the computers are fully reprogrammable from Earth. Stereo can continue with only two of the three cameras, but with more errors and (possibly) a narrower field of view. In the case of a complete failure, the rover can still be driven directly by experts from Earth.

TABLE 8.2 *Failure Modes*

Component	Failure Mode	Effect	Prevention and/or Response	Criticality
IMU	Single Failure	None	Use backup	3
	Dual Failure	Possible antenna tracking problems	Increase fix rate of star tracker and use data directly, or transmit to other rover	2
Star Tracker	Single Failure	None	Use backup	3
	Dual Failure	Loss of Antenna Pointing	Transmit through other rover	2
Stereo Camera	Single Failure	Reduced FOV	Use other cameras	2
	Dual Failure	Loss of Depth Info.	Reduced rover velocities	2
Light striper	Single Failure	Loss of Depth Info.	Reduced rover velocities	2
IR Sensors	Single Failure	Insignificant	Redundant sensors	2
	Multiple Failure	Possible blind spots	Reduced rover velocities	2
	Complete Failure	Loss of near-range	Reduced rover velocities	2
Contact Sensing	Broken switches/ contacts	No effect on rover operation	Use indirect methods of collision detection	2
Computing Hardware	Computers Stop Working	Can't Navigate Autonomously	Highly Reliable and Redundant Electronics	2

8.9 Open Issues

The implementation of the contact sensing has not yet been chosen. One rather elegant means of providing the contact sensing can be found on the TRC LabMate robots. In the LabMate robots, an insulating mesh separates a conductive foam material from a flexible metal backplate. The foam is then covered on the outside by a rubber sheath. An impact to the outer skin pushes the foam through the holes of the insulating mesh, causing it to make electrical contact with the metal backplate.[2]

It is still unclear precisely how the laser light striper will be implemented. A custom VLSI chip like that built by Kanade and Gruss but with a greater resolution (perhaps 60 x 64) would be the ideal solution. The VLSI sensor provides fast, accurate depth information. Other implementations such as scanning a collection of stripes in sets would be adequate but would be far slower.

The details of the navigations algorithms are still being refined, so the ultimate processing requirements have not been pinned down. However, the system has been demonstrated at speeds up to 0.3 m/s running on two Sparc 10s with power to spare (that was used for the user interface). This places an upper bound on the amount of computing needed for the rover. This estimate needs to be refined further.

The reliability of these algorithms needs to be tested for longer traversals and times. The longest run up to this point is 6 intermittent hours. Also, possible user interfaces need to be compared, keeping in mind the 5-6 second delay.

It is not clear that we can get a wide enough field of view with three equally spaced cameras. Two pairs, one on each side of the rover, would provide a wider field of view.

8.10 Summary Budgets

TABLE 8.3 *Summary Budget*

Component	#	Total Mass [kg]	Average Power [Watts]	Standby Power [Watts]
Stereo Camera	2	2	11	0
Light Striper	1	3	15	0
IMU	2	2	5	0
Inclinometer	3	1	2	0
Star Tracker	2	1	5	1
IR Sensors	~20	1	5	0
Average Total		10	23-27	1

References

1. J. Anthes, et al. “Non-scanned LADAR Imaging and Applications.” *SPIE Proceedings*, Vol. 1936, No. 1936-03.
2. Everett, H.R. *Sensors for Mobile Robots: Theory and Application*. (Rough Draft), 1994.
3. A. Gruss, S. Tada and T. Kanade. “A VLSI Smart Sensor for Fast Range Imaging.” *Proceedings of ARPA Image Understanding Workshop*, 1993.
4. T. Kanade, A. Gruss, and L.R. Carley. “A Very Fast VLSI Rangefinder.” *Proceedings of International Conference on Robotics and Automation*, 1991.
5. S. Nayar, et al. “Real-Time Focus Range Sensor” Columbia University Department of Computer Science Technical Report CUCS-028-94, 1994.
6. J.L. Novak and J.T. Feddema. “A Capacitance-based Proximity Sensor for Whole Arm Obstacle Avoidance.” *IEEE Proceedings of International Conference of Robotics and Automation*, 1992.
7. M.W. Scott. “Range Imaging Laser Radar,” Patent #4,935,616, assigned to the United States of America as represented by the Department of Energy, Washington, D.C.
8. W. Thompson et al. “Map-Based Localization: The Drop-Off Problem.” *Proceedings of Image Understanding Workshop*, 1990.
9. R. Volpe and R. Ivlev. “A Survey and Experimental Evaluation of Proximity Sensors for Space Robotics.” *IEEE Proceedings of International Conference on Robotics and Automation*, 1994.
10. E. Krotkov and M. Hebert. “Mapping and Positioning for a Prototype Lunar Rover.” *Proc. IEE Intl. Conf. Robotics and Automation*, 1995.
11. R. Simmons, et al. “Experience with Rover Navigation for Lunar-Like Terrains.” *Proc. Intl. Lunar Exploration Conf.*, November 1994.
12. E. Krotkov, et al. “Lunar Rover Technology Demonstrations with Dante and Ratler.” *Proc. Intl. Symp. Artificial Intelligence, Robotics, and Automation for Space*, October 1994
13. E. Krotkov, et al. “Stereo Driving and Position Estimation for Autonomous Planetary Rovers.” *Proc. IARP Workshop on Robotics In Space*, July 1994.

Chapter 9

Command, Communications, Control & Telemetry

The C^3T subsystem is responsible for the overall command and control of the rover. It is ultimately responsible for the rover's "health." C^3T must maintain constant communication with Earth to provide the imagery and telemetry as well as accept teleoperation commands. It must process, package, and transmit telemetry data from a variety of sensors distributed throughout the rover. There must be a means for operators on Earth to send commands to the rover and assume control of many of the subsystems.

9.1 Requirements

- Must monitor all aspects of operation (including communications, power, thermal, locomotion, and computing) and report status to ground station on Earth.
- Must transmit compressed video streams.
- Must communicate telemetry from GNC to Earth.
- Must process commands from Earth that control other subsystems.
- Ability to reprogram the code during the mission.
- Real time control and high reliability.
- Supply ~70 MIPS for navigation.
- Support common operating system and development tools.
- Tolerant of high radiation.

9.2 Interfaces

Figure 9.1 shows the main interfaces within this subsystem and to GNC and the other subsystems.

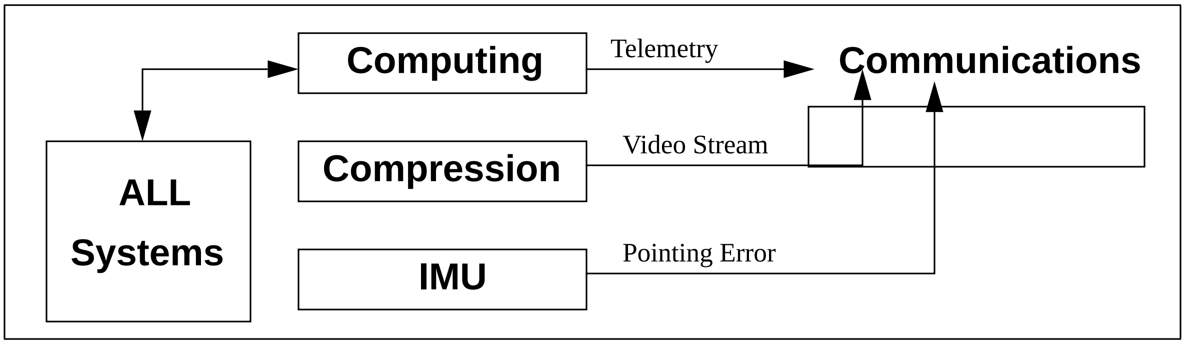

FIGURE 9.1 *Block Diagram of CCCT System*

9.3 Computing

The main functions for the computing system is to provide housekeeping & system tasks for all subsystems, and enable autonomous operation. For each subsystem two general tasks were associated: Housekeeping and System Tasks.

The Navigation subsystem requires the most processing power. According to the software requirements for stereo based navigation the computer processing speed is about 70 MIPS. The need for a "navigation computer" with significantly more processing speed than the other subsystems divided the design of the computer system into two parts: Subsystem Controllers and Navigation Computer.

9.3.1 Typical Controller

A subsystem controller provides real time control to the subsystems. The controller is an embedded radiation hardened computer with autonomous processing capability and high reliability. The controller can handle subsystem tasks and provide status telemetry. A basic controller is shown in Figure 9.2.

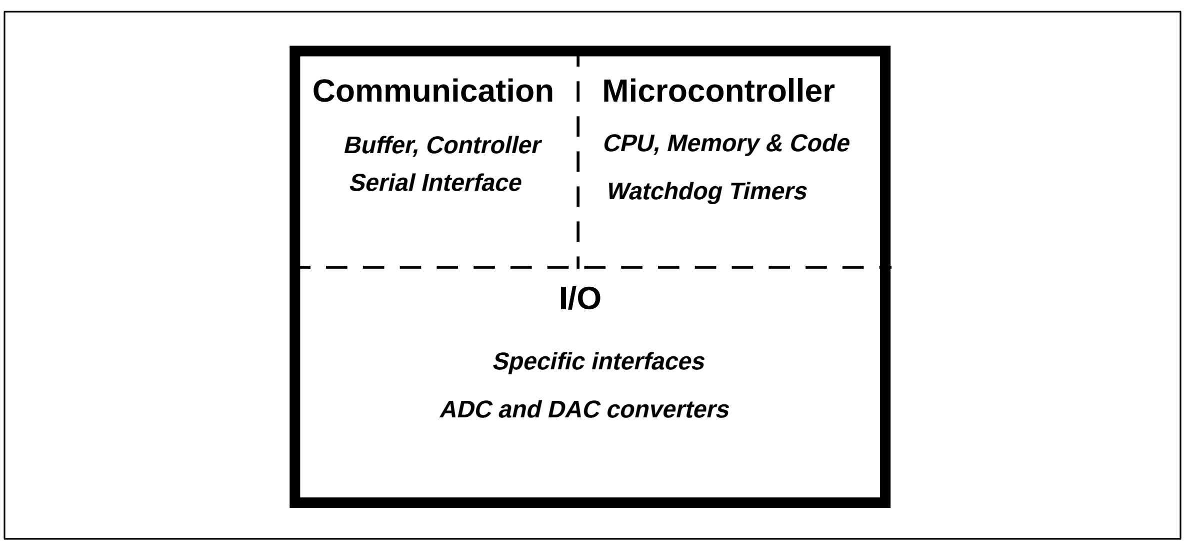

FIGURE 9.2 *A Typical Controller*

9.3.2 Navigation Computer

The navigation computer uses stereo perception (during the lunar day), light striping (at night) and path planning to enable semi-autonomous operation and avoid potentially hazardous situations. Stereo matching will require approximately 50 MIPS and path planning an additional 20. The most powerful rad-hardened boards achieve approximately 20-25 MIPS. Stereo is directly parallelizable, so three boards are sufficient to perform stereo matching at the required speed, and one additional processor will be used to perform path planning.

9.3.3 Hardware Survey

Existing computing hardware was evaluated according to the following criteria:

- Flight history
- Maturity
- Computing power of ~20 MIPS or greater
- Reputation of suppliers
- Support for software development(e.g., C, C++, and VxWorks)
- Network capabilities
- Size, weight, and power
- Computer speed and power consumption adjustable under software control

Only three computer boards were found to meet the above criteria:

1. RHC-3000 from Harris Corporation
2. RAD6000 from Loral Federal Systems-Manassas / IBM
3. RH32 from Honeywell Space Systems

As a more mature product and satisfying many of the requirements, the Harris RHC-3000 is recommended. See Table 9.1 for a comparison of the computer boards.

TABLE 9.1 *Comparison of selected computing boards*

Description	RHC-3000	RAD6000	RH32
Flight History	No	No	No
Support C, C++, VxWorks	Yes	Yes	Yes
Adjustable speed & power using software	Yes	Yes	Yes/Software?
Power @ speed	3.3W @ 2.5 MIPS 4.5W @ 4.9 MIPS 7.5W @ 19.7 MIPS	3.0W @ 5 MIPS 10W @ 35 MIPS	6W @ 18MIPS 8.7W @ 23 MIPS
VME board	Yes	Yes	N/A
Network support	Yes	N/A	N/A
Redundancy and Fault management	Yes	Yes	N/A
Off the shelf	Yes	No	No

9.3.4 Computer Architecture

Three computer architectures were considered:

- The first scheme is a centralized architecture (see Figure 9.3). In this scheme all subsystems are connected to a central computer containing all the processing power to service all subsystems requirements. This central computer has multiple computer boards and interfaces

  This scheme has a single point failure in the main computer: a fault in one of the computer boards might cause a failure of the entire central computer. As well, it is difficult to implement redundancy in this configuration.

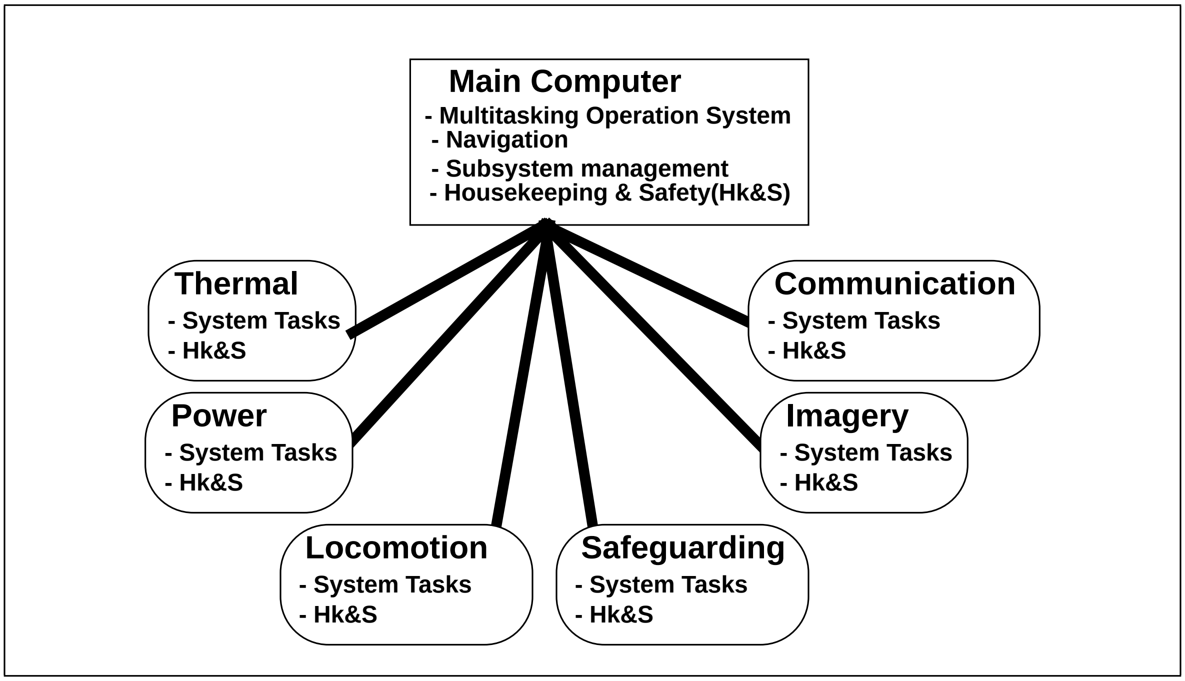

FIGURE 9.3 *Centralized Computing Architecture*

- The second scheme is a networked distributed computer system (see Figure 9.4). In this scheme computers 1 to 6 are subsystem controllers and computer 0 is the navigation computer. Each controller is a single board computer < 20 MIPS with adjustable computer speed and power. Each subsystem is normally controlled by one dedicated controller. If one of these fails, one of the other controllers can control two subsystems.

  This scheme has the advantage of being able to tolerate a failure of any single controller. The short distance between sensors/actuators to the controller is also an advantage. In case of failure of the navigation computer the navigation software will be running on Earth and will be transmitted directly as commands to the robot through the communication hardware. This scheme has many processors, most of which are under utilized. There is also much network software, which increases the software complexity.

- The third scheme is a modification of the second. In this architecture the navigation computer (computer 0) is the same as before. The controllers, now reduced to 4, are custom boards using RHC-3000 processors. Controllers 1 and 2 are connected to the navigation subsystem. Controller 1 is dedicated to control-

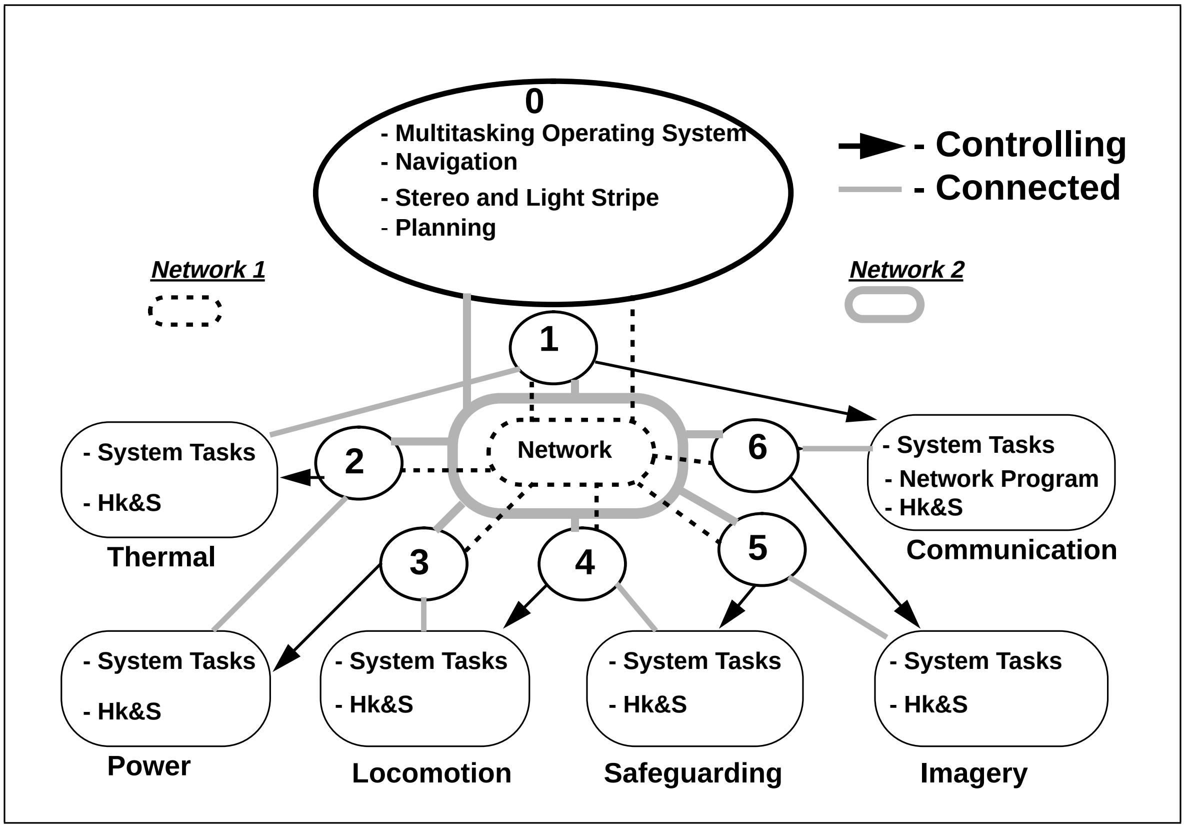

FIGURE 9.4 *A Decentralized, Moderately Fault Tolerant design. Numbered circles are independent computers.*

ling the locomotion subsystem and controller 2 is a backup and the only other board that can control locomotion. Controller 3 controls all other subsystems and 4 is a backup that can take the place of any controller, including those in the navigation computer, except controller 2.

9.4 Communications

The communications architecture consists of several antennas to allow for high-bandwidth communication between each rover and Earth and between the two rovers. Most of the attention here goes to the primary downlink from rover to Earth since its requirements are the most stringent (the same antenna is also used as the primary receiver). However, mention will also be made of the backup and inter-rover antennas. Although the design of the Earth-based communications stations has been considered and has impacted the design of the rover's primary antenna, the Earth station will not be discussed in detail here.

9.4.1 Antenna Options

The primary antenna serves to relay all the video and telemetry data to Earth. The data requirements are estimated to be on the order of 6 Mbit/sec. Three different communication technologies were considered for the main communications link to Earth: parabolic dish, phased array, and optical. The three technologies will be discussed (see Table 9.2) and then the antenna design will be detailed.

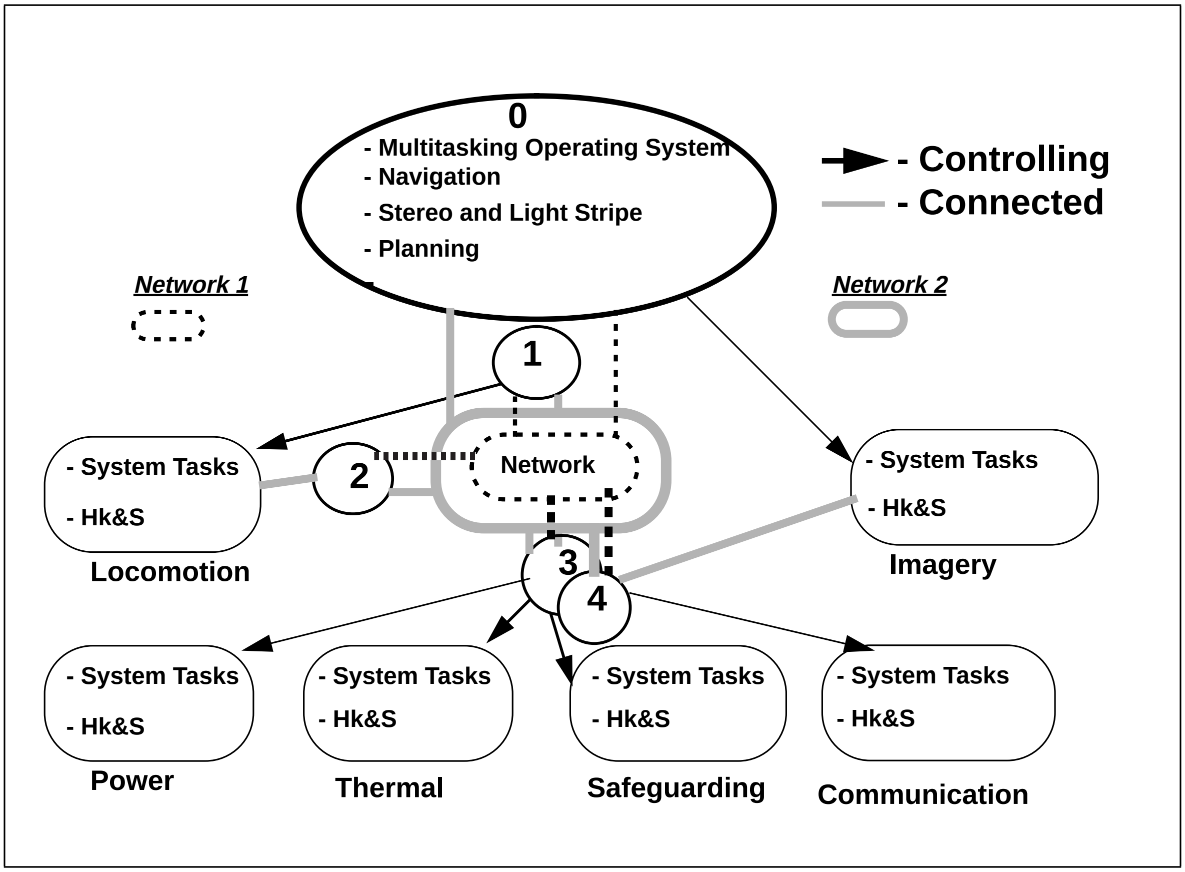

FIGURE 9.5 *Recommended Computer Architecture. Numbered circles represent independent computers. 2 and 4 are backups.*

Omnidirectional Antenna

Although omnidirectional antennas are widely used and have an extensive flight history, it would require hundreds of watts of output power (kilowatts of input power) to transmit the required bandwidth. Use of an omnidirectional antenna for the primary communications link could not be seriously considered for this reason.

Parabolic Dish

Parabolic dishes are the most widely used antennas for high bandwidth communications for space applications. The technology is well understood and has proven very reliable. They provide high gains, enabling high bandwidth communication over long distances without consuming much power. Parabolic dishes must be mechanically pointed with high precision which is a major challenge from a moving rover. The major drawback of parabolic dishes is their size. Although a parabolic dish sufficient for rover use operating in the Ku band would require a diameter of approximately 1 meter, a dish operating in the S-band would have a diameter of 6 meters. An S-band antenna is preferable for two reasons. The first is that it will likely be easier to license bandwidth from the Federal Communications Commission (FCC) in the S-band than in Ku. The second is that it is easier to construct a large S-band antenna on Earth than one operating in the Ku-band because the S-band antenna can tolerate a larger surface corrugation. Tolerances for antenna surface corrugation are proportional to the wavelength of the signal, and S-band wavelengths are 6 times larger than Ku-band wavelengths. A 6 meter dish, however, is clearly impractical for a 2-meter-long rover, so we were limited to Ku band if we went with a parabolic dish antenna.

Phased Array

Although a less mature technology than parabolic dishes, phased arrays have matured greatly over the last couple years and are beginning to see some flight tests. Phased arrays have several advantages. First, they are smaller than parabolic dishes, so it is possible to design an S-band phased array of a reasonable size (1 meter). Second, the beam may be electrically, rather than mechanically, pointed by adjusting the phases of the individual transmitters. This allows for very fast and precise steering of the communications beam which is very important for high bandwidth communication since the data rate is inversely proportional to the angular offset.

Optical Communication

Optical communication is relatively new and there are many unsolved problems. The main reason for its consideration is that the bandwidth licensing problems do not exist with optical communication since lightwaves can pass through each other without interference. It also has the advantage that the components are small and an optical communication device would not occupy a large percentage of the area on top of the rover. However, the pointing problem is severe, since an error of x degrees in the mirror angle causes an error of $2x$ in the beam direction. Additionally, building the ground station and its pointing device would also be difficult and very expensive. Since there is so little experience in the field, most of the hardware would have to be developed and custom-built. However, optical communication will be our only option if licensing adequate bandwidth from the FCC proves to be impossible. Optical communication hardware has almost no flight history.

TABLE 9.2 *Summary of Antenna Trade-offs*

Scheme	Maturity	Flight History	Notes
Optical	Low	Limited	- High data rates possible - Very precise pointing required
Omnidirectional Antenna	High	Extensive	- limited link capability; low data rates - High power (several hundred watts output) to achieve data rates
Phased Array	Medium	Some	- Rapid steering possible
Reflector Antenna	High	Extensive	- Precision pointing of antenna is required. - Low mass, cost and complexity

9.4.2 Primary Antenna

Based on the trade-offs outlined above, it was decided that a phased array antenna operating in the S-band portion of the frequency spectrum was the best option. Further trade-offs were involved in designing the complete antenna system. A bit error rate (BER) of 10^{-5} was deemed acceptable for video data. The coding scheme chosen, BPSK Plus RS and Viterbi, makes inefficient use of bandwidth, but takes less input power than other coding scheme alternatives. To achieve the necessary data rate, the phased array will consist of 225 elements and the Earth receiver station will have a 30 meter dish. These sizes are reasonable for their respective domains. The phased array antenna layout is shown in Figure 9.6. A functional block diagram for the communication system is shown in Figure 9.7.

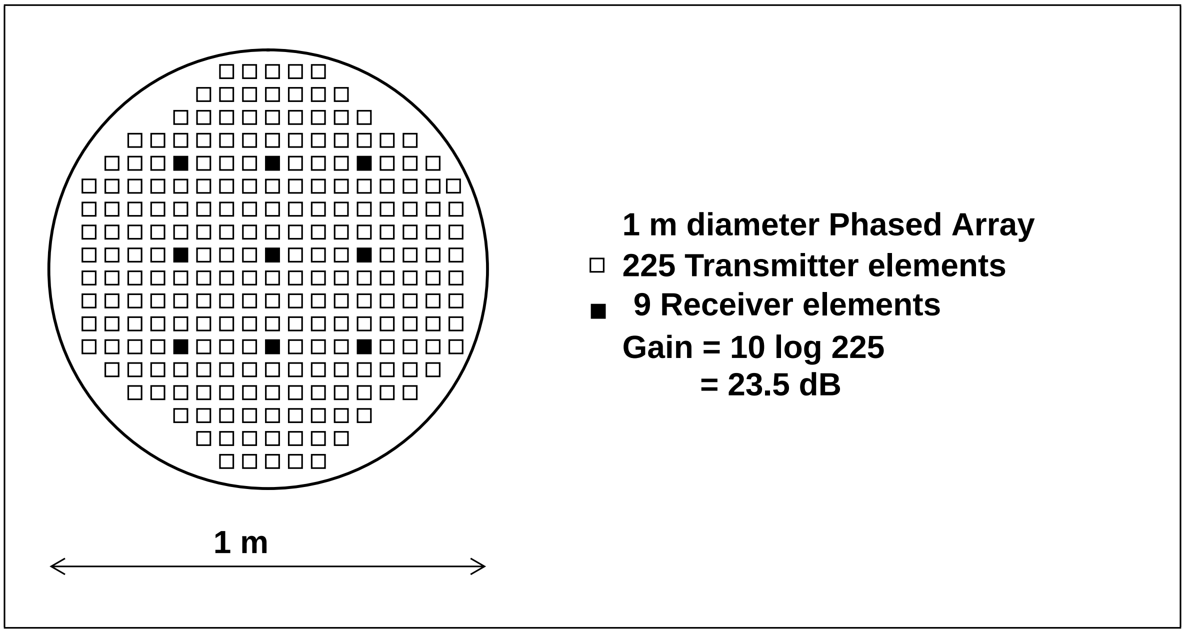

FIGURE 9.6 *Phased Array Antenna*

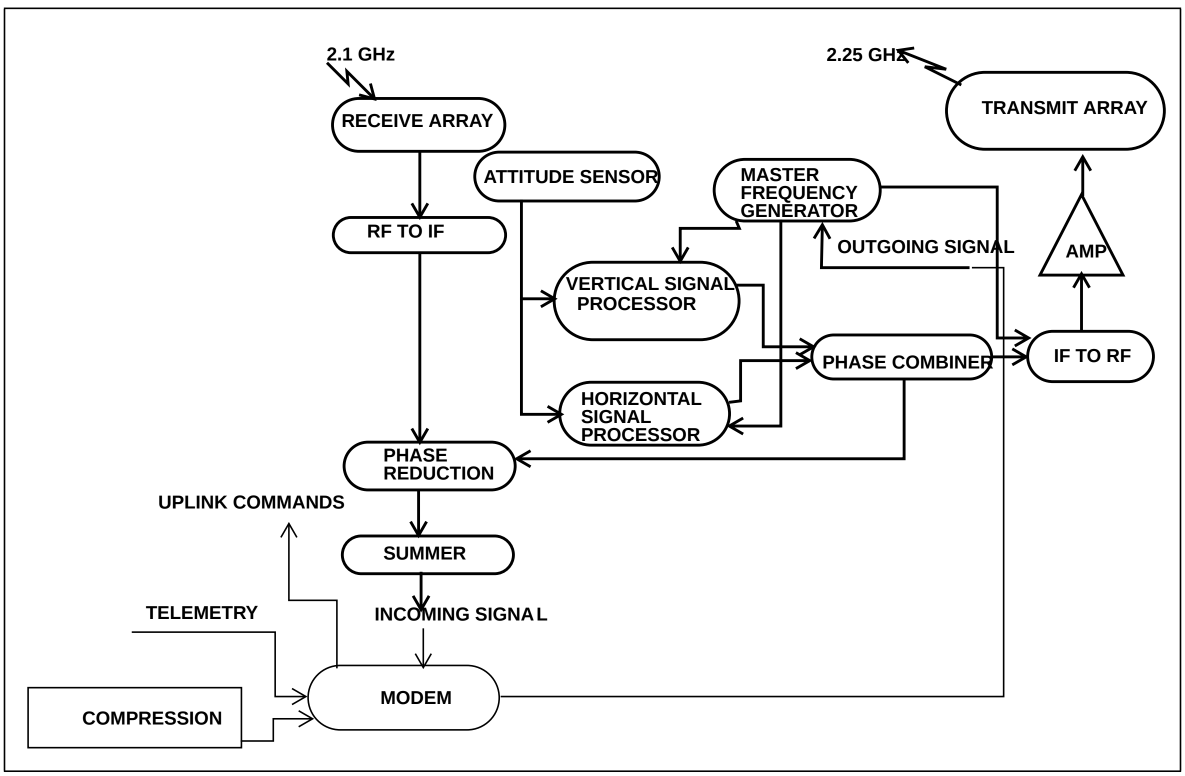

FIGURE 9.7 *Functional Block Diagram of Antenna*

The antenna will be mounted on an actuated platform. The front of the platform will rest on a ball-in-socket joint. The back end of the platform will be supported by two linear actuator links. Control of these two links will allow steering of the antenna based on the platform controller. The controller will read data from the Inertial Measurement Unit (IMU). Encoders on the linear actuators will allow body IMU coordinates to be transformed into antenna platform coordinates. The controller loop that adjusts the platform will be highly damped, so that the platform should point in the general direction of Earth but will not try to compensate for short-term disturbances. A fast control loop will adjust the phase of the transmitter units to steer the beam towards Earth.

The electronic steering is very fast and covers a range of +/- 30^o from the platform vertical. This range is enough to compensate for the angular excursions due to climbing rocks or changes in slope. The link budget used to analyze the communications array is shown in Table 9.3.

TABLE 9.3 *Link Margin Analysis*

Item	Value	Comments
Frequency	2.25 GHz	S-band
Power (Transmitted)	15 W (11.7 dB)	~ 80 W input power
Transmitter Gain	23.5 dB	225 elements
Receiver Gain	54 dB	30 m dish
Data Rate	67.8 dB	6 Mbps
Bandwidth	12 MHz	BPSK Plus RS and Viterbi
Space loss	211.7 dB	384,400 km
Implementation loss	1.5 dB	Line loss
Receiver Noise Temp	27 dB	230 ^oC
Eb/No	9.8 dB	
Eb/No (required)	2.7 dB	BER 10^{-5}
Link Margin	7.1 dB	Good for S-band

9.4.3 Inter-Rover Communication

There will be an omnidirectional antenna on each rover for inter-rover communication. The antenna will operate in the S-band as well since there is an abundance of available components in that frequency band. A similar link analysis was performed. The analysis showed that 0.02 W output (< 1 W input power) is enough to enable all data (6 Mbits/sec) to be sent from one rover to the other up to a distance of 2 km.

9.4.4 Backup Omnidirectional Antennas

Backup omnidirectional antennas were included in the communications system in case the primary antenna loses its lock on Earth. Since there are no pointing requirements for omnidirectional antennas, low bandwidth communications over the backup omnidirectional link is possible even when the primary antenna has lost its lock. This backup thus enables the system to send some sort of heartbeat signal and receive commands at all times. If the data feed from the rover ceases on Earth, it is possible to send a “lost signal” message and a “realign antenna/search for Earth” command. Only one omnidirectional antenna needs to be active at a time, and only if the primary antenna should fail. The omnidirectional antennas are currently designed to produce a

1 W S-band signal, requiring a power input of approximately 10 W. A link analysis shows that the omnidirectional antenna is capable of sending approximately 2 kbps of data to Earth.

9.5 Failure Modes

Complete failure of the communication would be disastrous to the mission. The communications system is robust to failure in several ways. First, the phased array has inherent redundancy: failure of a few transmitters will not seriously degrade antenna performance. Second, if the phased array does completely fail, communication to Earth is still possible via the inter-rover communications link and the other rover's phased array. Third, the backup omnidirectional antennas provide a link to Earth which is not subject to pointing problems, albeit at a greatly reduced data rate. There will be a redundant master frequency generator since this is the only single point failure in the communications architecture. Due to the inherent redundancy of the computer architecture, multiple failures of subsystem controllers is the main weakness. See Table 9.4 for more details on failure modes.

TABLE 9.4 *Failure Modes*

Component	Failure Mode	Effect	Prevention and/or Response	Criticality
Phased Array	Single/ Multiple Transmitter Failures	Insignificant	225 elements	3
	Complete Failure	Little or None	Transmit via other rover	2
Inter-rover Link	Single Failure	None or loss of product if phased array fails too	Inter-rover link is a secondary communication link	3
Omni-directional	Single/Dual Failure	None unless other systems are down	Omnis are tertiary link	3/1
Navigation Computer	Single/Dual Failure	Slower navigation	Redundant, rad-hard processors	2
	Complete Failure	No internal navigation	Rely on near-range safeguarding	2
Subsystem Controller	Single/Dual Failure	Backup controller takes over	Redundant, rad-hard processors	2
	Complete Failure	No computation	Redundant, rad-hard processors	1

9.6 Open Issues

The biggest stumbling block in the communications system is licensing the 12 MHz necessary to transmit 6 Mbps of data to Earth using the current coding scheme. If we are unable to secure such a large portion of the frequency spectrum, the coding scheme will have to be changed so that we can utilize the bandwidth more efficiently or the data rate will have to be decreased. Changing the coding scheme to utilize bandwidth more efficiently, however, will require more power for the communications array.

Telemetry data from the rover will also need to be transmitted to Earth. However, it has not been decided exactly which data will be transmitted and how often. Attitude data will need to be sent continuously. Temperatures and other subsystem operating data will also be sent, but many of these can be transmitted at a lower rate. Although we currently have budgeted for 100 kbps of telemetry data, this may be reduced depending on how much bandwidth we are able to license.

Communications protocols between rover and Earth need to be designed, as well as the serial hardware interface between boards in the rover.

9.7 Mass, Power Budgets

TABLE 9.5 *Summary Budget*

Component	#	Total Mass [kg]	Average Power [Watts]	Standby Power [Watts]
Phased Array	1	10	80	20
Inter-Rover link	1	2	1	0
Omni-directional Antennas	2	2	10 (not used unless phased array fails)	1
Linkages for Antenna Platform	2	4	10	0
Navigation Computing Boards	4	3.6	40	10
Controllers	4	2.9	12	12
Total		24.5	142/72	43

References

1. "Harris Standard Spacecraft Processor Module, Technical Description". *Harris Corporation, Government Aerospace Systems Division.*
2. "Radiation Hardened 32-Bit Processor". *Honeywell Space Systems.*
3. Larson, Wiley J and Wertz, James R., "Space Mission Analysis and Design", Kluwer Academic Publishers, 1992.

Chapter 10

Imagery

The imagery subsystem consists of cameras, their corresponding frame grabbers, and data compression hardware. The requirements for this system, the proposed configuration, and an analysis of the design are addressed in this chapter, followed by a description of failure modes, detailed camera specifications, and discussion of open issues.

10.1 Requirements

Being the primary deliverable, the major requirement of the video subsystem is to provide a realistic lunar telepresence, in addition to educational and scientific observation. To achieve this task, the imagery must be fully immersive (i.e. in the form of a panorama) with sufficient quality for theme park usage. Moreover, it is highly desirable to provide imagery of one rover moving through the lunar terrain as well as views of the Earth and stars. Following is a list of the requirements:

- Telepresence: Color panorama at flicker-free video rate.
- Reliability: The cameras must be able to survive the two-year traverse, which implies two years of vibration and shock from the rover.
- Redundancy: Single failures must not diminish the visual product.
- Night Operation: Since the rover is designed to operate during both lunar day and night, the video subsystem should yield decent imagery even during the lunar night under soft Earthshine and starlight.
- Science payload: Facilitate exploration by providing pan/tilt/zoom functions.

10.2 Interfaces

After imagery is acquired through the optical device and CCD chips, the analog signals are streamed through frame grabbers to video data compression hardware, which is linked to the communication subsystem. The functional diagram is shown in Figure 10.1.

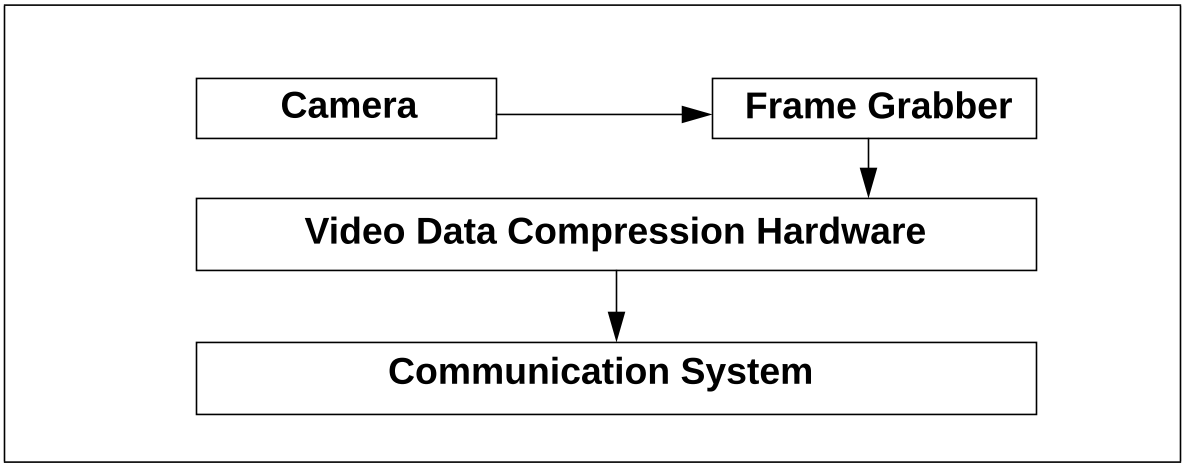

FIGURE 10.1 *Functional Diagram of the Video Subsystem*

10.3 Camera Configuration

The current design features an array of four color CCD video cameras (referred to as ring cameras) mounted around the periphery of the rover to provide a 360-degree real-time panoramic view, one color CCD video camera with a fish-eye lens mounted on top of the rover to provide a sky view, and one black and white CCD video camera with fish-eye lens mounted on the bottom of the rover (with a controllable lid) to provide a view of the ground beneath the rover body. Finally, a pan/tilt color CCD video camera with motorized zoom lens is mounted at the front top of the rover to facilitate scientific explorations.

The four ring cameras are mounted on the four sides of the rectangular rover, with the front one providing an 85x70 degree field of view and the rest providing 100x70 degrees each. This results in images which overlap by 25 degrees, allowing them to be stitched together into a panoramic view. Since the most interesting view will be around the horizon and in the near range, these cameras are mounted at 1.0 meter height on the rover body, tilted downward by 20 degrees to give a field of view which covers from -55 to 15 degrees in elevation. The pan/tilt camera is mounted above the front camera, at the height of 1.2 meters. The sky view camera is mounted on top of the rover. The belly camera is mounted in the center of the bottom of the rover. Figure 10.2 shows the top and side view of this configuration.

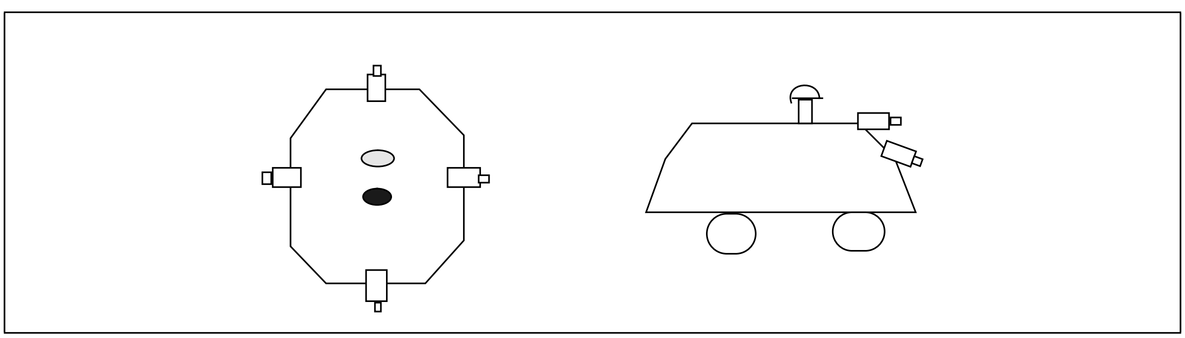

FIGURE 10.2 *Top and Side View of Camera Configuration*

Five frame grabbers are used. The first four are each connected to a ring camera, while the fifth is connected to the sky view camera, the pan/tilt camera and the belly camera, since they will not be used at the same time.

An LED light source is mounted between the front camera and the pan/tilt camera to provide illumination in the lunar night.

10.4 Design Analysis

10.4.1 Provide Imagery During Lunar Night

Calculations were carried out to determine that roughly 800 electrons can be gathered on a pixel that subtends 500 microradians in 0.07 seconds of camera integration time during the lunar night with full Earthshine. Assuming a noise level of 50 electrons for well-tailored cameras, this implies that the video subsystem should be able to provide 4-bit grey-level image data, which is sufficient for the purpose of theme park telepresence.

The current design proposes 4-bit grey-level panoramic imagery during the half of the lunar night in which the Earth is more than 3/4 full. During the other half of the lunar night, when the Earthshine is dim, only 4-bit grey-level images from the front camera and color images from the sky view camera are acquired and transmitted. Active illumination is provided for the front camera using the power saved on the other cameras and the communication load.

10.4.2 Work Within Limited Bandwidth

Finer CCD resolution will yield better quality imagery, but due to the limits of the communication subsystem and licensing issues, the data rate for image transmission is extremely limited. The current design approaches this problem through two procedures while assuming sufficient CCD resolution. The first step is to lower the transmission frequency by transmitting the panorama at 15 Hz (10 Hz in the lunar night to allow longer camera integration time) and the sky view at 0.1 Hz. Image interpolation needs to be carried out at the ground station to achieve flicker free imagery, which should not prove to be a problem. Secondly, MPEG-1 video data compression is applied to reduce the data rate to within the given bandwidth of 4.5Mbits/second.

10.4.3 Redundancy

Though even off-the-shelf cameras have been proven to be robust and durable in many tough robotic missions, there is always a chance for unexpected failure. Since the video subsystem should be the last part on the rover to fail, reasonable redundancy should be provided. The current design gives full redundancy for the panoramic imagery: identical cameras are mounted alongside the side and back cameras, while the redundancy of the front camera is provided by the two cameras that work together as binocular/trinocular stereo for safeguarding (described in Chapter 8). Only partial redundancy is provided by the star trackers for the sky view camera, since the sky view is considered a supplemental product rather than a necessity. No redundancy is given to the belly camera since it will most likely be used only when the rover becomes stuck, which should happen rarely, if ever. Provided as a luxury for encouraging scientific curiosity, the pan/tilt camera is designed with no redundancy. Full redundancy is provided for all frame grabbers and the light source.

10.4.4 Reduce Dark Current Effect

The dark current effect of the CCD chip degrades image quality, and it can increase by a factor of two for every eight degrees Celsius. Special purpose thermal electric cooling devices are applied to each CCD chip to keep them cool enough to provide satisfactory imagery.

10.5 Compression

The current design calls for 4 cameras returning video at 640 x 480 pixels at 15 frames a second. This amounts to 442 Mb/s. In order to transmit this or more over a 4.5 Mb/s communications link, the video needs to be compressed by roughly 100:1. Since video is the main product of the rover, we need to get the best possible picture quality at this ratio.

10.5.1 Comparison of Compression Methods

All compression algorithms can be classified as either *lossless* or *lossy*. In lossless compression, the data stream resulting from compressing and then decompressing is exactly the same as the original data stream. The best lossless compression methods can achieve compression ratios of, on average, about 2:1 for images and video of natural scenes. The different schemes are summarized in Table 10.1.

TABLE 10.1 *A comparison of various compression methods*

Method	Max Usable Compression Ratio	Comments	Acceptable
lossless	2:1	No degradation of picture at all	No
AVI / Indeo / QuickTime	10:1	Early multimedia formats	No
Px64 / H.261	100+:1	Trades quality for low latency	No
Motion JPEG	20:1	Doesn’t exploit interframe similarities	No
MPEG	150+:1	Designed for 1.15Mb/s video	Yes
Wavelet	200+:1	Still being researched	Yes, if available.
Fractal	200+:1	Requires great computational power	No

However, lossless compression isn’t required. We can take advantage of the limitations of the human eye and perform “visually lossless” compression, where the human eye won’t be able to tell the difference between the original and compressed-then-decompressed images. There are several such schemes for video.

AVI / Indeo / QuickTime

There were many proprietary schemes in the earliest days of multimedia, for both IBM compatibles and Macs. As the best boast compressions ratios up to 10:1, they won’t be considered here further.

Px64 / H.261

Developed by the CCITT, this format is designed for video conferencing. Px64 seeks to minimize encoding and decoding delay while achieving a fixed data rate. In digital telephony, delays larger than a few hundred milliseconds can be very annoying. It does this, in part, by assuming that motion is very limited. Although Px64 can achieve the needed compression ratio, the format sacrifices quality in order to get low latencies. Since our communication system has large latencies anyway (on the order of 5 seconds), it is better to have the quality.

JPEG and Motion JPEG

JPEG is the format for compressing still images developed by the Joint Photographic Experts Group of the International Standards Organization (ISO). Motion JPEG is a simple extension which applies the JPEG standard to each frame independently, and as such doesn't take advantage of interframe correlation to reduce the data rate. JPEG can typically achieve 10:1 to 20:1 without visible loss. 30:1 to 50:1 compression is possible with small to moderate defects. This is the current state of the art for still image compression, and is recommended for the high quality still images, to be done on one of the general processors. This is close to our needs of roughly 100:1, but is not acceptable. Motion JPEG is being used on U Maryland's RANGER project, and a variant of it was used on the Clemintine mission.

MPEG

MPEG (see Figure 10.3) is the format for compressing video and audio developed by the Motion Picture Experts Group of the International Standards Organization (ISO). There are now 2 different MPEG standards (named MPEG-1 and MPEG-2) which are both designed to get the highest quality video possible, but target different bitrates. MPEG-1 was designed for 1.15 Mb/s (the data rate from a single speed CD-ROM), whereas MPEG-2 targets 4 to 9 Mb/s. However, MPEG-2 was developed after MPEG-1 and contains several enhancements. It is not clear which performs better at our desired bit rates (0.8 - 1.2 Mb/s). MPEG-2 was recently chosen by the so called U.S. Grand Alliance of seven organizations to be the standard for HDTV.

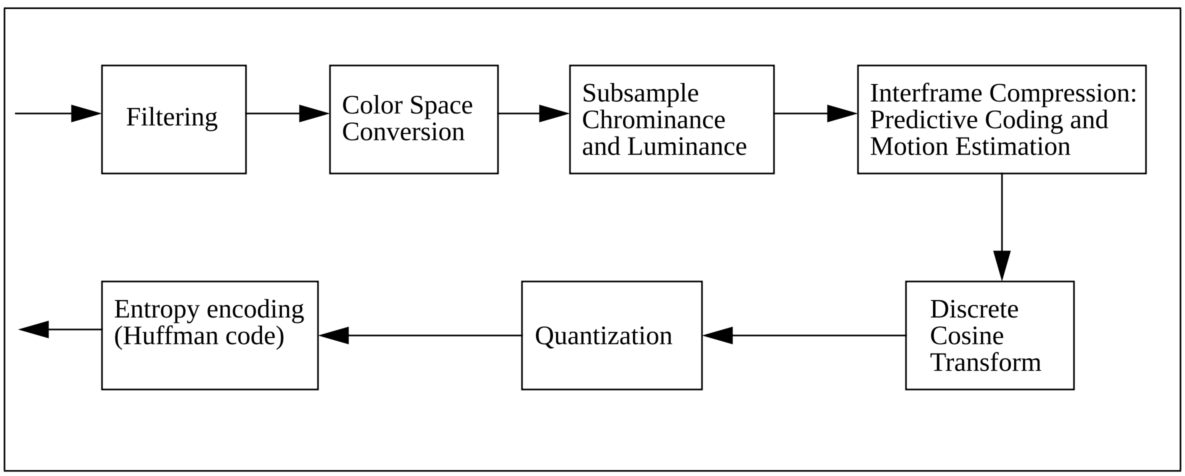

FIGURE 10.3 *The MPEG Compression Algorithm. The Motion Estimation and the Discrete Cosine Transform are the most computationally expensive components of the algorithm.[1].*

Although interframe compression can dramatically reduce the data rate of a video stream (in MPEG by an additional 10:1 or more), it has the disadvantage that if one frame is garbled, all following frames based on it are lost. In typical MPEG streams, a single faulty bit has a 2/3 chance of garbling a single frame, and a 1/3 chance of garbling up to 0.4 seconds of video.

Wavelet & Fractal

JPEG, MPEG and Px64 are all based on the DCT (Discrete Cosine Transform), which is similar to a Fast Fourier Transform. Some newer techniques promise higher compression ratios for comparable quality by replacing the DCT with a different transform. Wavelet compression represents an image in terms of functions called wavelets, and computes the wavelet coefficients using the fast wavelet transform. Fractal compression describes a picture in terms of a mathematical process which produces a fractal. Both these techniques are still image compression techniques, but if used independently on individual frames they could achieve the compression ratios of MPEG without the potential problems of interframe compression. Alternatively, if interframe compression is used, the rover could transmit more streams of higher resolution and quality. Both these techniques are still being developed in laboratories but are starting to enter the marketplace. However, fractal compression is too computationally expensive to be done in real time.

10.5.2 Comparison of Compression ICs

Current general purpose processors are simply too slow to perform MPEG compression in real time, so specialized hardware is needed. We currently have information about three chip sets from four different manufacturers.

- *C-Cube*: One of the oldest and the most successful producers of compression technology. Their system is based on their CL4000 chip. Two of these would probably be needed for one of our video streams. Each chip has 1.2 million transistors and operates at 60 MHz, performing 2450 MOPS. It can do an 8 by 8 DCT in 200 clocks and a motion sense estimation on two 16-by-16-pixel blocks in 70 clocks. It has 4 general purpose 32-bit processors and 16 motion estimation processors. The chip also contains a video interface, a variable length encoder and decoder and an 80 Mbyte/sec DRAM controller with a timer and a DMA controller. A seven-tap decimination filter is also available to preprocess input video pixels. These chips dissipate 4.5 W each. There are over 70 third party companies that provide end-user products that use C-Cube compression technology.
- *Array Microsystems:* Their two chip system is the Video*Flow* chip set comprised of the a77100 Image Compression Coprocessor (ICC) and the a77300 Motion Estimation Coprocessor (MEC). The ICC is a 1000 MOPS multiprocessor that is optimized to perform a collection of functionally similar instructions used in compression. Full MPEG-1 compression can be implemented in less than 128 instructions. The MEC contains an embedded 7000 MOPS Block Matching Processor as well as a 12 bit CPU. The two chips together dissipate 11W. There are 8 customers developing products that use the a77 chip set in video on demand, surveillance, non-linear video editing and video conferencing.
- *Texas Instruments:* The TMS320C80, known as the Multimedia Video Processor (MVP), is a new single-chip multiprocessing DSP which is optimized for general image and video processing applications. The MVP integrates a RISC and four advanced DSP processors, achieving more than 2000 MOPS, and has been successfully programed to perform real-time MPEG compression[2],[3]. This chip dissipates 9W.
- *Matra-Marconi:* Their radiation hardened video compression chip set was used on the Clemintine “Data Handling Unit” developed by Innovative Concepts, Inc. The compression chip set provides “real-time JPEG” and is rated at 30 Mpix/sec. The chip set consists of three chips: DCT, Huffman encoding, and PROM. Clemintine used the first two chips (RAM was substituted for PROM) and achieved 8-18:1 compression ratios. These relatively low compression ratios make it inadequate for our needs.
- Other MPEG semiconductor manufacturers include Integrated Information Technologies, LSI Logic and SGS-Thomson Microelectronics. It is also rumored that at least one Japanese and one European company are developing rad hard wavelet compression chips.

While these chips have some on-chip memory, suggested configurations include an additional 8-12Mbits of DRAM or VRAM, an NTSC decoder, and some bus interface logic. The communications computer needs to read the compressed data, compute error correcting codes, format it for communications and multiplex it with the telemetry and other data. 6 Mb/s corresponds to 107 instructions per 32 bit word on a 20 MIPS machine, so this may require it’s own processor (but only one total for all 4 compression boards).

Boards using the above chips have been built, and are available for approx. $15, 000. However, they have several drawbacks:

- None have been designed for low power use. They typically consume 30W, and as we need 4 in the current design, the total power draw for compression would be 120W.
- These boards contain their own frame grabbers but provide no way to get at raw digitized images without interrupting compression.
- They contain circuitry for decompression and NTSC encoding.
- They work at the “Constrained Parameters Bitstreams” resolution of 352x240x30 frames per second. While this is fine for computer screens, our panorama would benefit from higher resolution at lower frame rates.
- All components on these boards are soft.

Compression will therefore be implemented using custom boards.

10.6 Video Subsystem Payload

The ring cameras will have several operational modes. During the lunar day, they will be in full operation, providing 24-bit color panorama at 15 Hz. In the half of the lunar night during which the Earth is more than 3/4 full, they will provide a 4-bit grey-level panorama at 10 Hz. For the rest of the lunar night with dim Earthshine, only the front camera will be in operation, supplying a 4-bit grey-level front view at 10 Hz. The resolution of the ring cameras is 6 pixels/degree. The sky view camera provides a 24-bit color sky view at 0.1 Hz throughout the mission, with a resolution of 5 pixels/degree. The video subsystem payload is shown in Table 10.2.

Aside from the regular operation of providing the panorama and sky view, high quality stills can be provided by any of the ring cameras, the sky view camera, or the pan/tilt camera when the rover is not in motion and the transmission of the panorama is shut down. This is useful when the rover is exploring interesting sites.

TABLE 10.2 *Video Subsystem Payloads*

<table>
<tr><th>Operation Mode</th><th>Component</th><th>#</th><th>Data Rate [Mbits/second]</th><th>Update Frequency [Hz]</th><th colspan="2">Total Data Rate [Mbits/second]</th></tr>
<tr><td rowspan="2">Lunar day</td><td>ring camera</td><td>4</td><td>110.6</td><td>15</td><td>442.4</td><td rowspan="2">445</td></tr>
<tr><td>sky view camera</td><td>1</td><td>2.5</td><td>0.1</td><td>2.5</td></tr>
<tr><td rowspan="2">Lunar night with more than 3/4 Earth</td><td>ring camera</td><td>4</td><td>12.3</td><td>10</td><td>49.2</td><td rowspan="2">52</td></tr>
<tr><td>sky view camera</td><td>1</td><td>2.5</td><td>0.1</td><td>2.5</td></tr>
<tr><td rowspan="2">Lunar night with less than 3/4 Earth</td><td>front camera</td><td>1</td><td>12.3</td><td>10</td><td>12.3</td><td rowspan="2">15</td></tr>
<tr><td>sky view camera</td><td>1</td><td>2.5</td><td>0.1</td><td>2.5</td></tr>
</table>

10.7 Failure Modes

Failure modes for the video subsystem are shown in Table 10.3. For the current design, panoramic imagery will not be affected if both cameras at one location fail, or both of the frame grabbers connected to a single camera fail. Catastrophic failure, resulting in no product, will only occurs if all cameras completely fail. In this case, no video signal can be output from the video subsystem.

None of the compression chips exist in rad-hardened form at the moment, and it is unlikely that any of them will before launch. However, temporary failure of video does not endanger the rover, so we can tolerate non-permanent latch-ups. These highly optimized chips need to be examined more closely to see if we can program around such failure modes as a single bit of memory permanently latching up, or some part of one processor permanently failing. Also, these chips and the boards designed around them need to be tested to assess the probability of various non-damaging and damaging latch-ups. If non-damaging latch-ups are as rare as with other soft semiconductors, reset signals from an operator on the Earth will be sufficient to deal with latch-ups that aren't caught by the power system or watchdog timers.

For damaging latch-ups that can't be programmed around, we should carry two backup boards that are powered up only when one of the four stop working. The six boards should be connected to the cameras in such a way that any two boards can fail and we can still transmit from all cameras.

TABLE 10.3 *Failure Modes for Video Subsystem*

Component	Failure Mode	Effect	Prevention and/or Response	Criticality
Ring Camera	Single Failure	No Visible Effect	Switch to Backup	3
	Multiple Failure	Reduced Product	High Reliability Optics and Electronics	2
	Complete Failure	No Product		1
Sky View Camera	Failure	Reduced Product	Switch to Star Trackers	2
Belly Camera	Failure	No Product	High Reliability Optics and Electronics	2
Pan/tilt Camera	Failure	No Product	High Reliability Optics, Electronics, and Mechanics	2
Frame Grabber	Single Failure	No Visible Effect	Switch to Backup	3
	Multiple Failure	Reduced Product	High Reliability Electronics	2
	Complete Failure	No Product		1
Compression	Non-damaging latch-up	Temporary Video Upset	Reboot	3
	Damaging latch-up	Temporary Loss of Product	Redundant Electronics	2
	Data Corruption	Reduced Product	Error Correcting Codes	2
	Complete Failure	Greatly Reduced Product	Still Image Compression Using General Computing	2/1

10.8 Camera/Lens Specifications

10.8.1 Camera Specifications

- analog output color CCD cameras (except a B/W one for the belly camera)
- CCD chip 2/3”

  640x480 pixel format for ring cameras and pan/tilt camera

  1024x1024 pixel format for fish-eye cameras
- Auto iris
- Auto gain control
- Auto focus
- *Dark current* compensation by using low power thermal-electric cooler for CCD
- Ambient temperature: -10~50^{o}C

10.8.2 Lens specifications

- Field of view
  - Lens for front camera
    85x70 degree field of view, with 85 degrees horizontal to contribute to the panorama, tilted downward to cover from -55 to 15 degrees in elevation
  - Lens for the other ring cameras
    100x70 degrees field of view, with 100 degrees horizontal view to contribute to panorama. Each camera is tilted downward to cover from -55 to 15 degrees in elevation
  - Fish-eye lens
    180 degree field of view
  - Motor driven lens for pan/tilt camera
    47.5x36.5 degree field of view with zoom ratio 10
- Lens aperture: 35 mm
- Mount: C mount

10.9 Mass and Power Budget

The summary mass and power budget is shown in Table 10.4.

10.10 Open Issues

- Effect of compression on image quality
  After being compressed and decompressed, the quality of the imagery may be degraded due to non-ideal fidelity in either process
- Image contrast during lunar night needs more investigation
- The lunar dust is still a concern even though the cameras are considered to be mounted high enough. Feasibility of discharging electrostatic lunar dust by vapor depositing and electrical-grounding an ultra-

TABLE 10.4 *Summary Budget for Video Subsystem*

Component	#	Total Mass [kg]	Average Power [Watts]	Standby Power [Watts]
Ring Cameras	7	4	24	0
Fish-eye Camera	1	2	6	0
Pan/tilt camera	1	3	25	0
Belly Camera	1	2	6	0
Frame Grabber	10	2	20	0
Illumination	2	1	30	0
Compression Boards	6	3	60	0
Average Total		17	110	0

thin layer of gold onto the lenses is alluded. But this layer of gold may reduce optical throughput of the lens and make night imagery darker.

- The reliability of the communications system (including both physical aspects and error correcting codes in the protocol) need to be assessed to choose the proper ratio of I, P and B frames.
- The MPEG-1 standard meets its goal of 1.15 Mb/s by first scaling the input image to 352x240 at 30 frames per second. The effect on image quality of doubling or quadrupling the resolution (to 640x240 or 640x480) while halving the frame rate should be investigated.

References

1. Filippini, Luigi, “MPEG Frequently Asked Questions with Answers”, *http://www.crs4.it/~luigi/MPEG/mpegfaq.html*
2. Lee, W., Gove, R. and Kim, Y. “Real-time MPEG Video Compression using the MVP”, *ftp://image.ee.washington.edu*
3. Lee, W., Golston, J. Gove, R. and Kim, Y., “Real-time MPEG Video Codec on a Single-chip Multiprocessor”, *Digital Video compression on Personal Computers: Algorithms and Technologies, Vol. 2187, pp. 32-42, 1994. Also available from ftp://image.ee.washington.edu*

Chapter
11

Design Summary

This chapter summarizes the overall rover system design, from launch through to operations on the moon. This chapter also details the rover configuration and the launch and lander units.

The rover system with regard to this design consists of two rovers, a lander payload interface, the launch vehicle and lander, and ground stations on Earth. The ground stations are not considered in this design.

11.1 Rover Configuration

The two rovers share the same design, and will be operated in an identical fashion. Objectives that the rover will need to support are panoramic imagery, scientific investigation, and educational exploration. All of these operations scenarios need to be supported both during the lunar day and night. The different subsystems of the rover are summarized below. A cutaway view of the rover is shown in Figure 11.1.

Two rovers increase the reliability of the overall system in many ways. In the case of a catastrophic failure caused by terrain or micrometeorite damage, two rovers doubles the reliability. Two rovers also increase the reliability in the case of a randomly malfunctioning part. As long as the malfunction isn't caused by environmental effects or faulty design, two rovers again mean increased reliability. Lastly, having two rovers on the moon allows cooperation between the rovers. If a rover gets stuck in soft soil or becomes high-centered, the second rover can attempt to free the first rover from its problem.

11.1.1 Structures

The structural subsystem consists of a primary load bearing structure that runs completely around the vehicle. It is made of an aluminum honeycomb sandwich material. Most of the structure utilizes aluminum face panels on each side of the honeycomb, while the top surface and radiators use composite panels to minimize mass. The strutural designed was performed to meet launch and operating loads.

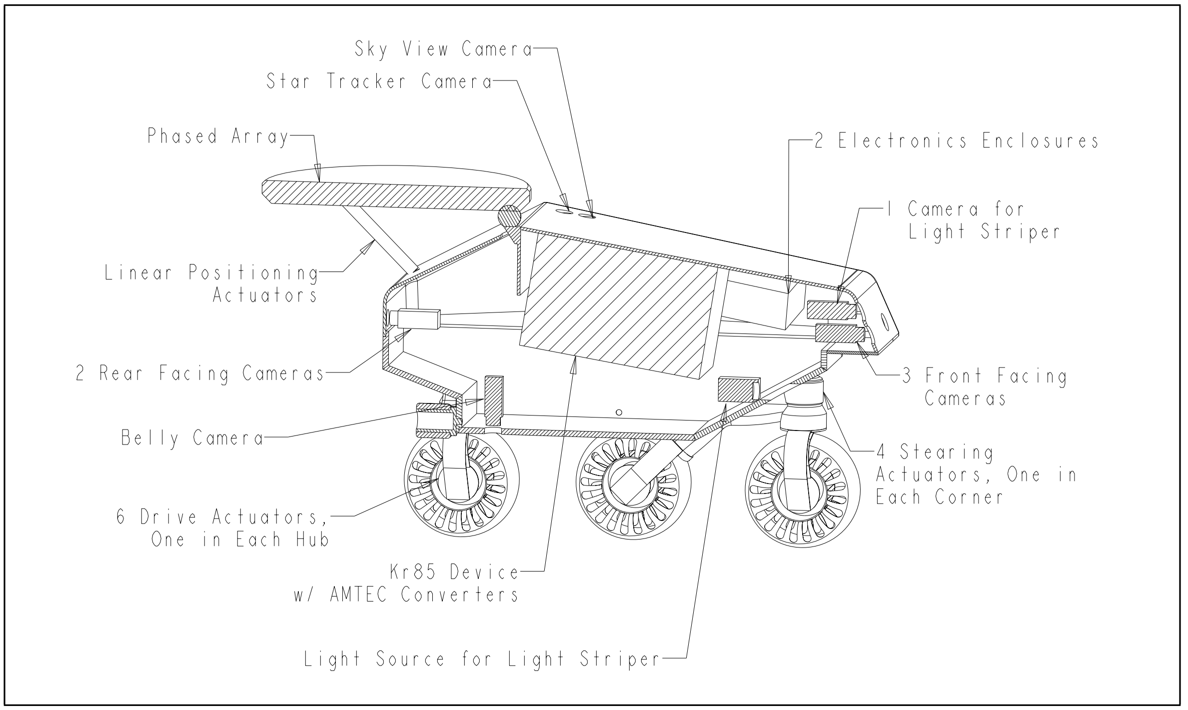

FIGURE 11.1 *Cutaway View of Rover*

11.1.2 Locomotion

The locomotion subsystem is made up of a six wheeled rocker bogie design. The wheels are all individually actuated, and the four corner wheels are individually steered. The wheel dimensions are sized to minimize sinkage into the soft lunar soil, with a diameter of roughly half a meter and width of thirty centimeters. The rocker bogie configuration will allow the rover to climb 30° slopes and to surmount obstacles with a comparable height to the wheel diameter. This design also allows point turns, which will be helpful in situations where the rover might have trouble maneuvering.

11.1.3 Electrical Power Subsystem

The electrical power system supplies power to the rover at all times, day and night. The power subsystem utilizes a Kr85 beta-decay heat source and AMTEC conversion cells. The excess heat generated by the Kr85 is utilized to maintain safe temperature ranges during the lunar night. The power is supplied at 32 Volts and controlled through a standard Power Management and Distribution device. Due to the decaying nature of Kr85, the amount of power supplied at the beginning of the mission is approximately 13% greater than what is needed, so that peak power requirements can be met at the end of the mission.

11.1.4 Thermal Control

Thermal control is achieved through mostly passive mechanisms. While there are small thermoelectric coolers and heaters on critical components, the majority of the thermal control is done through passive means. The main source of heat is the Kr85 gas, which will operate at a temperature of 1000 K. Radiators for the Kr85 will reject most of this heat at a high temperature, while a larger area will reject heat at a lower temperature to maintain the electronics. The rover's electronics are isolated as much as possible from the surface and the Kr85 heat source by large amounts of insulation. Critical components, like CCDs, contain active cooling devices where necessary.

11.1.5 Guidance, Navigation, and Control

The GNC subsystem is responsible for the determination and control of the rover's position on the moon. Position and attitude determination is achieved through a combination of star trackers, Inertial Measurement Units, and inclinometers. The GNC subsystem is also responsible for the control algorithms used for rover navigation. Safeguarding is implemented by the use of stereo cameras and a light striper for long-range sensing, and an array of IR sensors for near-range sensing.

11.1.6 Command, Communications, Control, and Telemetry

The rover's computing requirements are satisfied through the use of multiple radiation hardened processors. The majority of the computing power is utilized for stereo matching and safe route determination for safeguarding. Communications is implemented by an electronically steerable phased array antenna. The phased array is also pointed by a slow mechanical linkage. Backup and inter-rover communications is achieved through multiple omni-directional antennas in different orientations.

11.1.7 Imagery

The imagery subsystem consists of a ring of four camera locations to provide panoramic imagery to Earth. Due to the high data rates that this amount of imagery produces, high levels of compression are also required and implemented through special purpose hardware boards. Fisheye cameras are also provided on the top and bottom of the rover. The top fisheye provides a sky view to fill out the panorama while the bottom view is used when views of the wheels and the terrain around the rover are required.

11.2 Launch Configuration

The rovers will be launched upon a Phobos class lander in a Proton launch vehicle.

The Russian Proton launch vehicle was chosen for the launch of this system. The main driver for this decision was cost. The vehicle provides a payload fairing with a usable diameter of 3.80 meters. The main issue limiting the use of the Proton launch vehicle is the export controls of the United States. Due to the technical nature of the rovers, US Customs will have authority over the transportation of the rover to another country. This issue would be averted through the use of an American launcher, although that would raise the cost.

11.2.1 Lander

A Phobos class lander, based on the design for the Mars 96 mission, is baselined for this mission. This lander can deliver a substantial mass payload to the lunar surface. A payload interface and deployment mechanism was specified for the lander. The lander will allow both rovers to drive off of one side of the lander. During launch, transport and landing the rovers will stowed facing upwards, with their wheels together, which allows their radiators to radiate to space.

11.3 Mission Timeline

During the two-year mission baseline, the rover will support both theme park and science/educational users during the lunar day and night. Both the different users and environment dictate different operating timelines.

During the lunar day, the rovers will be able to see roughly 2 km to the horizon due to lunar geometry. But to obtain good views of the other rover while moving, the distance between rovers should be kept to less than half a kilometer. This distance allows the rovers to travel for roughly 1 km while keeping the other rover in sight. At an average velocity of 1 km/h, the rovers will be able to travel for 1 hr continuously.

During the lunar night, the distance that the rovers will be able to see will be smaller due to the amount of light available on the surface. When the Earth is greater than three quarters full, enough light will be available to allow panoramic viewing, but not to see far away. During the rest of the lunar night, the rovers will have to illuminate the path that they are travelling. These lighting restrictions will limit the inter-rover distance to less than quarter of a kilometer. At a similar average velocity as before, the rovers will be able to travel for half an hour continuously.

11.3.1 Theme Park Operations

Operations in support of a theme park is the primary mission objective for the rover system, and, as previously mentioned, is the main system driver.

Daytime Operations

During lunar daylight hours, the rover's motions will operate on the same cycle time as the theme park ride. This will allow the rovers to always be within close proximity of each other. Based on a 1 km/h average speed and ride time of 5 minutes, the rovers will be within 100 meters of each other at all times.

Nighttime Operations

During lunar nighttime hours, the rover will operate in a similar fashion as during the day. During the time when Earthshine provides enough illumination to operate the panoramic imagery, the rover will move at a slower speed than during the day. This is due to integration times within the camera. At these speeds, the rovers will probably stay within 50 meters of each other, which is close enough for good cross rover illumination and viewing. During the other half of the lunar night, the rovers will have to illuminate their way, and will similarly stay within 50 meters of each other. Because there is not enough light from Earth for the imagery subsystem to capture a panoramic view, a rover will only be able to see the other when it is facing it.

11.3.2 Science and Education Operations

Science and education needs do not dictate the need for the rovers to stay in close contact with each other. Because of this, the rovers will be able to travel up to 2 kilometers away from each other. Also, because panoramic imagery is not always required, it is possible for both rovers to be operated at once, with imagery from one rover being linked to the other, and then sent to Earth.

Daytime Operations

Because the lighting conditions can be quite harsh during the lunar day, and not very suitable for detailed imaging, science operations will not occur as often as theme park and educational operations. During education operations, the students will be able to drive the rovers around and utilize the controllable camera. Because education operations will not utilize the panoramic imagery, the ability to control the pan/tilt camera will provide the opportunity for students to examine the local environment. The rovers can be operated independently from different sites, but maintaining visual contact between the two rovers will be necessary.

Unlike the educational operations, where the rovers will probably be continuously moving, science operations will often halt the rover to examine an interesting feature or to determine what locale should be visited next.

Nighttime Operations

For science and education operations, the method and types of operations will not change from day to night. Science concerns will be able to obtain better data during the night, due to controlled illumination. But since neither education or science operations fully utilize the panoramic imagery, there will be no major differences between daytime and nighttime operations. The main difference will be the requirement for the rovers to remain within 50 meters of each other, so that they do not get separated.

11.3.3 Emergency Operations

The possibility exists for a rover to become stranded or stuck while operating. In circumstances like these, the second rover may be able to assist the immobilized rover through different means. The second rover may be needed to only provide a second view of how the first rover is stuck. Under certain circumstances, the second rover might need to physically interact with the first rover to free it. Of course, this would only be used when the possibility of the second rover also getting stuck is small. Other possibilities exist that are difficult to foresee before the need arises.

11.4 Summary Budgets

The numbers for the summary budgets were derived from the subsystem specifications, and are broken down by subsystem. A contingency factor to account for possible growth was then added to each value.

11.4.1 Growth Margin

Due to the nature of this design, many factors are not known at this time. For this reason, margin percentages are added to each component based on their level of technological maturity and risk. The basic contingency values are shown in Table 11.1, and are based on the NASA-approved contingency factors. Power margins were calculated with similar numbers. In addition to the subsystem contingencies, a system wide contingency was also added to account for any mechanisms that were overlooked.

TABLE 11.1 *Mass Margin Details*

Design Maturity	Contingency	
	Mechanical/ Structural	**Electrical Components**
Conceptual Design	30%	30%
Similar Hardware	13%	13%
Prototype Hardware	8%	8%
Actual Hardware	5%	5%
System Margin	5%	5%

Contingency values are also based on the criticality of the component. For example, a high contingency is placed on the Kr85 power components. Not only are they still in the design stage, but if the power system does not deliver the required power, the mission would have to be aborted or altered. Similarly, the items that drive the mass budget have a high contingency because this is the first design stage of the rover system.

11.4.2 Mass Budget

The mass budget is shown in Table 11.2. The total mass that the Phobos lander can deliver to the lunar surface is 600kg. Mass budget overruns are discussed in the following section.

TABLE 11.2 *Mass Budget*

Subsystem	Mass w/o Margin [kg]	Mass w/ Margin [kg]
Structures	69.5	76.6
Locomotion	75.0	82.5
Electrical Power Subsystem	118.4	149.9
Thermal Control	10.3	12.6
Guidance, Navigation, and Control	10.0	11.2
Command, Communications, Control, and Telemetry	24.5	29.1
Imagery	17.0	19.2
Subtotal	324.7	381.1
Overall System Contingency (5%)	16.2	19.0
Total	**340.9**	**400.1**

11.4.3 Power Budget

The power budget is shown in Table 11.3. This table shows the average power draw of the rover. Peak power and detailed power budgets are shown in Section 6.9.1 on page 57.

11.5 Budget Overrun

The rovers as currently designed exceed their mass budget. While this is a cause for concern, the preliminary state of the design is reassuring because many of the technologies specified are not currently mature. Additionally, most subsystems did not attempt to minimize mass. A few kilograms could be pared from individual subsystems, but the main mass drivers are the structure, locomotion, and power subsystems. Further design effort will be directed towards the first two subsystems, where more detailed analysis is sure to save mass. The power subsystem mass is driven by the need for high temperature materials for the pressure vessel. Further investigation into composite tanks, which would drastically lower the power subsystem mass, is required.

Since the fact that the rovers were overbudget on mass came to light late in the design cycle, redesign was not possible. Therefore, the design team brainstormed and came up with three possible scenarios to deal with the overrun.

TABLE 11.3 *Power Budget*

Subsystem	Average Power w/o Margin [W]	Average Power w/Margin [W]
Structures	--	--
Locomotion	75	90
Electrical Power Subsystem	35	42
Thermal Control	15	20
Guidance, Navigation, and Control	35	38
Command, Communications, Control, and Telemetry	150	175
Imagery	105	130
Subtotal	415	495
Overall System Contingency (5%)	21	25
Total	**436**	**520**

11.5.1 Multiple Launch Vehicles

Using 2 launch vehicles to place the rovers on the moon is one possibility for overcoming the mass problem. Placing each rover on its own lander also allows for the possibility of other payloads being launched along with the rovers. For instance, a fixed telescope could be placed alongside the rover. A telescope on the moon would not have the atmospheric interference problems that telescopes on the Earth have. They also would not have to deal with the periodic wobble that the Hubble Telescope undergoes every time it travels across the shadow line cast by the Earth. Additionally, utilizing two launchers reduces the chance of the mission being lost due to a launcher or lander malfunction.

11.5.2 Single Rover

The other method for dealing with the mass problem would be to launch one rover. This idea would require extensive redesign of the rover due to the need to acquire images of itself in the lunar terrain. While ideas ranging from panospheric or fish-eye optics to remote cameras appeared plausible, the extensive redesign that this would require was just not feasible.

11.5.3 Fissionable Heat Source

Because a large amount of mass is present in the power subsystem, it was examined to see where its mass could be lowered. The Kr85 pressure vessel, which is massive due to its design, could be replaced to significantly lower the power system mass. One option to lower its mass is to replace the Astroloy pressure vessel with a composite vessel. This replacement would save roughly 30kg. The use of plutonium General Purpose Heat Sources, which have much higher energy densities than Kr85, would save roughly 60kg. Because the drop in mass is so significant, roughly half of the power system mass, this option should be fully investigated.

Appendix A

Detailed Mass Budgets

TABLE A.1 *Component Masses and Margins*

Component	Subsystem	#	Mass Each [kg]	Contingency	Total Mass w/ Growth [kg]
Wingbase	Structure	2	2.22	10%	2.7
Hood	Structure	1	2.06	10%	2.3
Shell_Rear	Structure	1	4.25	10%	4.7
Shell_Sides	Structure	1	3.21	10%	3.5
Shell_Nose	Structure	1	1.15	10%	1.3
Side	Structure	2	6.74	10%	14.9
Front	Structure	1	0.73	10%	0.8
Bottom	Structure	1	9.59	10%	10.5
Front_Angle	Structure	1	6.01	10%	6.6
Rear	Structure	1	2.7	10%	3.0
Rear_Angle	Structure	1	3.21	10%	3.5
Rocker bogie Pins	Structure	3	2.27	10%	7.5
Fastners	Structure		25%	10%	15.3

TABLE A.1 *Component Masses and Margins*

Component	Subsystem	#	Mass Each [kg]	Contingency	Total Mass w/ Growth [kg]
Large link	Locomotion	2	5.5	10%	12.1
Small link	Locomotion	2	3.4	10%	7.5
Averaging link	Locomotion	1	1.8	10%	2.0
Wheel housing	Locomotion	6	2.6	10%	17.2
Fender	Locomotion	6	0.2	10%	1.3
Wheel	Locomotion	6	0.6	10%	4.0
Steering actuator	Locomotion	4	1.4	10%	6.1
Driving actuator	Locomotion	6	3.4	10%	22.4
Reducer	Locomotion	10	0.9	10%	9.9
Krypton Container	Power	1	79.0	30%	102.7
Krypton Gas	Power	1	6.6	20%	7.9
AMTEC Cells	Power	65	0.27	20%	21.2
PMAD	Power	2	2.25	8%	4.9
Insulation	Power	1	1.0	20%	1.2
Cabling and Connectors	Power	1	10.0	20%	12
Kr85 Heat Source Radiator	Thermal	1	1.2	20%	1.5
Electronics Enclosure Radiator	Thermal	1	5.0	20%	6.0
Kr85 Heat Source Insulation	Thermal	1	2.5	25%	3.1
Body Insulation Panels	Thermal	1	0.6	25%	0.8
Heat Pipes	Thermal	7	.07	25%	0.6
Thermoelectric CCD Coolers	Thermal	6	0.08	20%	0.6
Stereo Cameras	GNC	2	1	8%	2.2
Light Striper	GNC	1	3	15%	3.5
IMU	GNC	2	1	8%	2.2
Inclinometer	GNC	3	0.3	8%	1.0
Star Tracker	GNC	2	0.5	8%	1.1

TABLE A.1 *Component Masses and Margins*

Component	Subsystem	#	Mass Each [kg]	Contingency	Total Mass w/ Growth [kg]
IR Sensors	GNC	~20	0.05	15%	1.2
Phased Array	CCCT	1	10	25%	12.5
Inter-Rover link	CCCT	1	2	15%	2.3
Omni-directional Antennas	CCCT	2	1	8%	2.2
Linkages for Antenna Platform	CCCT	2	2	20%	4.8
Navigation Computing Boards	CCCT	4	0.9	15%	4.1
Controllers	CCCT	4	0.7	15%	3.2
Ring Cameras	Imagery	7	.6	8%	4.3
Fish-eye Camera	Imagery	1	2	8%	2.2
Pan/tilt camera	Imagery	1	3	8%	3.2
Belly Camera	Imagery	1	2	8%	2.2
Frame Grabber	Imagery	10	0.2	8%	2.2
Illumination	Imagery	2	0.5	25%	1.3
Compression Boards	Imagery	6	0.5	25%	3.8
Total					**356.5**

TABLE A.2 *Subsystem Totals and Percentages*

Subsystem	Total Mass w/o Margin[kg]	Total Mass w/Margin[kg]	Percentage of Total
Structure	69.5	76.6	20.3%
Locomotion	75	82.5	21.8%
Power	118.4	149.9	39.6%
Thermal	10.3	12.6	2.5%
GNC	10	11.2	3.0%
CCCT	24.5	29.1	7.7%
Imagery	17	19.2	5.1%
Total	**324.7**	**381.1**	--

Appendix B

Detailed Power Budgets

TABLE B.1 *Component Average and Peak Power*

Component	Subsystem	#	Average Power Each [Watts]	Average Power [Watts]	Peak Power Each [Watts]
Internal Frame	Structure	1	0	0	0
Body Panels	Structure	1	0	0	0
Rocker Arms	Locomotion	2	0	0	0
Bogie Arms	Locomotion	2	0	0	0
Connecting Arms	Locomotion	6	0	0	0
Averaging Link	Locomotion	1	0	0	0
Drive Actuators w/Gearing	Locomotion	6			
Steering Actuators w/Gearing	Locomotion	4			
Wheels	Locomotion	6	0	0	0
Electronics	Locomotion	?			
Krypton Container	Power	1	0	0	0
Krypton Gas	Power	1	0	0	0

TABLE B.1 *Component Average and Peak Power*

Component	Subsystem	#	Average Power Each [Watts]	Average Power [Watts]	Peak Power Each [Watts]
AMTEC Cells	Power	80	0	0	0
PMAD	Power	2	35	35	35
Insulation	Power	1	0	0	0
Cabling and Connectors	Power	1	0	0	0
Kr85 Heat Source Radiator	Thermal	1	0	0	0
Electronics Enclosure Radiator	Thermal	1	0	0	0
Kr85 Heat Source Insulation	Thermal	1	0	0	0
Body Insulation Panels	Thermal	1	0	0	0
Thermoelectric CCD Coolers	Thermal	6	2.5	15	2.5
Stereo Cameras	GNC	2	11	11	11
Light Striper	GNC	1	15	15	15
IMU	GNC	2	5	5	5
Inclinometer	GNC	3	0.7	2.1	0.7
Star Tracker	GNC	2	5	5	5
IR Sensors	GNC	20	0.25	5	.25
Phased Array	CCCT	1	80	80	80
Inter-Rover link	CCCT	1	1	1	1
Omni-directional Antennas	CCCT	2	1	1	10
Linkages for Antenna Platform	CCCT	2	5	10	10
Navigation Computing Boards	CCCT	4	10	40	10

TABLE B.1 *Component Average and Peak Power*

Component	Subsystem	#	Average Power Each [Watts]	Average Power [Watts]	Peak Power Each [Watts]
Controllers	CCCT	4	3	12	10
Ring Cameras	Imagery	7	6	24	6
Fish-eye Camera	Imagery	1	6	6	6
Pan/tilt camera	Imagery	1	10	10	25
Belly Camera	Imagery	1	.5	.5	6
Frame Grabber	Imagery	10	5	20	5
Illumination	Imagery	2	30	30	45
Compression Boards	Imagery	6	15	60	20

TABLE B.2 *Rover Power Budget by Subsystem, Different Operating Modes (Power in Watts)*

	Full Operation Mode	Hard Terrain Mode	Full Operation Limited Video	Scientific Mode	Idle
Locomotion	75	150	75	0	0
Thermal Control	15	15	15	15	15
Power Management	35	35	35	35	35
Communications	90	30	30	90	30
Computing	60	60	60	20	20
Imagery	45	11	11	45	0
Compression	60	15	15	60	0
GNC	35	35	35	0	0
Total	**415**	**351**	**276**	**265**	**100**