Conjoined Lander-Rovers for Planetary Exploration

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Abstract

This research explores the configuration of conjoined lander-rovers for planetary exploration. Technical evolution has refined landers and rovers, and improvement has been continuous, but ongoing evolution offers no leap of performance for a given launch. As long as rovers and landers are distinct, there is inevitable redundancy of structure, power, computing, and communication. For traditional rovers and landers, each redundant component is manifested in mass and volume, which precludes minimization of mobile planetary exploration systems. The opportunity devised is to eliminate boundaries demarcating lander and rover. This research explores the principles of conjoined lander-rovers. The great benefit is minimizing component counts, to do more with less. These payoffs equate to less mass, simplified integration, and lower costs than achievable with conventional configurations. This enables capable planetary exploration from small launch vehicles.

Many configurations for capable surface exploration succeed with hundreds of kilograms of dry mass. Only conjoined lander-rovers might cross the one hundred kilogram barrier. Results include the development of morphology, mechanisms, structure, and avionics to enable lightweight exploration. Developments detail specialized design to handle the hard vacuum, thermal swings, radiation, and dust on the moon within the restrictions of low mass and volume.

An exemplary mission used as context for this is research is the Google Lunar XPrize (GLXP). The GLXP offers a $20 million dollar prize to send a robot to the moon and transmit back high quality video and imagery.

Acknowledgements

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1. Introduction

1.1. Motivation

This investigation devises capable lunar lander-rover exploration from minimal launch capability. The great challenge of exploration robotics is configuring morphology, mechanism, structure, and avionics relative to the constraints imposed by missions. The largest constraint in the design of planetary landers and rovers is typically the method of getting from Earth to the destination. Big rockets enable landers and rovers with large mass and dimension, but come at high cost. Small launch vehicles reduce costs, but present the need for ingenuity to produce designs of low mass and small dimension that are capable of meeting mission requirements.

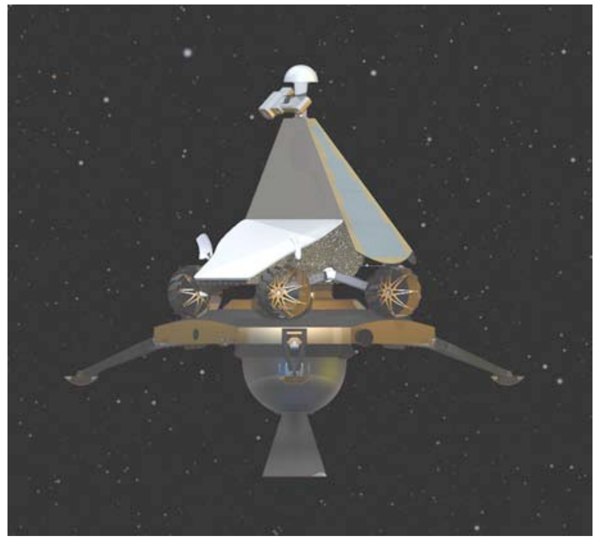

Figure 1: Conjoined Lander-Rover

With the resources of nations, mighty rockets once carried immense hardware into space. Ambitions for lunar exploration are re-invigorated but huge launch and injection stages are unaffordable, which compels success on much smaller launch vehicles. The burning question for robotic lunar missions is whether substantial exploration capability can be delivered with a class of lander-rovers with dry, landed mass of less than 120kg.

Decades have passed, technical evolution has refined landers and rovers, and improvement has been continuous, but ongoing evolution offers no leap of performance for a given launch. As long as landers and rovers are distinct, there is inevitable redundancy of structure, power, computing, and communication. As long as rovers are payload, they are necessarily compromised in exploration capability by inordinate constraints on mass and scale. For traditional landers and rovers, each redundant component is manifested in mass and volume, which precludes minimization of a mobile planetary exploration system. This research explores the principles of conjoined lander-rovers. The opportunity is to eliminate boundaries demarcating lander and rover. The great benefit is minimizing component counts, to do more with less. Payoffs equate to less mass, simplified integration and lower costs than achievable with conventional configurations.

1.2. Challenge

This research details the development of configuration for conjoined lander-rovers to explore the lunar equator. These exploration systems are intended for short-duration scouting missions to the lunar surface as precursors to human colonization of the moon. Short-duration is defined to be one lunar day or fourteen Earth days.

The lunar equator presents surface temperatures from as low as -170°C during the lunar night to as high as 120°C at lunar noon. Over the course of the lunar day, the sun traverses from horizon at dawn to directly overhead at midday to horizon at dusk. Mission length of a single lunar day removes the requirement of surviving during the fourteen day, -170°C lunar nights, which current space electronic systems cannot survive. This drives requirements to operate continuously and at higher speeds than traditional space robotic systems to perform all required actions in limited mission times.

An exemplary mission used as context for this research is the Google Lunar XPrize. The XPrize offers $20 million for a non-governmental group to send a robot to the moon and transmit back high quality video and imagery. To compete for this prize, the scale of assets available drives the need for a small launch vehicle. This dictates limitations on the mass and dimension of a lunar lander and rover. The mission concept is to win the XPrize by visiting the site of the Apollo 11 landing at the lunar equator. This is seen as the best location to inspire the public and increase excitement of lunar exploration.

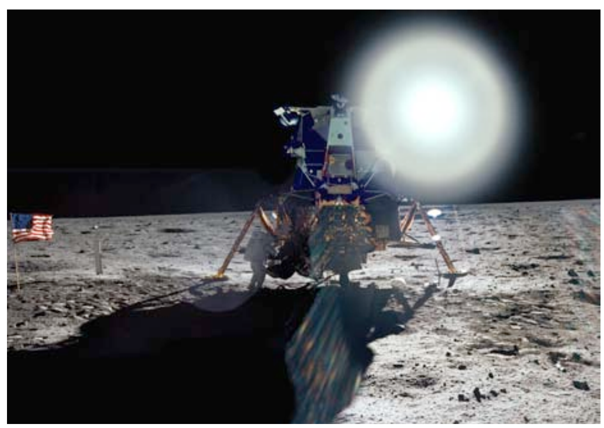

Figure 2: Apollo 11 site

2. Background

2.1. Assumptions

The goal of this research is to achieve capable exploration from a small launch vehicle to compete for the Google Lunar XPrize. This requires defining “capable” and determining a reasonable target for “low-mass.”

The lander-rover for the exemplary mission to compete for the XPrize must be capable of:

- Landing within 100 meters of a predetermined site,
- Trekking ten kilometer on the lunar surface in one lunar day,
- Collecting high-definition stereo video during trek,
- Communicating to return data collected over the course of the mission.

The mass of an exploration system derives from mission requirements and payload required for success. Mission requirements dictate data to be collected or operations to be performed. Payload takes the form of scientific instruments, imaging systems, or tools to perform operations like site preparation.

The XPrize mission places requirements on imagery to be retrieved and returned. Commercial missions add requirement for additional mass to carry contracted payload as a source of funding. Once mission requirements and payload are determined, lander and rover systems are sized in the form of a mass budget.

The largest driver in determining mass required for mission success is the power required. Data processing, sensing, communication, and mechanisms are sized based on mission requirements. Each of these draws a set amount of power relative to their performance and duty-cycle. As power usage escalates, the size of solar panels and radiators escalates and the lander-rover requires more structure and more mobility.

From mission requirements, appropriate electronics are selected and rough calculations for system power are made. The result for the XPrize is a system with continuous operating power of 120 watts. From operating power and duty cycle solar and thermal control surfaces are sized setting the scale of structure and mobility from which an approximate mass is determined for the lander-rover. A target mass budget of 120 kg was determined based off this initial sizing.

A sample mass budget for a 120kg, 120-watt equatorial conjoined lander-rover for the XPrize mission is shown in Table 1.

Lander-Rover System	Function	Mass Budget (kg)
Payload	Fulfill mission requirements	**9**
Avionics	Process and store data	**7**
Communication	Transmit data	**4**
Sensing	Localize lander Localize rover	**6**
Mechanism	Propel rover Point and place instruments	**15**
Power	Generate, store, and distribute power	**8**
Thermal Control	Radiate excess heat Heat cold components	**6**
Harness	Distribute data and power	**8**
Structure	Resist launch, transit, landing, and driving loads	**35**
Propulsion	Slowdown for landing Position for landing	**22**
Total System Mass:		**120**

Table 1: Mass Budget for 120kg conjoined lander-rover exploration system

Success can be achieved with lower mass components, though this increases mission risks. For example, lower mass Earth electronics can be used in place of heavy space-proven designs at the cost of increased risk of mission failure. Therefore an appropriate balance must be struck between risk and reward. For the XPrize mission custom developments are minimized for electronic components to reduce schedule and cost impacts. However, utilizing existing, newly developed hardware that has been tested on Earth, but with little to no space flight heritage is considered appropriate to achieve mass savings. Mechanisms and structure are custom developments, but harness materials, lubrications, actuators, and bearings that have been proven in a space environment.

2.2. Mission Mass

Mission hardware must launch into Earth orbit, propel itself toward the moon, brake to match the moon's speed upon arrival, and navigate to land on the surface. Every kilogram on the lunar surface back-propagates into kilograms of propellant required to launch, inject, brake, and land. The result is large increases in launch vehicle requirement and in overall cost for mission success.

Mission Stage	Delta-velocity required (meters/second)
Launch to Low Earth Orbit[1]	10,000
Injection[2]	3100
Braking[2]	2200
Landing	400

1: Based on Lunar Prospector mission [14]
2: Calculated using orbital mechanics [15]

Table 2: Required changes in velocity during mission phases.

Each stage of the trip from the Earth to the moon is accomplished through a change in velocity. Reaching Earth orbit requires accelerating to a certain velocity. To reach the moon from Earth orbit, spacecrafts change velocity when accelerating toward the moon, braking upon approach of the moon, and slowing down and landing at an intended landing site. Required changes in velocity depend on orbital maneuvers performed. Values for a sample lunar mission are shown in Table 2.

Using these delta velocities, the mass of propellant required can be determined using the Tsiolkovsky rocket equation [13]:

$$\Delta v = v_e \ln \frac{m_{fuel} + m_{dry}}{m_{dry}}$$

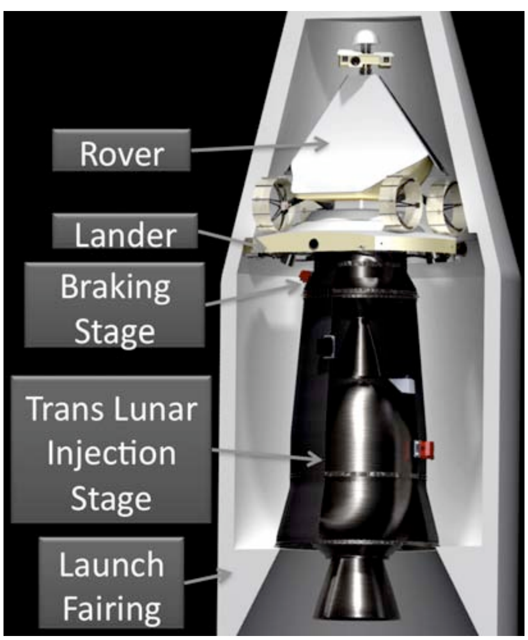

Figure 3: Mission stack inside a launch fairing

In this equation v_e is the effective velocity of fuel exhaust, which is a measure of the efficiency of a type of fuel to provide changes in velocity relative to expended fuel mass. There are two main categories of rocket fuel: solid and liquid. Solid fuels have less complexity and associated tank mass than liquid fuels resulting in higher propellant mass relative to tank mass, which is exaggerated in smaller rockets. Solid rockets lack the controllability of liquid rockets. Once ignited, solid rockets burn the entirety of their fuel at once, while liquid rockets can be turned on and off for controlled burns. Launch, injection, and braking work well with solid fuel since they require large changes in velocity with no need for specific control. Orbital adjustments and landing work best with liquid fuel since they require small changes in velocity and need specific control.

Full mission stackups are governed by the Tsiolkovsky rocket equation. Propellant requirements for each stage can be determined by starting with dry, landed mass on the moon and working back to Earth, adding on structural mass for each stage along the way. Table 3 steps through this process for a 120kg system used for the exemplary XPrize mission discussed in this research. In this example the launch vehicle is a four stage Athena II rocket that was used for the Lunar Prospector mission, a 1998 lunar orbiter with similar mass sent to the moon [14].

Mission Component	Required Mass (kg)
Mass on Moon	120
Propellant for landing[1]	18
Braking Structure[2]	40
Propellant for Braking[1]	208
Injection Structure[2]	130
Propellant for Injection[1]	1,018
Launch Structure[3]	9,800
Propellant for launch[3]	108,000
Total Launched Mass	119,334

1: Determined using the Tsiolkovsky Rocket Equation
2: Based on mass of ATK's Star motor line [4]
3: Numbers from the Athena II launch vehicle [4]

Table 3: Mass budget for 120kg lander-rover mission to the moon based on delta velocities in Table 2

2.3. Blastoff Mission

The Blastoff Corporation formulated a mobile landed mission from a small launch vehicle similar to that discussed in this research. Blastoff pursued a commercially funded mission to the Apollo 11 landing site.

The Blastoff mission configuration did not reach a technical solution within mass constraints of the intended Athena II launch vehicle. A change was made to a larger launch vehicle at higher mission cost. Eventually escalating mission costs and collapse in financial backing resulted in abandoning the mission. Successful commercial lander-rover exploration from small launch assets requires the advancement of configuration for low mass.

Figure 4: Blastoff lander-rover concept for exploration of the lunar equator [31]

2.4. Lunokhod

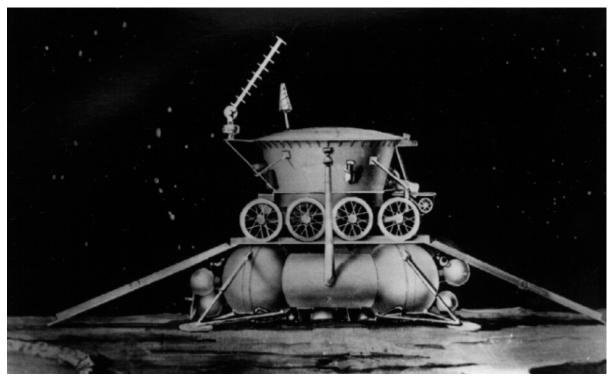

Figure 5: Lunokhod rover on Luna lander

The first planetary lander and rover were developed by the Soviets in 1970 for exploration of the moon. Principles from that era still govern design. The idea of distinct and separate lander and rover originates from the Soviet Union's Lunokhod campaign. The Proton rockets that launched the Lunokhods were capable of launching 5,600 kg directly toward the moon. The Lunokhods were 800kg rovers on 800kg landers with combined dimensions of 3.3 meters in diameter and 2.3 meters in height.

The Lunokhod rovers and Luna landers were distinct and separate systems with distinct mechanisms, structure, and avionics. They stacked up like a wedding cake in the Proton fairing and separated mechanically once on the surface on the moon. This presented the need for many duplicated systems: two computers, two communication systems, two localization methods, and two independent structures.

2.4.1. The Morphology of Lunokhod

The Lunokhod rover chassis was a magnesium shell, akin to a covered bathtub that was overlaid with a large hinged, convex solar panel lid. The rover trekked the surface on an undercarriage of eight large, widespread wheels giving the appearance of a military machine. Cameras, antennas, and sensors protruded from the tub structure. This appearance served as distinct and innovative solutions to the problems of the lunar environment.

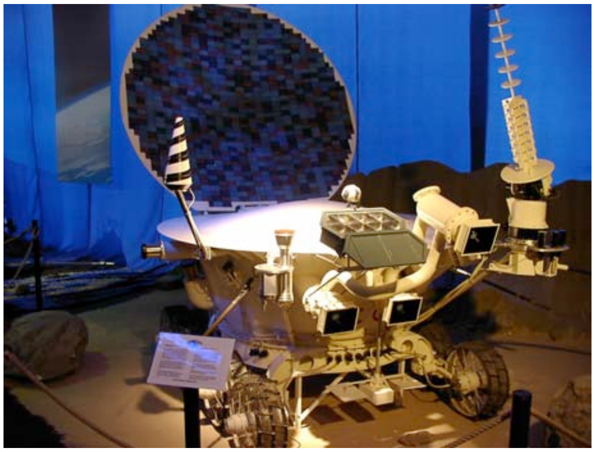

Figure 6: Lunokhod Rover

The bathtub chassis was a pressure vessel sealing in an atmospheric environment of nitrogen for the avionics of Lunokhod. This shielded components from the harsh vacuum of the moon facilitating thermal regulation. The hinged solar panel opened during the lunar day, gathered power from the sun and revealed the radiative top surface of the chassis enabling the rover's avionics to cool. The lid closed during the long cold lunar night covering the radiative surface to insulate the rover. During the night, heat generated from the decay of a radioactive isotope kept the rover avionics warm.

The undercarriage gave mobility to the planetary rover. The wide stance and eight wheels improved the obstacle and slope performance of the rover, producing a machine ready to handle almost any situation that may occur. The use of eight wheels ensured locomotion in the case of failure of a single wheel.

2.4.2. The Mechanisms of Lunokhod

The Lunokhod design incorporated mechanisms of eight independently driven wheels, torsion-bar suspension, solar lid tilt, and antenna pointing.

The undercarriage had eight rigid drive-wheels with perforated, cleated rims. The wheels did not swivel. Tank-like steering imparted different velocities to the left and right sides, turning the rover. Brushed, direct current motors with planetary gearing located within each wheel hub actuated locomotion. Wheel hubs were individually pressurized and sealed with custom vacuum grease, creating an atmosphere necessary to prevent sparking at brushes that causes wear and eventual failure of brushed motors in a vacuum environment. A shifting transmission in the gearing enabled two speeds of 1 km/hr and 2 km/hr. In the event of actuation failure in a wheel, an explosive disconnect could be fired to enable the wheel to free spin [1].

Figure 7: Lunokhod drive system

Similar actuators facilitated the pointing of Lunokhod's high gain antenna. This system was manually steered from Earth. The solar lid was actuated to point toward the sun.

Mechanisms were also in place to cover camera lenses to protect them from dust kicked up during landing. These covers simply dropped away once on the surface of the moon.

2.4.3. The Structure of Lunokhod

Special lightweight, high strength magnesium and titanium alloys were developed at Russia's Lavochkin Institute for use in Lunokhod [8]. The development of specialized materials to reduce mass highlights the importance of mass reduction even in a system with a comparatively large mass budget.

The structures of the rover and lander were completely separate and simply stacked on top of each other. Rover structure consisted of a pressure vessel chassis with titanium strut mounts supporting an array of cameras, antennas, and sensors. Pressurized compartments succeeded with thin magnesium casings.

2.4.4. The Avionics of Lunokhod

The pressurized compartment of Lunokhod protected avionic components from the harsh vacuum on the lunar surface, enabling components to be thermally managed by forced air. Availability of large mass enabled components like cameras to be shielded from radiation effects enabling use of commercial hardware.

Lunokhod was equipped with four TV cameras for driving and returning imagery. Three were panoramic cameras, and the fourth was mounted high on the rover for navigation. The navigation camera was added to Lunokhod 2 due to the difficulty of operators to observe terrain from low mounted panoramic cameras resulting in driving into an unseen crater, causing the failure of the first Lunokhod mission [7].

A five-man team of controllers drove the rover in real time. Communications to and from the rover were sent through a low data rate cone-shaped omni-antenna and a high data rate directional helical antenna [3].

Drive motors had automatic motion-control electronics. Rotational sensors provided feedback for wheel motion. A free-rolling wheel provided information on the distance traveled and determined wheel slip when compared to counts of wheel revolutions [2].

Scientific instruments included a cone penetrometer to test soil mechanics, a solar X-ray experiment, an astrophotometer to measure visible and UV light levels, a magnetometer, a radiometer, and a photodetector for laser detection experiments. It also carried a laser corner-reflector to enable precise measurement of location on the moon and the exact distance between the Earth and the moon.

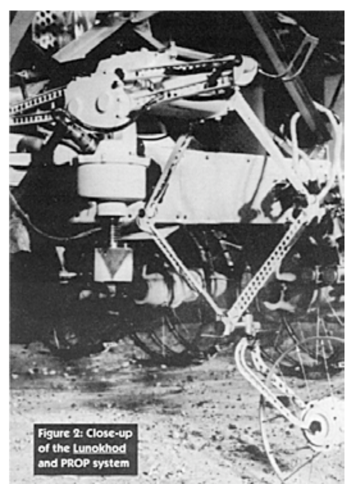

Figure 8: A free-rolling wheel was used to determine wheel slip

2.5. Pathfinder/Sojourner

The Mars Pathfinder mission was the first mission to investigate strategies for combining the functions of lander and rover. Hardware included the Pathfinder lander and the Sojourner micro-rover. Success of the program was achieved through low mass and low cost relative to prior NASA missions. The system had a mass of

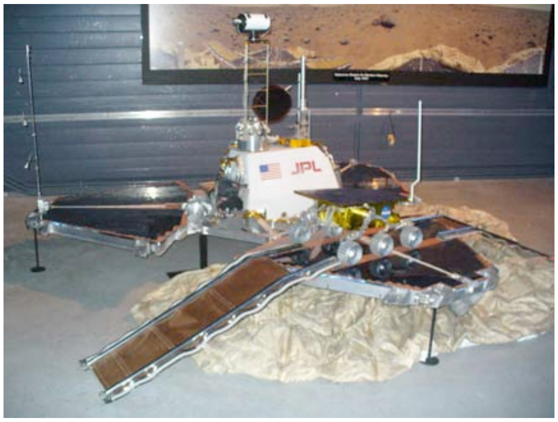

Figure 9: Pathfinder Lander with Sojourner microrover

275kg and cost $280 million [10]. The majority of systems were located on the lander with minimal capabilities on the rover for short distance traverses and collection of scientific data.

The Martian environment is less harsh for exploration robot hardware than the moon. The presence of an atmosphere limits thermal swings, enables convective cooling of components, and creates diffuse lighting and solar energy. The short Martian night mitigates extreme low temperatures. Terrain is less extreme and coloration and lighting facilitate easier identification of obstacles.

The Pathfinder mission succeeded with low mass due to limited exploration requirements. The Sojourner rover never trekked more than 10 meters from Pathfinder. Lander and rover shared tasks to reduce duplication of hardware. The methodology used placed the majority of capability onboard the lander and limited the rover to operations within line-of-sight with the lander.

2.5.1. The Morphology of Pathfinder

The Pathfinder lander came into Mars as a pyramid and opened like a flower revealing three solar petals and a central avionic housing and communication center with a variety of scientific instruments. The Sojourner rover was perched on one of the solar petals and looked like a boxy remote control car. A flat, upward-facing solar panel made up the top surface with a gold chassis and six wheel drive system suspended by thin aluminum members. Limited capabilities permitted a small rover of only 10.5 kg.

The Pathfinder lander slowed on approach to Mars through a heat shield to brake against the Martian atmosphere and through parachutes. Impact was absorbed by airbags. Heat shields and parachutes do not work on the moon due to the lack of atmosphere. These systems also led to an imprecise landing site, not suited to a mission that seeks to land within a few kilometers of the Apollo 11 site.

Figure 10: Sojourner rover

Diffuse lighting, minimal operation time, and an equatorial location enabled the use of the upward-facing, non-actuated solar panels on both the lander and rover. A charge-operate cycle permitted the rover to draw more power in operation than it produced from solar cells. The rover only operated a maximum of four hours a day. Avionic compartments have minimal heat rejection requirements in the relatively moderate thermal environment of Mars.

The Sojourner rover served as short-range data collection, transmitting and receiving data through the lander, which communicated with Earth. Six-wheeled locomotion with a rocker-bogie suspension provided excellent rough terrain mobility to the slow moving rover.

2.5.2. The Mechanisms of Pathfinder

Six wheels propelled sojourner with brushed motors and planetary gearing contained within each wheel. The two front and two back wheels were rotated using four individual actuators causing the rover to turn. The atmosphere and moderate temperatures of Mars facilitate the use of less advanced grease and oil lubricates and brushed motors, which are not possible in the hard lunar vacuum. Rover speed topped out at .036 km/hr [11].

Sojourner used a passive method of differencing known as rocker-bogie. Suspension joints rotate and conform to the contour of the ground, providing stability for traversing rocky, uneven surfaces. This system enabled the rover to climb rocks up to twice the diameter of its wheels.

2.5.3. The Structure of Pathfinder

Sojourner's chassis was primarily aluminum. Actuator housings and bearings were integrated into the chassis to reduce mass for appended components. Light weighted aluminum linkages were used in the rover suspension system.

2.5.4. The Avionics of Pathfinder

Avionics in both the lander and rover were packaged tightly together and surrounded by a layer of Aerogel, an extremely light insulating material, to maintain temperature of components for minimal mass. This strategy worked well in the colder environment of Mars where heating is the primary concern.

The Pathfinder lander included communication to Earth, an array of sensors, computing, and cameras. The lander and rover communicated through modems for line-of-sight communication. To save on cost the modems used were commercial hardware with minimal in-house adaptations for space flight [12].

Sojourner included minimal avionic components as most computing was located onboard the lander. These included a light-striping system for navigation. This system used fixed laser range sensors to scan the terrain immediately in front of the rover for automated detection of obstacles. The rover carried an Alpha Proton X-ray Spectrometer to analyze the composition of rocks. It was also equipped with a camera to access the lander.

3. Thesis Statement

Lunokhod and Sojourner solutions do not provide low-mass capable exploration. Lunokhod succeeded with high mass and high mission costs. Sojourner lacked exploration capability. Both succeeded with large launch vehicles relative to a 120kg lander-rover.

This research devises capable lander-rover systems that meet mission objectives within the restrictions of extremely small launch vehicles. The configuration of a 120kg, conjoined lander-rover is investigated in the framework of a mission to compete for the Google Lunar XPrize. This is accomplished through developing innovative morphology, mechanism, structure, and avionics to minimize dimension and mass.

4. Morphology

The morphology of a space exploration system is the form it takes based on the configuration and placement of components. Morphology for a conjoined lander-rover includes the methodologies for integrating lander and rover functions, and the configuration of propulsion, power, thermal, control, camera, and communication systems.

4.1. Integrating Lander and Rover Functions

Developing configurations for conjoined lander-rovers requires determining where to draw the lines demarcating lander and rover. An extreme is a rover with thrusters appended to the chassis and mobility systems that double as landing appendages. This eliminates duplication of components, as the lander is the rover. Roving capability, however, is hampered as propellant tanks and propulsion add bulk and mass to the mobile system. The lack of a separate lander means the mobility system and rover underbelly are not shielded from dust kicked up on landing.

A configuration with remarkable advantages reduces the lander to a platform with propulsion components arrayed about its base. Propulsion is controlled by avionics on the rover through an electrical umbilical connection. All avionics and software reside in the rover, and the rover flies the propulsive-only lander to the surface. Once on the surface, the rover separates from the landing pallet and drives away. The true distinction is that the lander is bereft of avionics, and that the rover avionics are the only avionics. Collateral advantages are capabilities for dual-use of structure, avionics, perception, communication, and control to achieve capable, ultra light surface exploration.

Figure 11: Devised conjoined lander-rover configuration; avionic components reside in the rover; the lander is only a pallet with propulsion appended.

4.1.1. Advantages of Conjoined Solution

Conjoining the systems of landers and rovers facilitates meeting mass budgets in capable exploration systems. Conjoined lander-rovers have significant advantages over traditional split architectures in the areas of structure, avionics, perception, communication, and software.

Structure: Stack height, fairing diameter, and taper are all constrained in small launch vehicles. A discrete, wedding-cake stack of lander and rover cannot minimize vertical height. The advantages of monolithic design reduce stack dimensions and achieve an overall mass advantage by reduction of elemental sections and reduction of material volume.

Avionics: Traditional landers and rovers are distinct spacecraft that require separate avionics hardware for control, power and thermal management, and communications. Combining lander and rover functions enables the system to make dual-use of one computer, one power system, and one communications system. This single avionics system simplifies testing, reduces the cable harnessing required, and saves power and mass that is duplicated in split architectures.

Perception: Cameras and an Inertia Measurement Unit (IMU) are mainstays of sensing for rover exploration. Radar and an IMU are the mainstays for entry, descent, and landing (EDL) range and pose estimation. The system envisioned makes use of one IMU, active while landing and while roving. Cameras guide for roving, but are also used to match imagery captured during landing to satellite imagery to determine pose and navigate for a pinpoint landing.

Communication: Communication for landing and roving are traditionally distinct systems. The innovation in a conjoined system is a monolithic communication system that has only one transponder and multiple antennas for landing and roving.

Software: Software, firmware, and computing for flight traditionally are intrinsic to flight, and inactive once a spacecraft reaches the surface. Software, firmware, and computing for roving traditionally are intrinsic to a rover, and inactive during flight. Necessary utility software like device drivers, operating systems, communications, power management and thermal management are common in a split lander rover setup. This commonality is exploited in a conjoined lander-rover. By reducing the amount of redundant code, the spacecraft flies with fewer lines of code that are developed in a shorter period of time and tested more rigorously.

4.2. Propulsion Methodology

Large mass systems with an excess of propellant succeed with long rocket burns imparting low acceleration loads on spacecrafts. Small mass margins lead to rocket burns with short durations and high accelerations to improve efficiency of propellant use.

Lightweight missions exploit the short forceful burn methodology, utilizing powerful solid stages to impart most of the necessary changes in velocity in burn times of only one or two minutes. Liquid braking thrusters on the lander perform the final slow down, bringing the craft to near-zero velocity relative to the moon with a few strong short bursts.

Small attitude control thrusters on the lander adjust direction to hone in for a pinpoint landing. These thrusters slow the craft to a slow constant velocity a few meters before touchdown on the lunar surface.

Innovative low mass options such as ion propulsion and solar sails provide the possibility for future systems to traverse from Earth orbit to their intended destinations in low mass packages. The downside is these processes work by incredibly slow changes in velocity expanding a four day lunar journey into several months or more. This adds cost to the mission in terms of increased lifetime of parts and increased timeline for use of communication centers.

4.3. Solar and Thermal Configuration

Lander-rovers for lunar exploration must provide power and thermal control in flight, as well as on the surface. Solar power is readily available during the lunar day and is an inexpensive, safe, and low mass solution to provide continual power over the course of a mission. Solar panel design for rovers traversing the moon is different from that of satellites. A constantly changing solar incident angle due to the rover's movement and sun elevation continually changes the power profile. At the lunar equator, the sun treks across the sky from horizon to overhead to horizon and the lack of an atmosphere eliminates all diffusion of solar energy. This requires solar configurations to capture solar energy originating from a variety of angles for continuous operation. Similarly, radiative surfaces must account for the changing location of the hot sun.

Lunokhod solved solar and thermal challenges using an actuated solar panel to point to the sun at any angle and a radiator facing directly up. This solution does not solve the configuration for lightweight exploration. Actuation adds mechanism and mass. Upward facing radiators preclude action at midday when the sun is overhead.

A symmetric configuration for equatorial rovers seeks to provide power and thermal regulation with any direction of travel with no actuation. The form is a symmetric four-sided pyramid with surfaces inclined at three different angles. Solar panels inclined at 90° from the ground collect power in the early and late day, while steeply inclined solar panels collect power near midday. Radiator surfaces are at an intermediate angle to reject heat evenly regardless of which side the sun is on. Refinement placed all solar cells at one inclination, removing 90° panels that pulled in too much heat from the surface.

Symmetric configurations are infeasible. Radiator surfaces on the sun side aggregate more heat than other surfaces can compensate. Components mounted near the sun side would not maintain thermal limits. Solar cell mass would be significant to achieve enough power when driving in any direction, since at least half of cells would go unused in any orientation.

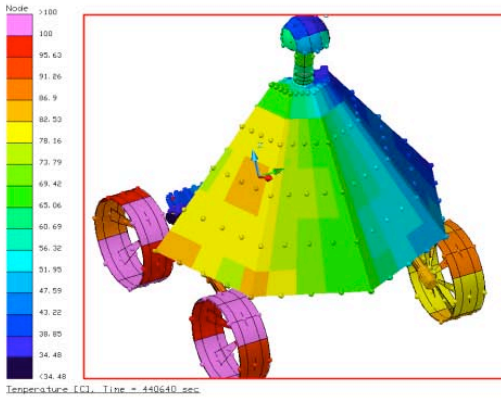

Figure 12: Analysis of thermal conditions for asymmetric configuration.

Asymmetric configuration succeeds relative to solar and thermal challenges. When mobile on the surface, rovers drive with solar panels into the sun for power, with radiator pointing away from the sun, toward black space for cooling. The inclined facets on one side gather solar power during the changing sun angles that occur from dawn to dusk. An upward-looking facet on the other side ejects heat to black space. The balance of the solar heating and radiative cooling are means for the essential regulation of the temperatures of internal electronics. During a rolling cruise, the same arrays and radiators generate power and regulate temperatures. The innovation is to generate power and regulate temperature both in cruise and on the surface without duplication of components or actuation of solar arrays and radiator surfaces.

The solar arrays regulate their own temperature. This is done by constructing the structure of the four solar facets out of a continuous piece of highly conductive carbon composite to distribute heat away from illuminated panels. Cells that are not illuminated act as radiators, rejecting heat to black space.

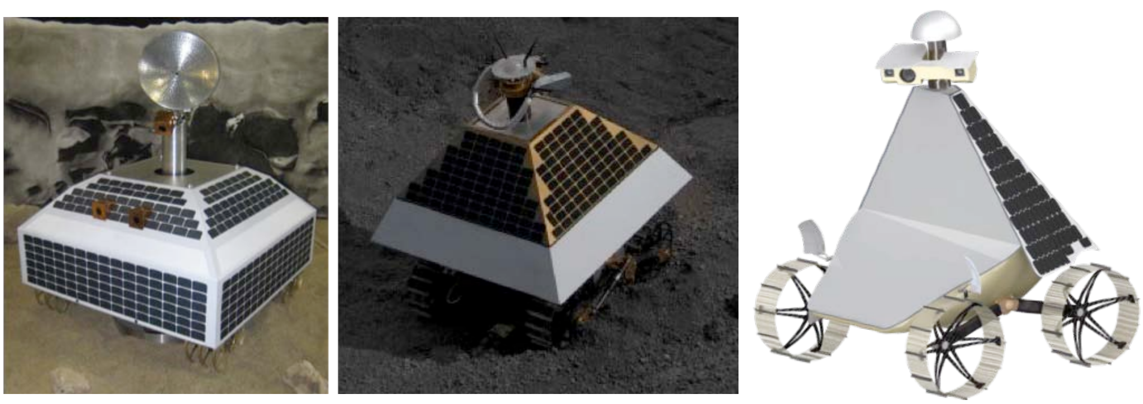

Figure 13: Evolution of solar and thermal configuration from a symmetric system to a lower mass, optimized directional rover

Configuration of power systems for conjoined lander-rovers includes optimization of panel angles, cell string design, and charging system. Four facets permit orientation at a range of angles relative to the sun while still gathering power. The ability to travel in either direction is achieved by reversing wheel spin. Results of a simulation quantifying power at different sun elevation angles and different rover driving angles relative to the sun for a sample solar configuration developed are shown in Figure 14.

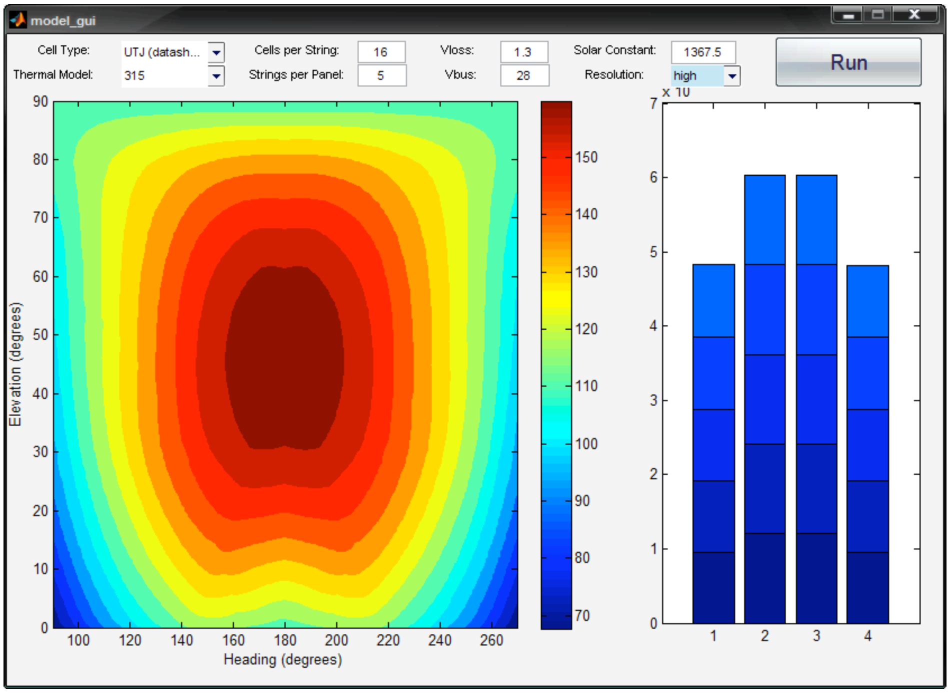

Figure 14: Power at different sun elevation angles and different rover headings relative to the sun. A heading of 180° indicates the solar panels are pointed at the sun. A 0° elevation is when the sun is on the horizon.

4.3.1. Component Placement

Placement of avionic components is determined largely by thermal requirements. The connection between components and radiator surfaces determine the temperature range experienced. The more direct the contention, the closer the component temperature is to the radiator temperature, and the more sensitive it is to fluctuations in radiator temperature.

Density of component packing impacts thermal performance. Close packing helps components share heat in a cold environment, while spreading out components facilitates radiative heat rejection.

Equatorial rovers experience the extremely high temperatures of the lunar day. This results in a configuration with components connected either directly to the radiator or through high conductivity pathways. Components are distributed across the radiator to improve efficiency of heat rejection.

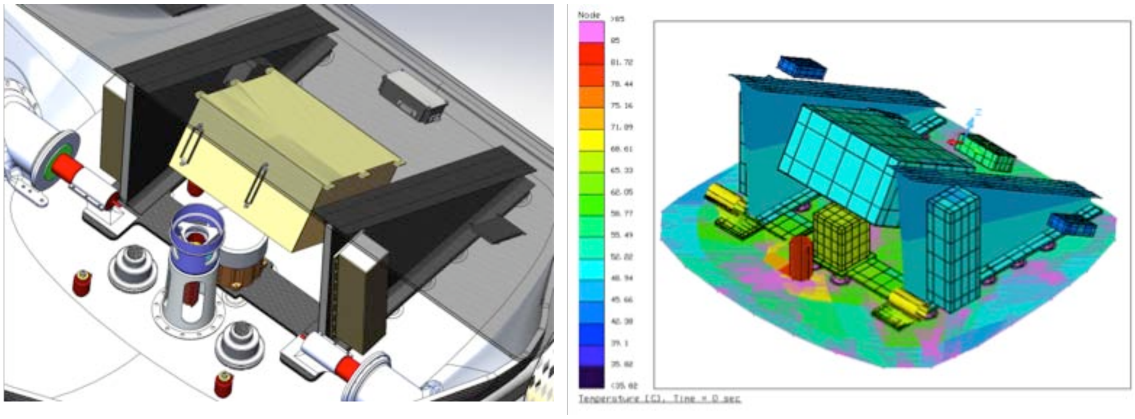

Figure 15: Avionic components are connected to the radiator either directly or through high conductivity pathways. Distribution across the radiator improves efficiency of heat rejection.

4.4. Mission Control

Lunar rovers are tele-operated from Earth through a time delay and require constant attention from their rover operators. In order to achieve the mission objectives in a timely and cost effective manner, rover operations must be fast, flexible, and efficient. Because of the expense of communication bandwidth for remote operations, small improvements to the efficiency and safety of rovers can lead to large mission cost savings.

Terrestrial mission control designs traditionally form tight loops between robots and human operators [24]. They require many people to analyze an inordinate volume of data returned from the vehicle [25]. Time to analyze data impinges on decision-making. Successful configurations of mission control for lunar rovers optimizes presentation of data to operators and assists in the decision making process.

Rover control leverages existing techniques to integrate user interface tools, aiding in decision-making. This includes systems to visually suggest next actions, sliding scale autonomy, and to provide three-dimensional models. What is lacking in current mission control is seamless integration of these tools and techniques into operator work flow [27].

Figure 16: Terrestrial mission control centers present inordinate volumes of data to operators.

The innovation of rover control is the improvement of remote operation by changing the way in which the rover operator interacts with the rover. The control system developed presents rover interfaces that are simple, effective, and safe such that, with minimal training, operators can

Figure 17: Flow of data in mission control configuration

directly control the rover. The major advancement is the design and integration of tools for predicting vehicle safety in response to commands issued by operators.

Testing on terrestrial rover prototypes is essential to the refinement of remote control centers. These improvements come in the form of reduced volume of data presented to operators by the formation of integrated tools that present meaningful data products to operators based upon what is most commonly used.

Predictive views of trajectories improve tele-operation of rovers. Operators are provided with estimates of future rover positions overlaid on stereo imagery. These estimates are based on inertial navigation systems, camera angle and position, the foreshortening of the image, and an estimate of the position of the terrain. Operators control waypoints and predictive modeling produces the intermediate steps. If terrain is rough, operators can choose to slow down in which case the chain of steps move closer together and the uncertainty lowers. This enables operators to dynamically choose how to mitigate risks given the structure of local terrain. Rover safety systems can also override operator commands. This ensures that, in the event of a sudden communication loss or gross error in projections, the rover will be capable of protecting itself. This interactive risk management increases system efficiency and assists operators in assessing the advantages and disadvantages of different navigation routes.

Figure 18: Rover trajectory is overlaid on camera views based on predictive modeling.

4.5. Camera Configuration

Morphology must be designed around the primary deliverables of the mission. The Google Lunar XPrize is first and foremost about movie making. Desired imagery determines the type of camera systems and their placement. Cameras for this mission must be capable of:

- Creating panoramic imagery,
- Pointing in either direction to enable two directions of driving,
- Zooming in to see historical hardware without disturbing the site,
- Viewing at least 40% of the surface of the rover,
- Capturing 3D imagery and video.

Sample morphology combines an upward facing camera and a bowl shaped mirror to collect panoramic imagery, as shown in Figure 19. Forward and backward facing cameras record 3D imagery and enable driving in either direction.

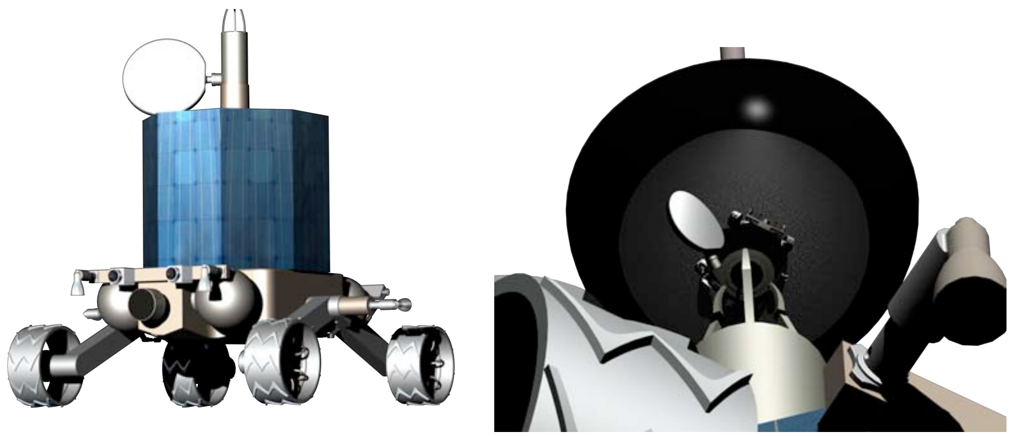

Figure 19: A combination of an upward facing camera and bowl shaped mirror collect panoramic imagery; forward and backward facing cameras collect 3D imagery.

A modification exchanges the bowl and upward camera for a gimbaled camera and stereo navigation cameras only on one side. The gimbaled camera collects panoramic images and includes a zoom mechanism, a requirement that is missed in the bowl-mirror configuration. The gimbaled camera is also used to drive backwards eliminating the need for rear navigation cameras. This succeeds when combined with a symmetric solar and thermal configuration so driving in any direction is possible by first turning in place.

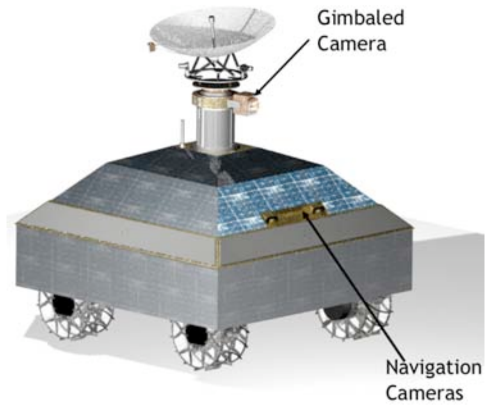

Figure 20: An iteration of camera design introduces a gimbaled camera and only places stereo navigation cameras on one side of the rover.

The optimal camera configuration for the XPrize is adapted to the asymmetric, directional rover. This design places three cameras on a pan and tilt system high on the rover mast. One camera includes a zoom mechanism and the other two collect 3D imagery. This enables any form of imagery to be captured on any side of the rover. The high vantage point is ideal for driver perception.

Self-viewing is achieved by the inclusion of side view mirrors. These mirrors permit the rover to see its drive system to assess danger and view a front logo panel to provide the inclusion of sponsor logos improving mission profitability.

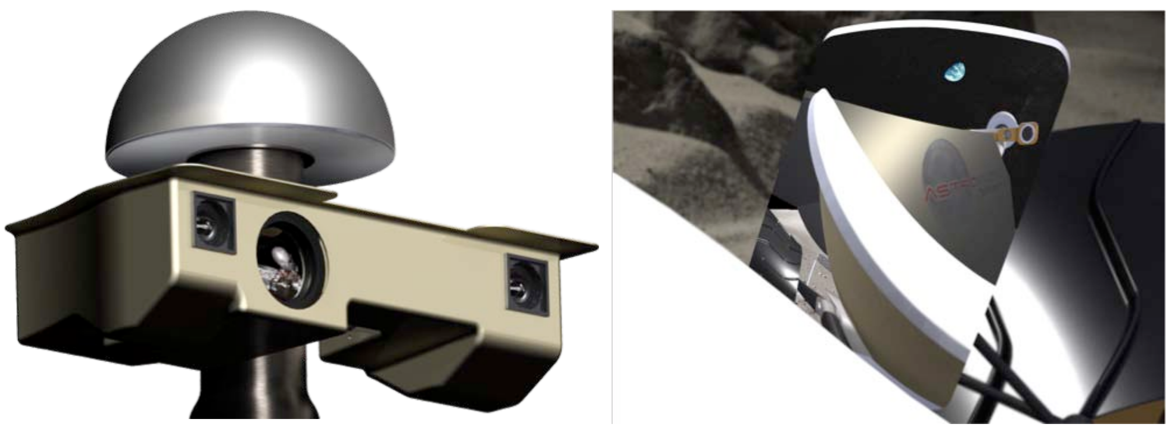

Figure 21: Zoom and stereo pair cameras were moved to pan and tilt mechanism at the top of the rover. Mirrors enable the rover to see the locomotion system and a logo panel.

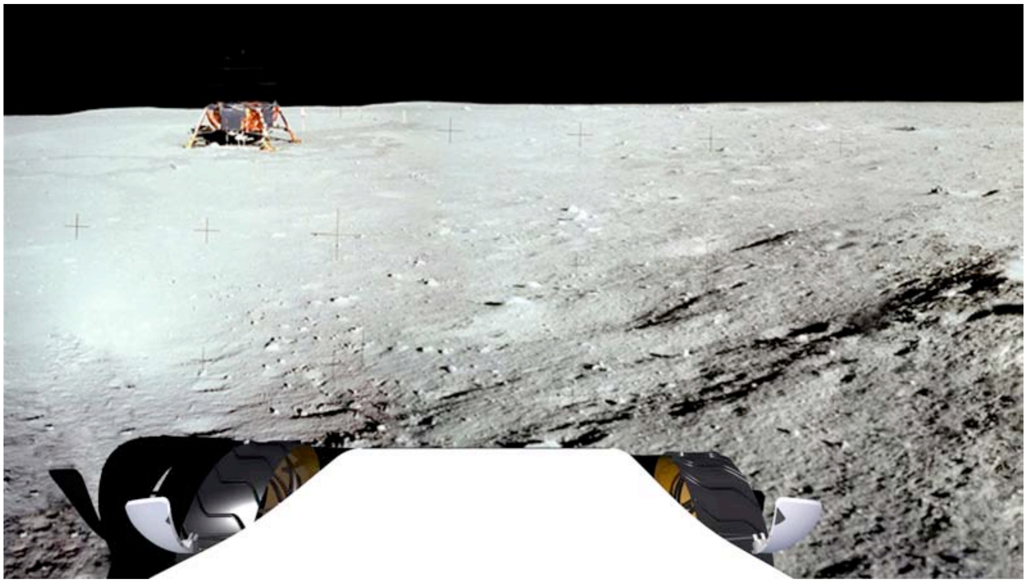

Figure 22: View from mast cameras as the XPrize rover approaches the Apollo 11 site

4.6. Communication Methodology

The morphology of communication systems for conjoined lander-rovers must provide a link to Earth during all phases of a mission. In transit, a spacecraft must maintain communication with Earth during all flight attitudes in order to send telemetry and receive commands for orbital adjustments. On the lunar surface, communication must deal with changing rover orientation relative to Earth while providing data rates capable of transmitting necessary data for operations and to fulfill mission requirements. Configuration of a communication system includes selecting antennas on the exploration system as well as ground stations on Earth. The larger the antenna on Earth, the lower the requirement for antenna size and communication power on the exploration system.

Communication is critical to any robotic space mission, but more so for the XPrize, since the mission requires voluminous video and imagery. There is no precedent for achieving such communication bandwidth from a planetary robot. This requires a breakthrough in lunar communication.

A sample configuration uses a low rate omni-directional to transmit data relevant to operations and a steerable high gain antenna to transmit data to Earth. The system conceived would use a small camera to identify and point to the Earth.

An optimal configuration for the XPrize takes advantage of cutting-edge antenna technology for surface operations. The technology selected is that of an evolved antenna. These antennas appear similar to bent paperclips, but the specific bends are designed using machine learning techniques to optimize the antenna's beam pattern and efficiency for a given mission [15]. This beam pattern design encompasses the Earth regardless of rover orientation. This system continually transmits data for operation interspersed with imagery. Imagery is prioritized for transmission and trickles in when excess bandwidth is available through the course of the mission.

Figure 23: One design uses a steerable antenna guided by a small camera. The XPrize rover succeeds with a low mass stationary evolved antenna.

In addition to the roving antenna, two low power antennas reside on the lander deck. The antennas reside on opposite sides and have large beam widths to enable communication with Earth during transit regardless of spacecraft orientation.

5. Mechanisms

Mechanisms that succeed for lander-rovers have to fly, land, and rove subject to high loads within low mass and volume of small lunar missions.

The harsh lunar environment necessitates unique mechanism design. Hard vacuum and extreme temperature ranges demand specialized lubrication methods. Thermal expansions cause internal friction without meticulous design. Even the lunar soil (or regolith) possesses unique challenges to mechanisms, as it is made of small loosely packed, highly abrasive particles that pose significant contamination problems. Solutions must overcome these challenges within the constraints of limited power, mass, and volume.

5.1. Landing Mechanisms

Lander mechanisms absorb landing impact and secure the rover during launch, cruise, and landing. These low mass mechanisms must be capable of surviving high loads from rockets firing and landing impact.

Lander legs stow for flight, deploy for descent, and flex on impact. Stowing facilitates mechanism survival during launch, cruise, and braking. However, successful leg design must endure accelerations from landing thrusters and landing impact while in a deployed state. Use of carbon composite materials in leg design improves strength at a minimal mass. Pressurized pistons absorb impact on landing reducing loads transmitted to the lander and rover.

Leg design and placement facilitate stability. Three-leg design ensures all legs will be in contact with the ground on uneven terrain, preventing rocking between legs during rover egress. Wide stance inhibits tip-over during landing.

During flight and landing, loads are transmitted between lander and rover through a separation mechanism. Once on the surface, the rover separates, the pallet lander is inert, and the rover drives away. For the XPrize lander-rover separation is achieved through the use of shape memory alloys. Shape memory alloys are materials that produce large and predictable changes in size and shape when heat is applied. The lander and rover are connected via bolts notched to fail at predetermined locations. Release mechanisms heat shape memory alloy materials to stress the bolts in tension until they break. Use of these mechanisms facilitates testing by reducing danger and increasing reuse of components between tests relative to traditional explosive separations.

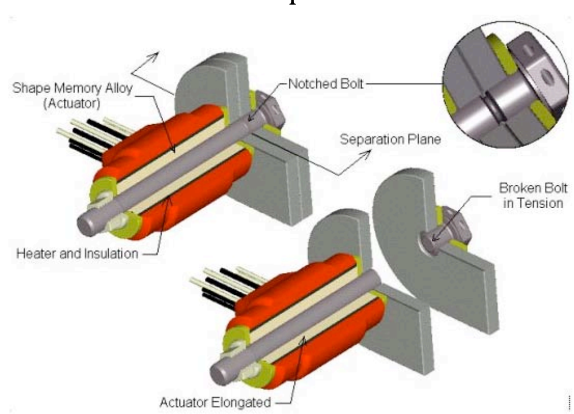

Figure 25: Shape memory alloy actuators break bolts connecting the lander and rover [30].

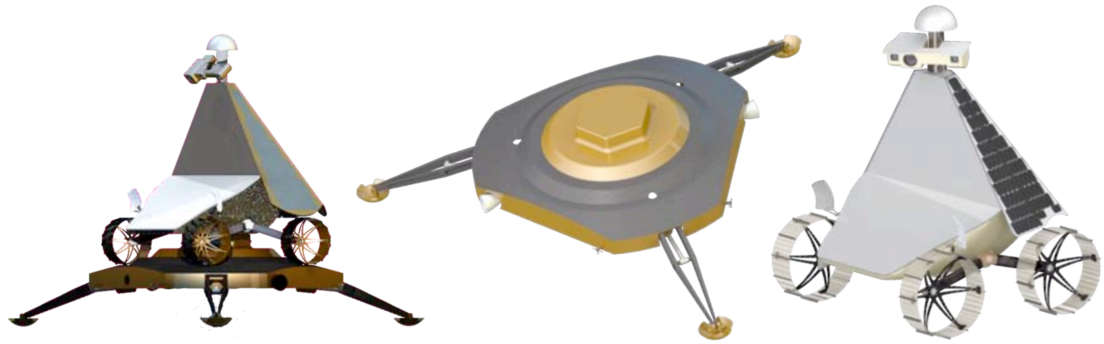

Figure 24: Once on the surface, the rover separates, the lander is inert, and the rover drives away.

5.2. Mobility Mechanisms

Once on the surface, a rover must be capable of maneuvering over terrain between points of interest. Anticipated surface terrain, speed of travel, and level of safety in operation are key factors in design. A many-wheeled extremely safe and capable system means added mass and dimension. Solutions that succeeded on Lunokhod and Sojourner are overdesigned relative to the requirements of ultra-light rovers. Improved ability to sense terrain and avoid major obstacles facilitates success with a simplified system by circumventing hazardous terrain.

Mobility mechanisms include actuation, suspension, and traction element design. Requirements of a drive system include vehicle speed, torque, power usage, traction, obstacle performance, and slope performance.

In the design of mobility, sizing of gearing and motors ensures sufficient performance. A system with inadequate torque could become stuck with no means to recover, stranding the rover. Significant safety margins are required to preclude mechanism failure. The XPrize rover accounts for mission uncertainties through design for full operations on Earth. Since lunar gravity is one sixth that of Earth, the rover will have six times less weight to move around on the moon. This method enables simplified testing without gravity offloading to test mission operations on Earth. The downside is additional actuation mass and lower power efficiency, since an actuator is less power efficient at lower torque output.

The process of sizing actuation begins with derivation of output power required by determining torque and speed needed ($P = T\omega$). Power requirements are increased by a factor representative of expected gearing efficiency loss. Motors are selected that supply necessary power. A gear ratio for the actuator can then be determined based on torque and speed ratios between motor specifications and desired actuator outputs. Speed ratio provides an upper limit on gear ratio and torque ratio provides the lower limit. Gearing is selected to achieve a ratio within this range that is capable of surviving the anticipated loading cycles. This process can be iterated as needed based on tested loads and gearing efficiency relative to assumptions.

Testing ensures mobility systems meet performance requirements. Obstacle surmounting tests reveal obstacle performance. Power performance is measured using a test setup to load the actuator with a set torque using a mechanical brake. This measures actuator efficiency in terms of electrical power in relative to mechanical power out. Estimates of power are particularly important for space systems to appropriately size power systems.

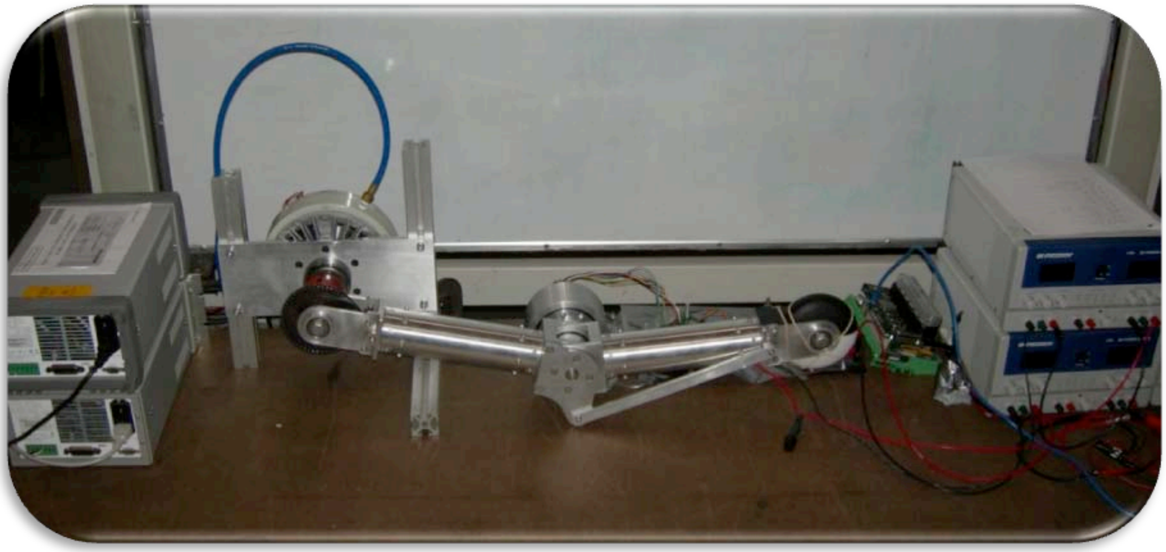

Figure 26: Mechanical brake setup to test actuator power efficiency

Traction performance can be assessed through testing on slopes or through a drawbar pull test. In this test the rover must drive on flat ground with a measured resisting force. This is comparable to the resistance caused driving up a slope. The percentage of wheel slip is plotted against resistive force as a percentage of vehicle weight. These results can be translated to traversable slope angles. Results are interpolated to determine a range of safe slopes, dangerous slopes, and insurmountable slopes. An example result is shown in Figure 27.

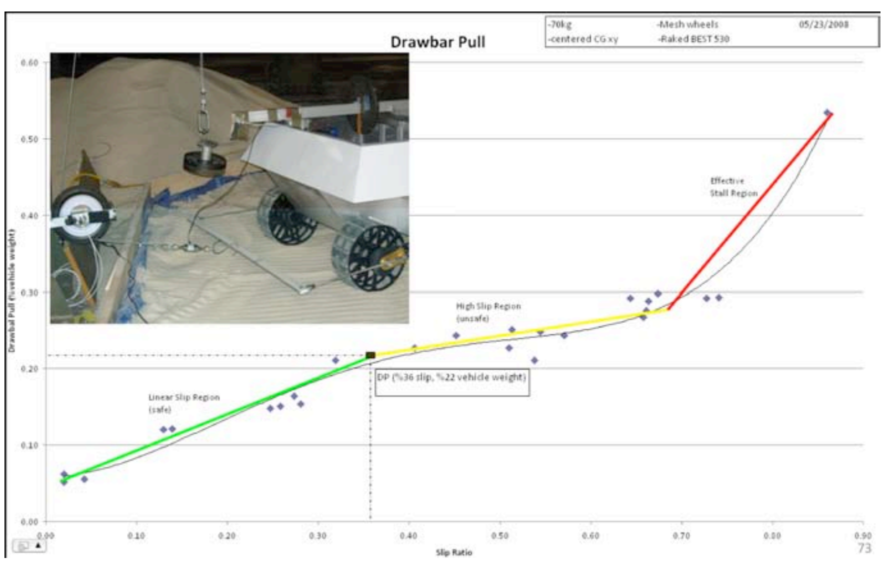

Figure 27: Graph resulting from a drawbar pull test. Slip ratio is plotted vs. resistance force as a percentage of vehicle weight.

5.2.1. Drive Actuation

Actuation for a drive system must provide the power necessary to propel and steer a rover on the lunar surface. Excess power capability is designed to handle extreme situations. Slippage, entrapment, or tip over might occur, but lack of drive power will not be a failure mode.

Steering can be accomplished through additional mechanism, but lightweight minimalist approaches require no additional mechanism. The configuration devised rotates by skid steering, or turning wheels on one side forward and the other backwards. This reduces required mechanism mass and complexity.

Midday temperatures at the lunar equator would overheat motors at the wheels, so drivelines are preferred that remove actuators from wheel hubs. This leads to shoulder driven mobility configurations. Shoulder drives have a collateral advantage of enabling skid-steer rovers to operate with a single actuator per side. Each actuator transmits torque to both wheels on one side. This enables two actuators to propel and steer the rover. Shoulder drives can transmit torque through series of miter gears and drive shafts from shoulder to wheel. Such systems have high levels of complexity, requiring high-precision gear meshing and complicated implementation to produce adequate torque, as the torque capability of miter gears is minimal.

To reduce complexity and mass and improve torque performance, a chain driven configuration is optimal. This system locates gear reeducations at the shoulder and transmits torque to two wheels through roller chain. Roller chain transmits high torques with minimal mass and complexity. Such a mechanism has not been used in space applications to date because of a concern for cold-welding. Cold-welding is a phenomenon where similar metals fuse together in a vacuum environment especially when forcefully pressed together or under thermal swings. This occurs because of the lack of an oxide coating on metals in an oxygen free environment. For short duration missions, this can be overcome with light coatings of lubricant. Dissimilar metals can also be used in roller chain elements to prevent cold welding in systems for long duration use. Initial vacuum chamber tests showed no sign of cold-welding in a week-long test.

Figure 28: Miter gear sidearm configuration transmits torque to wheels through a complex gearing system.

Figure 29: Mobility sidearm drives two wheels with a single actuator at the shoulder and roller chain to transmit torque to wheels.

Figure 29: Testing roller chain in vacuum.

Iteration of mechanism sought to drive down mass and size of components optimizing based on loads experienced in testing. The result is a low mass drive system.

Figure 30: Mobility mass reduced through analysis of load conditions.

A stack of a brushless motor, planetary gearing, and a harmonic drive[1] performs shoulder actuation of roller chain in the XPrize rover. Brushless motors are employed due to excellent reliability in space environments. Brushless motors do not have sparking problems common with brushed motors in vacuum, and reject all generated heat through the external casing rather than the rotating portion simplifying thermal control. Lunokhod used sealed compartments for brushed motors to overcome this failure mode, and the atmosphere of Mars enabled Sojourner to use brushed motors. A harmonic drive provides the majority of the gear reduction for the XPrize rover. Harmonic drives provide large reductions in a single stage and handle large torque outputs in a small volume, low mass package.

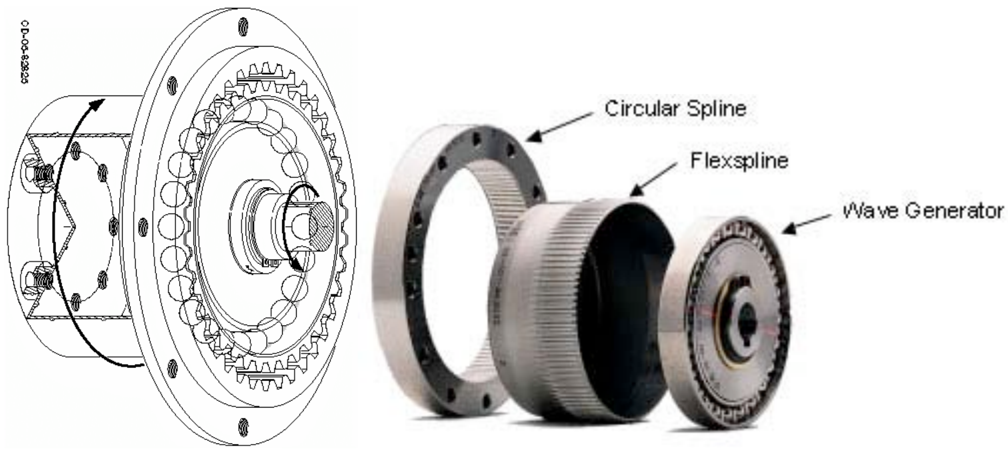

Figure 31: Harmonic drives provide large gear reductions in a small volume, low mass package

5.2.2. Drive Suspension

Drive suspension seeks to maintain wheel contact and equalize rover weight carried by each wheel. Equal weight distribution balances the traction potential of each wheel so that if one wheel encounters an obstacle, the other three are capable of supplying traction to assist in surmounting the obstacle. Equal weight distribution reduces the danger of a single wheel becoming entrapped by sinking into the soil more than the others.

Two sidearms passively rotate about the shoulders and are connected through a rocker-bogie suspension, similar to that used by Sojourner. This set of passive linkages with no elastic elements ensures all four wheels maintain contact with the ground. This low mass solution ensures near equal weight distribution over all four wheels on uneven terrain, dramatically improving mobility capability.

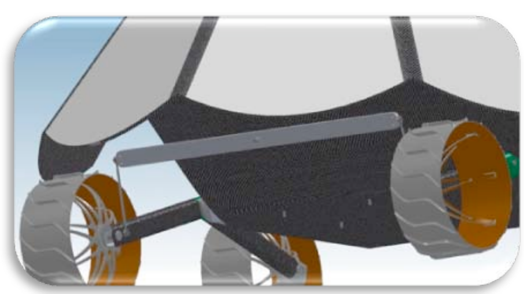

Figure 32: Rocker-bogie suspension system

[1] The XPrize rover uses a Maxon brushless and planetary gearhead [32] coupled with an HD harmonic drive [33].

5.2.3. Traction

The fundamental function of a mobility system is to generate traction to move the rover. Traction is the result of thrust at the interface between a wheel and the ground [28]. Traction for rovers is determined by ground pressure and soil interface design. Soil interfaces must maintain traction while traveling over loosely packed lunar regolith. Failures of traction occur when wheels slip relative to the top layer of soil, or when shear forces within the soil cause shear failures within the soil.

Successful wheel surface design grips the soil preventing slip between wheel and soil. Designs with ideal traction do not slip until soil shear failures occur. Rovers utilize grousers, or blades on the wheels to dig into the soil increasing the tractive forces by spreading forces deeper into the soil. Sharp grouser points also facilitate grip on rocky terrain.

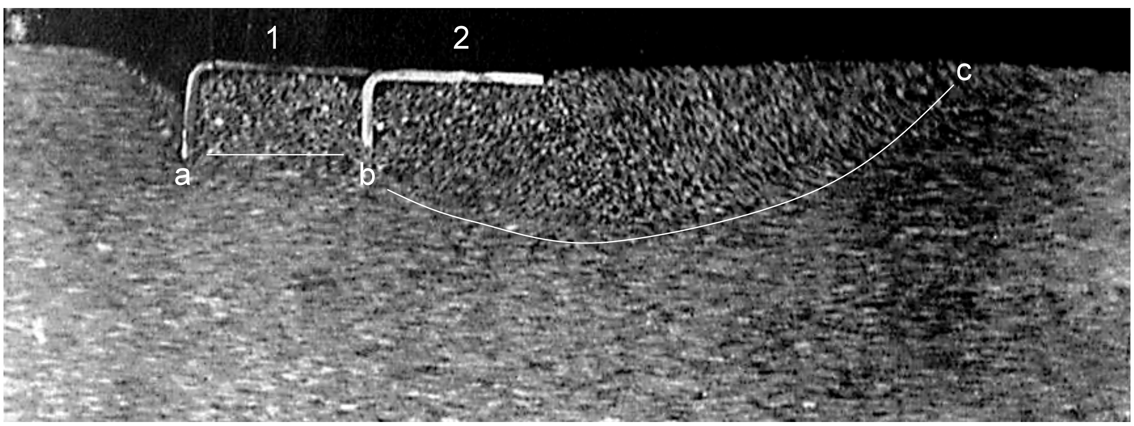

Figure 33: Wheel grousers dig into the soil increasing tractive forces [29]

Decreasing ground pressure reduces soil shear failures by spreading out shear forces over larger areas of soil. Low mass and low lunar gravity result in low vehicle weight. Number and size of wheels determine contact pressure with the ground. A low weight system requires less wheel contact area than a heavy machine to reach the same ground contact pressure. Design for lightweight rovers takes this into account selecting a four-wheel system to minimize mechanism mass. Variance in wheel diameter and width tune ground pressure by changing contact area. This leads to a system with four large wheels.

5.3. Camera Mechanisms

Space missions require mechanisms to point, place, or manipulate sensors and payload. The XPrize mission necessitates mechanisms to point camera systems and zoom optics.

Camera pointing and zooming require accurate absolute positioning, driving the use of stepper motor actuation. Stepper motors "step" through fractions of a rotation by alternately activating four electromagnets.

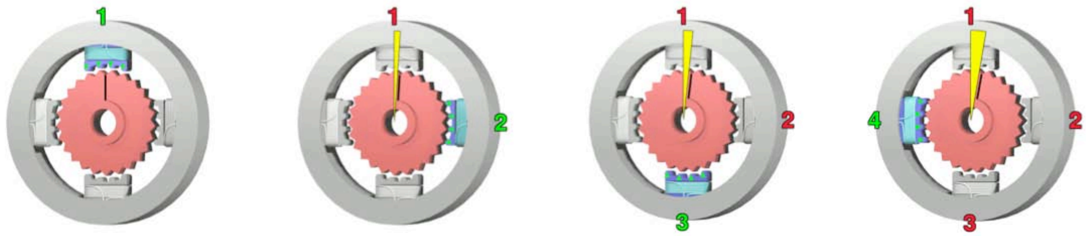

Figure 34: Stepper motors maintain absolute positioning by stepping through fractions of rotations by alternately activating four electromagnets.

Cameras are placed high on the XPrize rover and utilize mechanisms to perform panning and tilting motions. Cable management drives designs with cable slack for flexibility during rotations. Panning motions make use of the long distance cable run up a central mast tube to provide slack for cables to twist. Tilting motion bends and unbends cables. Cables are locked in place at either end of the tilt motion to create a region for bending with slack to limit torque requirement of tilt actuation.

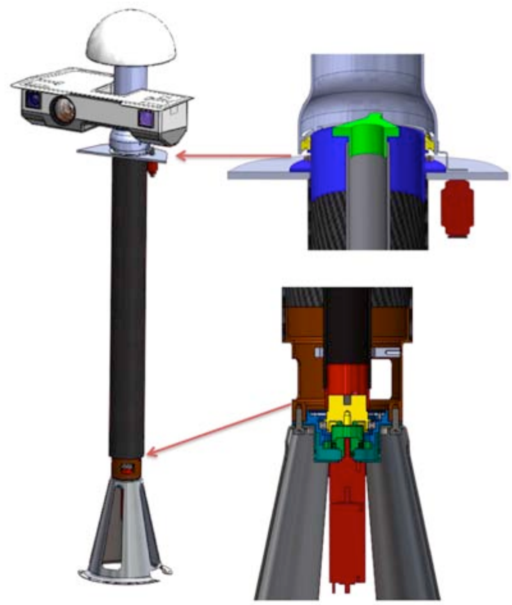

Figure 35: Long distance from rover chassis to camera box facilitates cable management for panning motions by twisting cables inside the mast tube.

Motors to produce pan and tilt motions must be cooled during operation. Motors are located near existing thermal pathways to radiators minimizing required mass for thermal control.

For operations on the moon, telephoto lensing is essential for sensing and data acquisition. Terrestrial telephoto lenses are highly automated and advanced, but no automated telephoto lens has operated on the moon.

A lunar telephoto zoom lens for equatorial rovers must be robust to vacuum, radiation and regolith contamination on the lunar surface. To reduce costs development time, rovers make use of existing lens designed for terrestrial application. Modifications are required to replace lubrication and actuators with space-relevant equivalents.

5.4. Regolith Protection

Mechanisms must be protected from impingement of highly abrasive lunar regolith to prevent increased friction and eventual failure of moving parts.

During landing, a significant amount of regolith is kicked up by thrusters. Conjoined lander-rovers use the pallet lander structure to shield dust from reaching mechanisms, cameras, and solar/radiator surfaces. Since the moon is a vacuum, all dust kicked up is propelled ballistically, meaning that a small lander pallet is capable of completely preventing dust from reaching the rest of the exploration system.

Drive mechanisms make use of shoulder drive to shield actuators from regolith. Shoulder actuators have no external rotating parts. Roller chain running from a shoulder to wheels is encapsulated within structural tubes to shield the chain from regolith. Rotations at the wheel are vulnerable to dust intrusion and make use of labyrinth seals to minimize dust reaching internal bearings and chain. Safety factors in drive actuation take up any additional friction caused by dust.

Additional mechanisms for pointing and zooming are located within the chassis or high on the rover where dust is unlikely to reach in significant quantities.

6. Structure

Minimizing the structural mass of space robots matters, since every kilogram spent on structure cannot be spent on payload like electronics and sensors. Conjoined lander-rovers demand the robotic structure to be high performance, yet lightweight.

6.1. Structural Loading

The structure of an exploration system must survive a variety of load conditions through the course of a mission. Structures for rover, lander, and connections between rocket motors must be configured relative to these loads.

Accelerations are imparted when rockets fire to launch, inject, or brake. These accelerations act much like increased gravitational acceleration imparting loads on structures as though components were several times heavier than they are on Earth. These accelerations are larger on a low mass system, since similar rocket forces will result in higher acceleration as system mass decreases.

Structure must withstand vibrations imparted during launch and stage separations and from acoustic effects as the rocket takes off. Structures must be stiff to survive vibrations with minimal deflections.

In addition, landing impact and driving also impart structural loading. Landing shock absorption must be designed to limit landing loads experienced. Locomotion must be integrated to the chassis such that loads are handled.

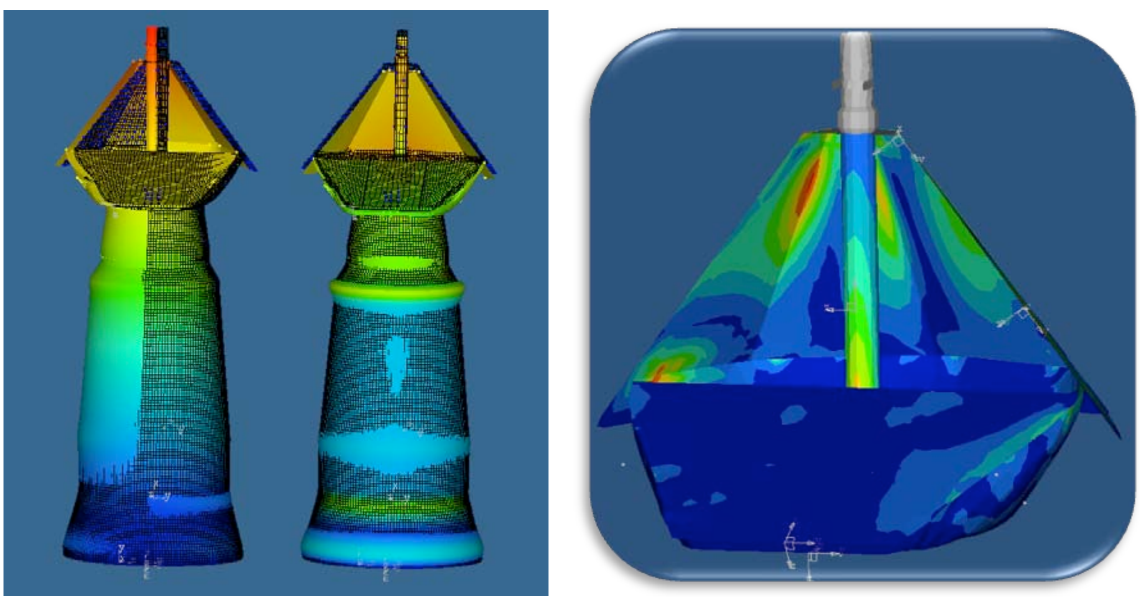

Figure 36: The structure of a conjoined lander-rover must survive vibration and acceleration loading during launch, lunar injection, braking, and landing.

6.2. Composite Materials

Much as the application of advanced magnesium and titanium alloys led to the success of the Lunokhods, the application of cutting-edge composite materials provides the potential to dramatically improve performance of modern lander-rovers.

Use of fiber-reinforced composite materials is prevalent in the aerospace industry and composites are materials of choice for today's cutting-edge aircraft and spacecraft. Advanced composite materials, once the domain of government aircraft, are now ubiquitous. They are utilized in golf clubs, sail and motor powered watercraft, automotive race vehicles, production sports cars, wind turbines, commercial jet liners, and structural reinforcement in bridges. Worldwide composite growth is burgeoning in today's efficiency-driven economy, ushering in a new era of materials. Utilization of composites has not yet permeated to space robotics.

Composite structures unlock a new realm of possibility in advanced space robotic applications. Mass reductions of up to 30% and increases of three times the stiffness compared to traditional metallic structures can be realized. Structural mass savings enable unprecedented sensing and actuation payloads. Appendages such as arms and wheels can be lightened, reducing power required for actuation. Stiff composite structures survive vibrations during launch and increase sensing accuracy by reducing uncertainty caused by material deflections. Material property advantages of carbon fiber composites over traditional metals are shown in Figure 37.

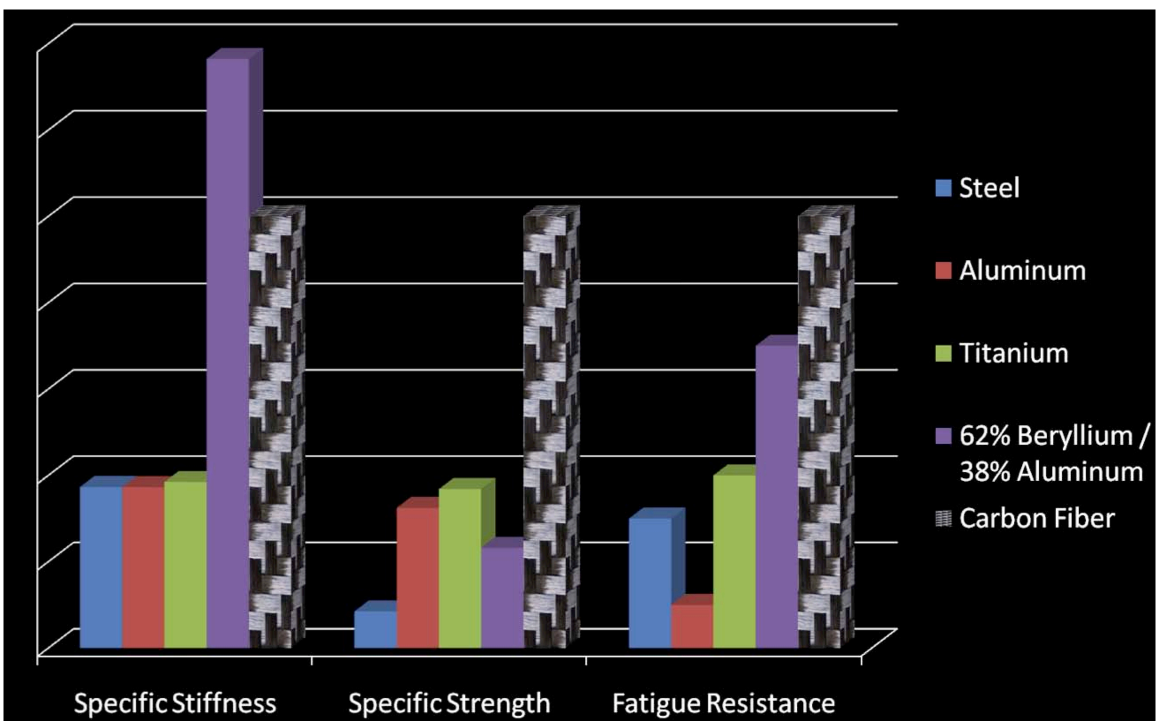

Figure 37: Comparison of carbon fiber material properties to metals relative to component mass

Composite construction layers dissimilar materials to create a "layup" that harnesses the strengths of each layered material. These layers are placed and oriented optimally to add strength and stiffness in the exact locations and directions needed.

Fiber layers, like carbon fiber, used in composite layups are fabric with all fibers pointed in the same direction. These are oriented for high stiffness and strength in the direction of the fibers. This is unlike metals, which always have the same strength and stiffness in every direction. The result is significant mass reduction for the same performance in a part by aligning fibers with load paths.

Lightweight core materials, like aluminum honeycomb, add thickness to dramatically increase flexure strength at minimal mass. Complex surface geometry can be constructed sandwiching a layer of aluminum honeycomb between layers of carbon fibers. This creates a structure that carries tension loads through the carbon face sheets and resists bending through the honeycomb core.

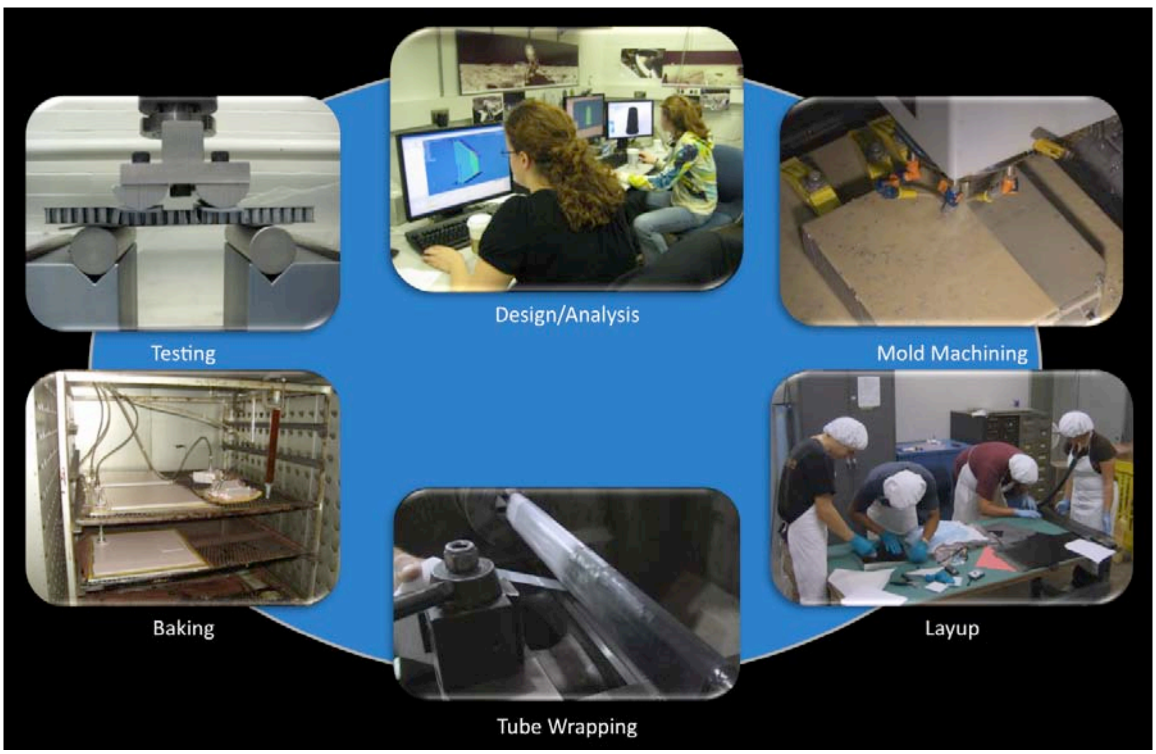

Figure 38: Composite development cycle.

6.2.1. Rover Chassis

The XPrize rover uses a chassis with a carbon-honeycomb sandwich skin. The loads imparted to the spacecraft are carried through this skin minimizing the need for separate structural members. This method of carrying loads through the skin is known as monocoque design. This technique minimizes mass by carrying loads through every part of the chassis with no additional mass for connections between structural members.

Figure 39: Carbon-honeycomb chassis design makes use of carbon face sheets to handle tensile loads and aluminum honeycomb to resist bending.

The chassis takes full advantage of required surfaces, using carbon-honeycomb panels to provide backing for solar panels and as the radiator surface. These elements are integrated through a carbon honeycomb base and sidewalls so that the entire structure assists in handling loads.

6.2.2. Lander Structure

Lander structure must endure loads from upper stages, landing propulsion, and landing legs. During flight and landing, loads are transmitted from lander to rover through a separation mechanism.

The great configuration problem is to keep the lander pallet thin. This reduces stack height in the launch fairing and reduces the step-off for the rover to dismount. Successful configuration is accomplished by protruding the braking solid rocket motor into the center of the lander pallet with propellant and oxidizer tanks clustered closely around it.

The XPrize lander pallet is comprised of a triangular carbon composite shell with stiffeners for strength and rigidity. This pallet is dual-used as a shield to prevent dust kicked up during landing from reaching the rover.

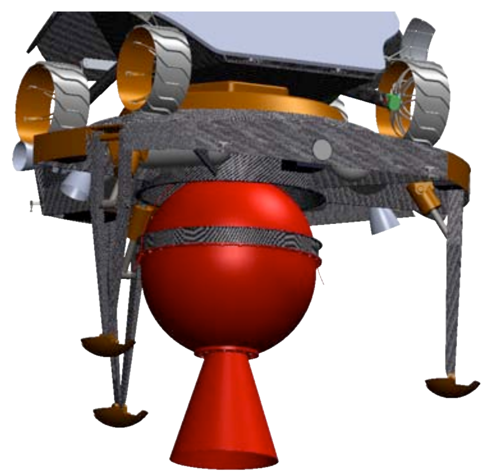

Figure 40: The braking solid rocket protrudes into the lander pallet reducing stack height.

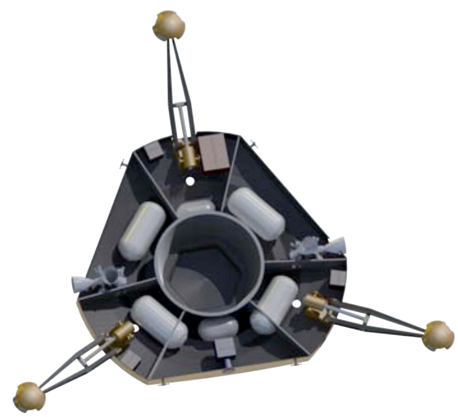

Figure 41: The lander pallet is comprised of a triangular carbon composite shell with stiffeners for strength and rigidity.

6.2.3. Secondary Structures

Secondary structures like lander legs, wheels, tubes, and I-beams exploit composite design to reduce mass.

In the XPrize lander-rover, tubes carry loads from the lander legs, rover wheels and camera mechanisms to the chassis. Structural I-beams inside the chassis provide direct transfer of loads from the radiator surface to the chassis floor. These are used to support heavy electronic components that are mounted directly to the radiator. Specialized composite designs have been developed to fit these applications with significant mass reductions. Sample structures are shown in Figure 42.

Figure 42: Secondary lander-rover structures, like I-beams and tubes exploit composite design to dramatically reduce mass.

Large wheels dramatically improve mobility performance for a low mass lander-rover, but come at a higher mass. Use of carbon composite materials enables larger wheels by dramatically reducing mass relative to metal alternatives.

Figure 43: Carbon wheel designs enable dramatic mass reduction relative to metal wheels[2].

6.2.4. Composite Thermal Regulation

Specialized tyes carbon fiber provide excellent thermal conductivity properties. Composites are heavely used in the XPrize lander-rover thermal systems to provide highly directional heat conduction at a low mass.

The radiator used to configure a low mass exploration system is a carbon honeycomb structure. It has highly conductive carbon facesheets, with a dense honeycomb core. The facesheets spread out the heat across the panel and the dense honeycomb increases conductivity through the panel. Honeycomb also adds stiffness to the panel ensuring good contact between components and the radiator.

High heat producing components are mounted directly to the radiator. The motors and Inertial Measurement Unit are thermally strapped to the radiator through thermally conductive structural I-beams. These pathways use directional carbon fiber to conduct heat efficiently.

Thermal straps and I-beams are separated from the chassis floor with isolation cones. Isolation cones are made of extremely low conductive plastic and the cone shape minimizes conduction with the chassis, which is 120°C near lunar noon, while maintaining structural needs.

Solar panels operate at higher efficiency at cooler temperatures. Thermally conductive carbon is used as the backing for solar panels to improve performance. This is accomplished by distributing heat away from illuminated sections and rejecting it to black space from non-illuminated sections.

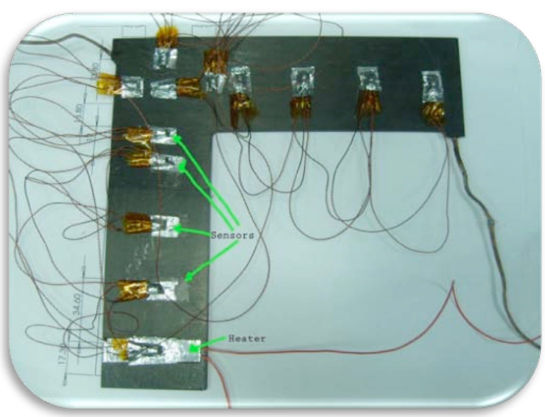

Figure 44: High conductivity carbon fibers are used to create highly efficient, low mass thermal pathways.

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[2] The composite wheel pictured achieved a mass of 300 grams compared to metal designs with mass of approximately one kilogram.

7. Avionics

Avionics are the electronics of a space system. Lander-rover avionics must succeed with low mass and packing volume. Conjoined lander-rovers dramatically reduce mass by eliminating redundancies in avionics. The same avionics are utilized in cruise, landing, and roving. All avionic hardware resides in the rover, and the rover avionics control the lander while in flight through electrical umbilical connectors between lander and rover. These umbilical connectors separate upon landing.

Avionics differ from terrestrial electronics in terms of power, thermal control, radiation hardening, and shock and vibration survival.

Power for space electronics is limited to minimize requirements for power generation as well as to minimize heat production. Heat generated by components must be conducted away from individual chips in the electronics to radiators that reject heat to black space. Power and thermal requirements of avionics drive the overall size and mass of lander-rovers by driving the size of solar panels and radiators. This calls for lightweight systems to select avionics that require as little power as possible to complete a mission.

Radiation dosage received by the electronics often limits components that can be selected. The Earth's magnetic field protects terrestrial electronics from the majority of the radiation. However, once a spacecraft travels beyond the Van Allen Belt, it is bombarded by large amounts of radiation. Electronic systems do not tolerate high dosages of radiation because their fundamental building blocks, transistors, are small, energy sensitive devices. Three major types of radiation events can disrupt a digital system. The first is a Single Event Upset (SEU) where a highly charged ion can cause a bit to flip. These events are easily handled by writing software that can recover from small corruption errors. The next is a Single Event Latch-up (SEL) where a transistor becomes shorted until it is power cycled. Circuitry that is considered to be latch-up immune includes extra circuits that automatically power cycle the transistors when an SEL is detected. The last type of event is a Single Event Gate Rupture (SEGR). This occurs when a high energy, heavy particle passes through the electronics and makes a hole in the transistor. After an event like this, the transistor will be permanently destroyed. Gate rupture is extremely rare.

Radiation is a significant issue for spacecrafts that are designed to last for many years and will receive large radiation dosages. However, for short-duration missions the expected radiation dosage is minimal[3]. Components that are not hardened for radiation can often succeed in these scenarios.

During launch and when firing secondary stages, a spacecraft undergoes high shocks and vibrations. Under these conditions, most Earth electronics fail.

[3] A one month mission to the moon would receive a radiation dosage on order of 1krad [36]

7.1. Commercial Off-The-Self (COTS) Avionics

Traditional space avionic systems are heavily overdesigned relative to expected needs. Mass is added to a computer chassis to improve dynamic loading, radiation shielding, and thermal mass. Boards are loosely packed with large chips to improve radiation tolerance. In a traditional space system like a satellite, the mass of avionics is a small fraction of total system mass so the additional mass does not significantly impact launch requirements. Low mass systems that are sent farther from Earth push the margins on avionic mass as additional kilograms dramatically impact launch requirements.

Conventionally, avionic systems involve a significant amount of custom development and are comprised of special computer chips designed to withstand radiation. Custom developments impose significant cost in development and testing.

Use of commercial off-the-shelf (COTS) components can dramatically reduce mass and development cost. COTS components are terrestrial electronics with minimal customization to enable space flight. The avionics of a COTS system still enables customizations. Cards with fixed sets of chips are used as the building blocks of COTS avionics relative to exchanging individual chips in traditional avionic design. This leverages configurations that have been implemented in the past to minimize development and testing. COTS systems selected for the XPrize use avionic cards with higher feature-density due to tighter packing and smaller individual board components, reducing the number of cards required.

Use of Field-Programmable Gate Arrays (FPGAs) enables a COTS system to be flexible to a variety of applications. FPGA chips are hardware that can be reprogrammed to serve different functions that would typically require exchanging custom computer chips. For example, the I/O board can be reprogrammed to accept RS422, serial, or Analog/Digital inputs without changing hardware. FPGAs are also used to run specialized processes without overloading the main processor. For example, a specialized FPGA can compress incoming video and images automatically without loading the processor.

Mass reductions for a COTS avionic system come largely from optimization of the avionics chassis. A low mass system does not have the luxury of large margins on thermal mass and radiation shielding. Characterization of the expected radiation environment based on mission length and destination and the expectation of thermal swings can be used to optimize the mass of the avionics chassis. Chassis mass can be reduced by 50% by reducing these margins[4].

[4] Based on the Broad Reach Engineering chassis [34]

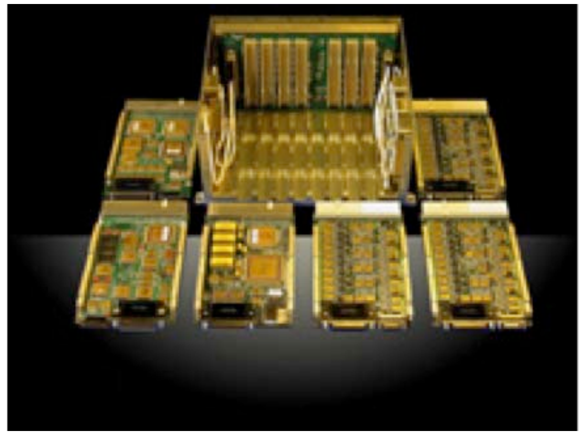

Figure 45: Low mass COTS avionic chassis

COTS solutions also provide significant benefit in lander-rover communication hardware. Ground system compatibility restricts communication signals to low frequencies in the S-band. While this does result in decreased bandwidth, S-band is similar to cellular telephone frequencies that have been developed and tested extensively. Cutting edge COTS communication systems replace heavy inefficient designs[5].

7.2. Pose Sensing

Localization is a fundamental problem for any mobile robotic system. In route to the moon and on the lunar surface, conjoined-landers must determine position and orientation in the absence of terrestrial specific solutions like GPS and compasses.

Landing requires fast feedback of precise position and orientation to accurately control thrusters and guide a lander to a safe landing at the intended site. Inertial Measurement Units (IMUs) are used to determine acceleration and to derive changes in position and orientation or pose. Landing radar returns distance measurements to determine distance to the surface.

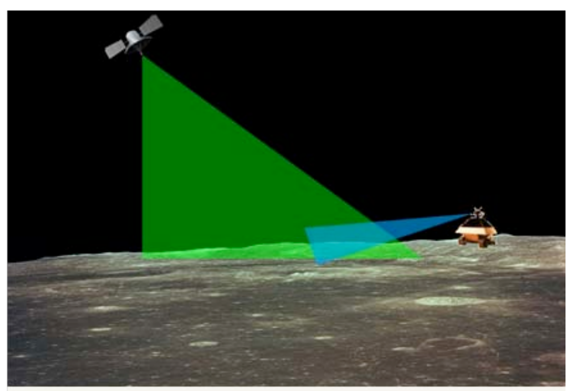

Figure 46: Images captured by lander-rovers are correlated with satellite imagery to determine absolute positioning.

Pinpoint landing requires determination of absolute position. Digital Scene Matching Area Correlation (DSMAC) is a terrestrial solution to this problem, commonly found in cruise missiles. DSMAC uses a camera to collect imagery during flight and correlates those with stored satellite imagery to determine absolute location [9]. Conjoined lander-

[5] Aero Astro Gallium Nitride based amplifiers double power efficiency over traditional communication avionics. [36]

rovers dual-use rover navigation cameras to take images required for DSMAC eliminating the need for specialized hardware.

During surface operations, IMU and wheel encoders are used to determine motions. Encoders count revolutions to estimate odometry. The same IMU for landing is used for roving. Since fast feedback and high accuracy are required for landing, dual-using the landing IMU enhances rover capability relative to typical roving IMUs. While roving, the imagery recorded from navigation cameras is exploited to perform feature and structure based registration with satellite maps. Features such as intensity, texture, and elevation can be used to register what a robot sees with orbital maps to localize the exploration system. This is similar to the DSMAC approach for landing.

Once localized on the surface, 3D data from stereo cameras is incorporated into a digital elevation map. Techniques such as evidence grids are employed to probabilistically fuse data from the stereo cameras, the zoom cameras, and the original orbital data. Data fusion techniques enable the continual integration of data from multiple sources to improve a map. This map is used to determine safe routes of travel.

7.3. Motor Control

Motion control is pervasive and essential in all robotics. Traditional commercial motion control is common, but it does not exploit technology to miniaturize, harden, achieve reliability, and do more with less. Lightweight conjoined lander-rovers require customized motor control to reduce mass and improve power efficiency.

Field-Programmable Gate Arrays (FPGAs) enable sensing, commutation, and drive motion with the gamut of control strategies from classic PID to adaptive force methods. FPGA chips enable quick development and customization of motion control boards.

FPGA-based motion control provides flexibility in number and type of motors from stepper motors to phased brushless motors. The system is capable of monitoring all motors for heart rate, efficiency, and heat. Vast control options are available for each of the motors (speed, steps, shutdown, startup, monitor, etc).

Figure 47: Custom motor control board utilizes FPGAs to minimize componentry.

7.4. Software

Software for a conjoined lander-rover requires specialized development. Sharing the resource of a single avionic system dictates software that provides functionality for cruise, landing, roving, and data management.

Landing and roving software share some basic functionality and are distinct in other functions. Solutions requiring software that controls either lander or rover functionality leave state uncertainty and add complexity for implementation and testing. The approach for handling this uncertainty that is introduced in conjoined systems is to create two distinct bootable software images, one for cruise and landing and one for roving. Switching between the two requires a reboot that resets the software's initial state. Rebooting is a common occurrence in a space avionic system as it is the primary way to handle disruptions due to radiation events. This approach speeds parallel software development and testing of lander and rover functions.

Many low level blocks of code would be duplicated in these distinct images. To handle this, a common code bank is introduced containing code that both systems can access, like hardware drivers. This reduces duplication of code development and enables both lander and rover testing to catch bugs in shared software.

Selecting the proper operating system is important in a space system. Functions of landing require precise timing dictating the need for a real-time operating system. Possibilities do exist for terrestrial operating systems to be applied for space flight at little to no cost for licensing. However in-house development increases with these operating systems leading to similar cost relative to licensing of space-tested software. Heritage software is selected for a low cost mission for high reliability and existence of hardware drivers for space electronics to reduce development time[6].

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[6] VX Works was identified as the operating system of choice due to flight heritage [38]

8. Conclusion

Robotic exploration on the moon's equator from extremely small launch vehicles drives the configuration of conjoined lander-rovers with asymmetric morphology, chain drive, skid steer, innovative structural design with composite materials, and commercial-off-the-shelf avionics.

8.1. Claims

8.1.1. Configuration

The configuration of a low mass, capable lander-rover for exploration of the lunar equator has been devised. The system devised conjoins the functions of landers and rovers reducing redundancies of structure, power, computing and communication. These payoffs equate to less mass, simplified integration and lower costs than achievable with conventional configurations.

Reaching 120kg systems with conjoined lander-rovers opens the door to reduced mission cost through the use of small launches. New ambitions for lunar exploration call for fiscal responsibility and safety. Low mass configurations enable low cost exploration for scouting and preparing sites for future human colonization.

8.1.2. Morphology

The morphology of lander-rovers to explore the lunar equator has been devised. The form of a system is laid out that delivers capable exploration during the changing sun angles, high surface temperatures, roughness of terrain, and upward angle to Earth at the lunar equator within the constraints of small size and low mass.

Power and thermal design optimizes equatorial operation. An asymmetric morphology rejects heat to black sky on one side and gathers solar power on the other. Tacking like a sailboat enables this low mass unactuated configuration to succeed in the varying sun angles and extreme temperature.

Camera configuration is minimized to reduce mass. The camera arrangement places all cameras high on the rover mast, enhancing operator perception and enabling imagery to be captured on any side of the rover without redundancy.

Rover control is improved by presenting rover interfaces that are simple, effective and safe such that, with minimal training, operators can directly control the rover. The major advancement is the design and integration of tools for predicting vehicle safety in response to commands issued by operators.

The Earth maintains a near constant position in the equatorial sky, enabling successful communication with a fixed antenna and a set transmission beam. Cutting-edge antenna technology optimizes communication bandwidth for a given mission. This system continually transmits data for operation interspersed with imagery and video.

8.1.3. Mechanisms

Mechanisms with low mass and volume have been devised to survive the harsh lunar environment. The extreme temperatures, hard vacuum, and abrasive dust at the lunar equator drove the configuration of a shoulder driven rover with roller chain, precise camera pointing, and a zoom lens.

The four-wheel, skid-steer drive devised minimizes mechanism mass, and provides traction through wheel grousers. Ground pressure is tuned by varying wheel width and diameter. Midday operation at the lunar equator presents extreme temperatures mitigated by locating actuators near radiator surfaces. Drive motors are shifted inside the chassis at the shoulders with roller chain to wheels. Transmission of torque drove the innovation of a space roller chain mechanism. This low mass, high efficiency mechanism makes use of specialized lubricants to function in the hard vacuum and extreme temperatures.

Camera pointing and zoom mechanisms developed enable lander-rovers to precisely point and zoom in to provide desired imagery. Thermal and wiring design are specialized for camera pointing mechanisms. Tolerance and lubrication design are specialized for zoom mechanisms.

8.1.4. Structure

Innovative structural design for a conjoined lander-rover has been devised. A high performance robotic structure was conceived relative to low mass.

The application of cutting-edge composite materials provides improved performance for modern lander-rovers. Mass reductions and increases in stiffness over traditional metallic structures have been achieved. Structural mass savings enable unprecedented sensing and actuation payloads. Stiff composite structures enable survival under vibrations during launch. Structural loads are transmitted through the chassis skin eliminating mass of additional structural members.

8.1.5. Avionics

Avionic systems for lightweight conjoined lander-rovers have been devised. Avionics devised optimize mass by reducing margins on power, thermal control, radiation hardening, and shock and vibration survival relative to traditional avionics.

COTS components are leveraged to dramatically reduce mass and development cost. Avionic cards used have high feature-density reducing the number required. Use of FPGAs enables flexibility without exchanging chips. Avionic chassis design optimizes mass by reducing margin on thermal and radiation shielding. Characterization of expected radiation environment based on mission length and expectation of thermal swings are used to optimize the mass of the avionics chassis.

Pose sensing for landing and roving make use of shared sensors minimizing componentry in a conjoined system. Similarly, lander and rover software architectures share building blocks of code to streamline development and testing.

8.2. Future Work

This research lays out the considerations of a conjoined lander-rover and the subtleties and pragmatics of implementation. Current state-of-the-art results in a lander-rover mass just inside the 120kg requirement with minimal mass margin. Further reductions of mass to increase the mass margin on a 120kg scenario or to drop to a smaller launch are possible with future technologies, components, and materials.

The possibility exists, for ultra light lander-rovers, to dispense with radar and to dual-utilize cameras for landing, roving and science. Cameras can be used to precisely estimate altitude, velocity, pose, and avoid obstacles. This scenario is increasingly viable with the advent of ultra-high quality imagery available from orbital missions and processing power for pose estimation. The ponderous mass and power consumption of radar could also be avoided.

Innovative vision techniques like structure from motion or structure from shadow present the opportunity to provide 3D imagery with only one camera. This would dispense of the power and mass of additional hardware and reduce the size of image data sent to Earth.

Increasing popularity of higher frequency communication bands present the opportunity for future lander-rovers to communicate more efficiently. Higher frequency communication enables significantly higher bandwidth for the same power increasing the size of data a lander-rover can transmit. High-speed traverses become increasingly feasible as lander-rovers are capable of sending back more data.

Surviving the lunar night would open the door to dramatic changes in capability of conjoined lander-rovers. Equatorial lunar explorers would be capable of multiday journeys. This would enable a mission like the one envisioned to expand from a visit to Apollo 11 into a tour of lunar historic sites, trekking across the moon to see other Apollo hardware, the Lunokhod rovers, NASA Surveyor landers, and Soviet Luna landers. Surviving the extreme cold of a -170°C lunar night requires innovation of avionics, batteries, and mechanisms with improved thermal tolerances.

Innovation of enhanced mobility mechanisms presents the opportunity for exploration in increasingly rugged terrain. The development of mechanisms like tracked locomotion would enable missions to include short ventures into craters in search of ice or into lunar lava tubes, which are sites for potential future colonization of the moon. Increased traction also enables the development of low mass work machines, capable of working the lunar soil to prepare a site for future human colonization.

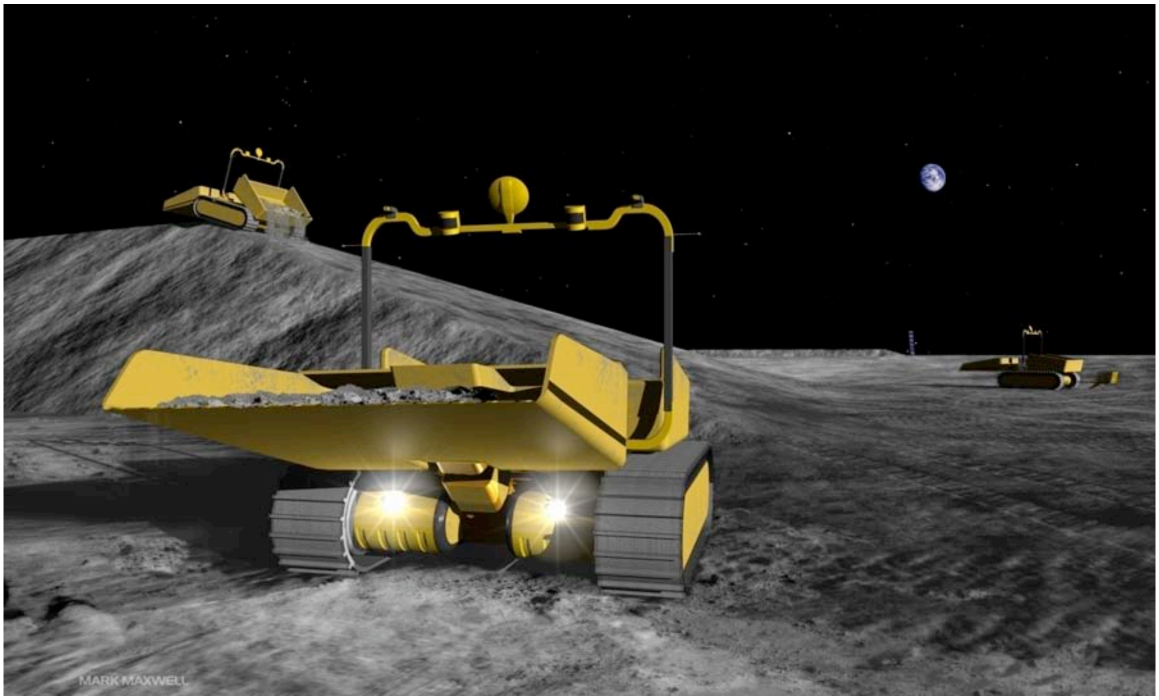

Figure 48:Innovations in mobility would enable low mass lunar work machines.

9. Perspective and Contribution

The research discussed incorporated the work of a team of faculty, staff, and students at Carnegie Mellon University. My work on mission configuration designs of the XPrize lander-rover and detailed design, analysis, prototyping, and testing of low mass space mechanisms and structures contributed to this project.

I mastered developing configurations for space robotic systems. This included selecting rockets to launch, transit, and land rovers on the moon as well as partitioning mass among subsystems. Evolution of system morphology proceeded as a team effort providing me with perspectives on design of systems including landing propulsion, solar and thermal, mobility, communication, and camera placement.

My contributions included detailing mechanical designs. I led the design of rover mobility mechanism. I iterated designs, analyses, and prototypes. These included sizing of actuation, analyses to minimize mass, and tests of wheel traction and obstacle performance. I also worked on the detailing of structural design for lander-rover spacecraft. Structure-related contributions included leadership of analysis of carbon composite designs subject to acceleration and vibration loads during launch, cruise, and landing as well as loads imparted during landing and roving. My contributions included in-house manufacturing of composite materials creating a full design cycle to iterate composites.

Participating at every level of the XPrize project from high-level system design to detailed subsystem design provided me with a broad perspective on the design of space robotic systems.

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