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Design and Analysis
of a
Lightweight Lunar Rover

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Todd D. Taber
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By

Prof. David P. Miller

Prof. Robert L. Rennaker II

Prof. Zahed Siddique
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Abstract

Rovers are critical to future space exploration. While many designs exist, there still remains the need for a rover that compromises between mass and traversability. This thesis is a description of the design of a lightweight rover that still maintains a fair degree of traversability. This design was based on the Solar Rover II, a four-wheeled rover. This design was first scaled down and a mass comparison was made. This new design was built out of aluminum and massed 1.18kg. A new building material was selected and the design process was reiterated. The material chosen for the new lighter weight design was MS-1A, a compression molded carbon fiber. This new design is called the Micro Lunar Rover and it massed .81kg. This new suspension design was then examined using Finite Elemental Analysis. The static carrying capacity was determined to be 13kg. A dynamic analysis then was used to determine the suspension’s capacity during operation. Using the current wheel design, the rover could mass 2.86kg and sustain a fall from 4cm in Earth’s gravity, half the wheel diameter. If the wheels were redesigned, allowing for as little as 13mm of flex, the suspension could carry up to 4kg of total mass.
Chapter 1

Introduction

Konstantin Tsiolkovsky, the father of theoretical rocketry, said, “The planet is the cradle of the mind, but it is impossible to live in the cradle forever." [16] The current thinking by certain NASA and government officials echoes these sentiments. “In the long run, a single-planet species will not survive”, says NASA director Mike Griffin [34]. Beliefs like these are the motivation for the exploration of our neighboring planets and moons. If there is any hope for human advancement beyond the planet Earth, there must first be exploratory robotic missions sent to determine the geological makeup of the regolith and locate any future fuel sources present on the foreign surfaces. The knowledge of the planet’s surface composition may lead to the location of possible water sources. The presence of water is a key component to the existence of human life. Water provides both sustenance for human survival and represents a possible fuel source. These elements are critical for the advancement of the human race beyond the Earth’s atmosphere.
1.1 The Moon, Mars, and Beyond

On January 14, 2005 President George W. Bush indicated his new vision for space exploration. In this new vision there are humans with a permanent presence on the Moon by 2020 [34]. Rovers can greatly increase this mission’s probability of success. In order for the goals of human expansion to be achieved, there must first be robotic missions sent to search for possible fuel, water, and shelter sources. As the terrain can be mapped from orbit, the geological makeup can be tested from the surface. “They [interplanetary rovers] thus comprise a central plank in all planetary exploration missions both manned and unmanned from the ability to provide in situ data not obtainable from orbital or flyby missions. Robotic rovers are uniquely suited to special applications such as seismic survey and local site preparation.” [11] Using a combination of terrain mapping and surface geology, possible mission landing sites, mining sites, and other areas of interest can be carefully chosen. The possible base sites can even be prepared well in advance by robots, so that any manned mission would have minimal construction to complete before being able to occupy the surface. The driving force behind robotic exploration is to make human habitation easier. This is done
by improving safety, learning about surface geology, and making any preparations necessary for human existence.

### 1.2 The Need for Rovers

To best conduct the scientific analysis required for human development of the Moon’s surface, the first missions must be performed by planetary rovers. Using a rover mission has several advantages over a manned mission. The first of these advantages is safety. A remote controlled rover can survey the planet’s surface without exposing humans to the hazardous environment. On a foreign surface such as the Moon’s, the temperatures can range from -173°C to 100°C [15, 43]. These are temperatures that would make it extremely difficult for humans to inhabit the surface without tremendous measures for shelter. A lost robotic mission is an error that can be overcome. A lost manned mission is a tragedy that threatens the future of space exploration.

A rover mission is also much cheaper than a manned mission. NASA’s Mars Exploration Rover (MER) missions cost $820 million, compared to the estimated cost of $1 trillion that a manned mission might have cost [27]. This is a
significant cost savings in a time where mission success is measured in dollars and can be the difference between theoretical and actual mission execution.

The final advantage that a rover has is that its life expectancy on the planet’s surface is longer than a manned mission might be. The NASA MER missions first reported back to Earth from the surface of Mars on January 3, 2004, and are still actively conducting scientific experiments as of the time that this thesis was written [25]. A robotic mission can perform sample acquisition and testing the entire time on the surface, while reporting the data back. When the robotic mission is complete, the rover can then either be turned off, or it can be used to conduct other scientific research. Because there is no need for resupply, cost and mission difficulties are further reduced. There is also no need for fuel to be stored or harvested; solar panels can supply all the necessary power. Lastly, because there is no requirement of return a to Earth, the complexities of a return flight can be avoided.

1.3 Current Rover Design

There are several examples of current rover design. For the purpose of this thesis, only four will be examined. The first design to be looked at is NASA’s
MER Missions. These rovers, the Spirit and Opportunity, are an extremely robust design with a six wheeled, rocker-bogey suspension. This suspension design is highly capable of covering varying terrain with minor difficulty. They each carry a scientific package that includes a spectrometer, a rock abrasion tool, a microscopic imager, an x-ray spectrometer, antennae, and cameras [25]. These rovers are an example of NASA’s attempts to create a design more capable than required. This is further supported by the fact that the suspension was actually installed in reverse, putting the more efficient climbing wheels on the back. The logic behind this was that no matter what the rovers drove into, they could always back out of it. Figure 1 shows an artist's conception of what the rovers might look like on Mars.
The second rover design examined is the Solar Rover II (SRII). The design goal was to build a simplified rover design while still maintaining the majority of its traversability. For this, the suspension utilizes four wheels with a differential separating the two suspension halves. This gives the rover the ability to articulate and leave three driving wheels on the ground while the fourth climbs an obstacle. The debate over which design is optimal, four or six wheels, is far from over. The choice between the two often depends on the environment. The arguments for and against a four-wheeled rover are presented further in [27]. While the overall design certainly allows for more scientific instrumentation, to keep the design as
simplified as possible, the SRII was limited to antennae and camera. Figure 2 shows the SRII being tested in a Californian desert.

![Figure 2: SRII](http://coecs.ou.edu/Matthew.J.Roman/pics%20movies/sr2a%20desert.jpg)

Both the SRII and MER designs have specific operational goals. The Opportunity and Spirit rovers were designed to slowly traverse Martian terrain and use the equipped science package to analyze geology and discover more about Mars’ history. There were hopes of discovering a history of water, or possibly even current sources [25]. The SRII was designed to be “energy
efficient, lightweight, and robust”. It should be faster and require less battery life to traverse the same terrain [27].

Each of the previous designs fit a specific need. There are, however, other design goals that these rovers cannot meet. Neither of these designs qualifies for a limited payload launch of, for instance, less than 4kg. Spirit and Opportunity each weighed in at 185kg, while the SRII weighs a total of 22.07kg [25, 27]. While the SRII is much lighter than MER, still lighter rovers are desirable. There are currently several lightweight designs in existence.

Two such lightweight rover designs are the Minerva Surface Hopper and the JPL Nanorover. Each of these designs is innovative. The Minerva hopper was designed to travel with the space satellite Hyabusa and land on the surface of a near Earth asteroid. This design was forward thinking because it abandoned the typical rover locomotion. Due to the extremely low force of gravity on the asteroid, the Minerva used momentum wheels to rotate this “coffee can shaped” rover about the surface [22]. Figure 3 shows an image of the Minerva hopper.
The JPL Nanorover was a little more “inside the box” thinking. This rover was designed to mass a total of 1kg. It too, was designed to be sent to an asteroid where only microgravity held the rover to the surface. This rover had four wheels on a small articulating suspension. The suspension was designed so that if the rover were to ever end up upside down the legs would rotate, right itself, and continue on its way [21,26,27]. Figure 4 shows an image of this rover.
While both these designs pushed the limits for design and technology, neither is an optimal lunar surface rover. The force of gravity on the Moon, while smaller than Earth’s, is too large to have momentum wheels be effective, as in the Minerva hopper. Also, the ground clearance on the JPL Nanorover is insufficient to traverse the lunar regolith. To create a rover that is optimal for the Moon’s surface, a combination between the two types of rovers, large and small, must be reached. This calls for a new design. This is the motivation behind the design of the lightweight, small-scale rover.
1.4 Thesis Organization

The remainder of this thesis is a more detailed description of mission motivation, material selection, design, analysis, conclusions, and future steps for the lightweight rover. Chapter two more thoroughly discusses opportunities for a lightweight rover design. Chapter three is an in-depth description behind the material selection process. Chapter four is a discussion of the design of the rover and all of its components. A Finite Elemental Analysis (FEA) was performed, and is presented in chapter five. The last chapter summarizes the findings of all phases of this thesis, and presents the next logical steps in the creation of a Micro Lunar Rover.
Chapter 2

Missions of Opportunity

As space exploration advances, the need for Moon exploration increases. If the President’s goal of a permanent human presence on the Moon by 2020 is to be met, there must first be several advanced rover missions [34]. For many of these missions, rovers similar to the MER and SRII could be used. There are, however, opportunities for other, smaller designs similar to the Minerva Hopper or the JPL Nanorover to be implemented. But, as stated before, neither design functions extremely well on the lunar surface. Many times during mission planning, a launch mass is predetermined and is a limiting constraint during payload design and selection. Sometimes, the payload comes in under the specified launch mass. This is the opportunity for a lightweight, compact, but still traversable design to be implemented.

As an example, suppose a lunar mission was proposed that called for a specific launch mass and volume. But, after completing design for this mission, there is still some available room. For simplification, a design constraint of 4kg for total available mass is assumed. The smaller and lighter a rover can be made,
while still maintaining surface traversability, the more likely it is to be used in a mission of opportunity. A scaled down SRII might fit this situation. While the available mass and volume do allow for a rover of small design, they don’t leave much room for scientific packaging. This would limit this small rover’s abilities. A small rover with limited scientific instrumentation still has worth.

2.1 Design Goals

When a situation such as a limited amount of volume and mass are available, the design goals are fairly clear. The design must fit inside the volume, and the total system and payload mass must be under the allotment. There are other factors to consider though. Things like ground clearance and payload capacity are not explicitly defined. For these items the goal is simply maximization. In the concept of ground clearance, the more clearance available the better. If the rover maintains its dimensions, but increases clearance, it has the capability of going over rockier terrain without becoming stuck, thus increasing traversability.

Any decrease in system mass, while maintaining structural integrity allows for a greater payload capacity. If the system takes up three of the four kilograms available, then only one kilogram is allotted to payload. If, however, the system
only occupies two kilograms, it leaves two open for payload, and possibly other scientific instrumentation. Using this technique for improvement, the scaled down version of the SRII could become critical to future missions. By designing a rover of roughly half the linear size of the SRII, the new design will be a step closer to reaching a compromise between traversability and system mass.

2.2 A Scaled Down SRII

Modeled after the design of the Solar Rover II, a scaled down version would be very much the same. The drive train and suspension are nearly identical, with some minor changes made to reduce the amount of fasteners used, and further reduce overall system mass. For a more detailed description of the SRII design see [27]. Figures 5 and 6 show the overall rover design of the SRII and a scaled down version of the SRII with soda cans for a size comparison.
Several minor differences can be noted between the two rovers. The first is most obviously the size. The second difference is the wheels. Many different designs
were examined for wheel setup [44]. For this exercise a simple six-spoke design was chosen, but is not considered an optimized design. A third difference is the relative size of the lower suspension knuckles. Due to the desired gear ratios, the bevel gear was the limiting factor for these knuckle sizes. There are many other minor differences, but the overall system closely resembles the SRII. To more carefully examine the differences between the two designs, a table with key characteristics is presented. Table 1 displays these relationships.

<table>
<thead>
<tr>
<th></th>
<th>Rover</th>
<th>Total System Mass</th>
<th>Size (cm)</th>
<th>Ground Clearance</th>
<th>Wheel Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRII</td>
<td>5.73 kg</td>
<td>84.2 x 42.1 x 68.1</td>
<td>23.1 cm</td>
<td>20.6 cm</td>
<td></td>
</tr>
<tr>
<td>sdSRII</td>
<td>1.18 kg</td>
<td>43.2 x 18.7 x 30.1</td>
<td>8.5 cm</td>
<td>8 cm</td>
<td></td>
</tr>
</tbody>
</table>

More on the gear ratios, design, and motivation behind the scaled down SRII design is presented in Chapter 4.

### 2.3 Design Reiteration

While this current scaled down design is effective in meeting the mission requirements, there is still room for improvement. The area that has the most potential for improvement is the system mass. If the system mass is reduced, the payload can be increased. This payload increase can be beneficial in multiple
ways. The most obvious benefit is that the amount of scientific instrumentation included in the rover can be increased. Items like a better camera, a spectrometer, or an improved communications system could be included, where they were left off before. Other possible advantages to a lighter system mass are things like larger motors to increase speed or more batteries to lengthen system life span. Whatever way the extra payload weight is used, its presence is clearly advantageous.

There are a few ways to reduce mass from this scaled down rover design. One such way is yet a further redesign. Using a Finite Elemental Analysis (FEA) to analyze structural requirements, the design could be improved. Parts of the rover that are overly robust could be lightened, and pieces that are too weak could be bolstered.

Another way to reduce system mass is to more carefully select a building material. For the initial scaled down design, aluminum was chosen as the building material. If a lighter or stronger material, perhaps titanium or a composite, were implemented along with a new design, the system mass could be even further reduced. Using a combination of both these two methods a new rover is designed. Examining various factors, specifically material properties and
their manufacturing techniques, the design is reduced in mass. Maintaining the capability of carrying the required elements of a rover that do not scale down well with size, such as communication and control, was a design condition. The following chapter discusses the factors that go into the material selection.
Chapter 3

Material Selection

The material selection phase of the project has been conducted to determine which were the most effective materials that could be used in a new, even lighter design called the Micro Lunar Rover (MLR). Aluminum, titanium, carbon fiber, and other “space-safe” composites were researched to determine which one to implement in the design. Because system mass is the primary issue of concern, structural integrity is secondary. The plan was to focus on the lightest possible component design, and then add material where it is weak. The system design was created while trying to minimize structure, fasteners, and using the selected lightweight materials. An analysis was then carried out to verify the structural capabilities of the design and material. The weight bearing abilities of the suspension should match those of the overall rover design. The total system mass, payload, and the gravitational constant of the Moon have been considered together while addressing overall structural strength. The additional forces experienced by the rover during launch have also been considered.
For the design, concepts such as outgassing and temperature range have been considered. The material selection was based on the results of this study. Keeping that material selection in mind, the resulting design is the MLR. The main focus of this design exercise is the MLR’s suspension and drive train. All portions of the system design are further discussed in the following chapter.

3.1 Material Considerations

Material considerations were primary issues of importance during the material selection. These considerations were thermal expansion, outgassing properties, and electromagnetic concerns. Due to the critical nature of each of these properties, current technology was examined and evaluated to determine which materials best fit the purpose of this application. Each of these items was addressed during the research and will be discussed further. The selected materials are then presented at the conclusion of this chapter.
3.1.1 Aluminum, Titanium, or a Composite

The first material considered during design was aluminum. Aluminum is the standard material, in which, lightweight, low-cost structures are built. Because of its low cost, lightweight, and moderately high strength, aluminum is ideal for many situations. The problem is that this was the material that was initially used during the scaled down rover design, so no material substitution can be made. Only a redesign of the structure can reduce system mass.

Titanium was the second material considered. Because of titanium’s high strength, this is the material selected for many aerospace structures. The difficulties with titanium are that its expensive, extremely difficult to machine, and slightly denser than aluminum. While the structure is much stronger, the mass would also increase. If, however, a design were created that optimized structure based on a compromise of mass and strength using titanium, it would be beneficial, compared to aluminum. For a large system mass that requires a great deal of strength, titanium may be the material of choice. To further illustrate this point about aluminum and titanium, Table 2 should be referenced.
### Table 2

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's Modulus</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>75 GPa</td>
<td>2700 kg/m³</td>
</tr>
<tr>
<td>Titanium</td>
<td>110 GPa</td>
<td>4500 kg/m³</td>
</tr>
</tbody>
</table>

From this table, if you compare aluminum’s modulus to its density, a ratio of .028 is achieved. This gives aluminum’s strength to weight ratio. Therefore, if the ratio of titanium is less than .028, aluminum has a better strength to weight ratio.

Titanium’s strength to weight ratio is found to be .024. Because this ratio is slightly less than aluminum’s, titanium has a smaller strength to weight ratio.

This ratio is important because it determines which material would build the lightest structure if both were designed to withstand the same amount of force. In this instance, aluminum would be the lighter structure.

The last group of materials considered during design was that of composites. A composite is defined as the combination of two or more elements joined together to form a single component. The two types of elements that make up the component are the matrix and the reinforcement. The matrix material coats and surrounds the reinforcement and acts as its support. The matrix resists shear stress and is typically a resin or epoxy. The reinforcement material is inside the hardened matrix and it gives the component’s overall tensile strength.
Reinforcement materials include glass fibers, Kevlar, and carbon fiber. The combination of the two materials together gives the component it’s compressive strength and resists buckling [37]. Because there are so many different kinds of matrices and reinforcements to choose from, almost any application’s requirements can be met. Regardless of whether the requirement is compressive, tensile, or torsional strength, there is a combination to fit nearly every situation.

The saved weight is a clear benefit of using a material like a composite. Using this savings along with comparable strength that is discussed further in this chapter, the material can be used in a variety of applications. The uses of composites range from rover structure to suspension, from instrumentation housing to robotic manipulators. With the manufacturing methods available, the material can be formed to nearly any shape that can be machined.

To accurately compare the three materials evaluated: aluminum, titanium, and multiple kinds composites, their varying characteristics should be compared. Figure 7 is the first of these comparisons.
In this figure it is important to note the Young’s Modulus on the X-axis variable. The Young’s Modulus is another term for the modulus of elasticity. The modulus of elasticity is a property of a material that is related to the slope of the curve in a stress-strain diagram of the material. It is a linear relationship between an applied load and the elongation experienced by the material [13]. High stiffness is generally desirable while density should remain low. It can be seen from the above figure that carbon fiber’s modulus of elasticity is comparable to those materials already being used in space, and its density is lower.

There are other composite materials besides carbon fiber, however. Another main category of composites is glass-reinforced composites. These composites
are more commonly known as fiberglass. Similarly to carbon fiber, fiberglass is used as matrix reinforcement. Fine pieces of glass fibers are woven or matted together giving the composite its structure. To determine which material is to be used in this project, three key factors were considered. The first can be noticed from Figure 7 above. Carbon fiber has a superior modulus of elasticity and a lighter density. The second trait is that of the materials available for application in the project, the easiest to obtain and most prevalent were carbon fibers. The third determining factor was a recommendation made by an industry professional to use a specific manufacturing process that involved the use of a carbon fiber [10]. For these reasons, the composite materials that will be considered from now all will be carbon fibers.

Table 3 shows other material comparisons such as density, tensile strength, and thermal expansion.
In the above table, it is important to note that most carbon fiber products have improved modulus of elasticities. Also, the two Toray and YLA products have different manufacturing methods, which yield extremely varying values for this modulus. The YLA products are compression molded, while the Toray products are sheets. The two varieties of manufacturing methods will be further discussed later in this chapter.

### 3.1.2 Thermal Expansion and Contraction

One of the primary concerns addressed in this material selection was thermal expansion and contraction. There are two varieties in the measurement of thermal expansion; they are called the volumetric and linear thermal expansion coefficients. A thermal coefficient is defined as the expression of a material’s
expansion to heating or cooling. The volumetric thermal expansion coefficient, sometimes just referred to as the thermal expansion coefficient, is given by Equation 1.

$$
\beta = -\frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p = \frac{1}{V} \left( \frac{\partial V}{\partial T} \right)_p
$$

(1)

In this equation the variables $\rho$, $T$, and $V$ are the material density, the temperature, and the volume of the material, respectively. The derivatives are taken at constant pressure. The volumetric thermal expansion coefficient can be applied to either liquids or solids. Equation 2 shows the relationship for the linear thermal expansion coefficient.

$$
\alpha = \frac{1}{L} \frac{\partial L}{\partial T}
$$

(2)

In this equation the variable $L$ is the length of the material and again the variable $T$ is the temperature. The linear thermal expansion coefficient can only be applied to solid materials [6, 36]. The importance of these relationships is for part mating and interference considerations. For example, if two unlike materials are
assembled against each other and experience a change in temperature, the thermal expansion rates of each must be compensated for during the design.

### 3.1.3 Outgassing

Another consideration that was made during the material selection for the project was that of vapor outgassing. Outgassing is defined as the slow release of vapor trapped, frozen, absorbed, or adsorbed inside a material. The difficulty with outgassing is that the escaped vapor can have harmful effects on equipment and instrumentation. With the possibility of condensation of escaped vapor onto critical instrumentation such as optics, care must be taken to select a material that has minimal outgassing threat. Negative reactions can happen when outgassing occurs. This was the case in both the Stardust and the Cassini-Huygens space probes; outgassed vapor condensed on optics creating reduced image quality and further complications [42]. To prevent this from becoming a future problem, the composite’s matrix must be carefully chosen. The use of low moisture absorbent resins, epoxies, and cyanates reduce the threat of outgassing. It can be assumed that aluminum and titanium both have negligible outgassing threats. There are currently several varieties of resins produced for aerospace application on the
market today [7]. The choice must simply be made which one best fits the specific application.

The measurement of outgassing is a measurement of the mass of the escaped vapor. The important variables for the measurement are the Collected Volatile Condensable Material (CVCM) and the Total Mass Loss (TML). To determine a materials CVCM a test apparatus is set up and collector plates are placed inside the setup. The mass of the plates is known prior to the experimentation, and again found after going through a change in temperature. The change in mass of the plates is considered the CVCM. Equation 3 shows this relationship.

\[
CVCM\% = \frac{(W_g - W_p)}{W_m} \times 100
\]  

(3)

The variables \( W_g \), \( W_p \), and \( W_m \) are the final mass of collector plates after the test, the initial mass of the collector plates before the test, and the mass of the material before the test, respectively. The CVCM is the amount of hazardous material that could condense on optics, like in the Stardust and Cassini-Huygens space probes.

To determine the TML the mass of the sample is recorded before and after the change in temperature. This value gives the mass percentage of outgassing of the material. Equation 4 gives this relationship.
In this equation, the variables $W_o$, $W_f$, and $W_m$ are the total specimen mass, the total specimen mass after the test, and again the mass of the material before the test, respectively [9].

For space applications NASA has a set standard of each value for a material to be considered “Low Outgassing” and therefore a potential material for aerospace application. The Collected Volatile Condensable Material ratio must be less than 0.10\% and the Total Mass Loss must be less than 1.0\% [19]. The material selected at the conclusion of this phase must have outgassing properties that meet these qualifications.

3.1.4 Electrostatic

The final significant issue of concern when addressing any material for space application is the buildup of static charge. Momentum transfer from electrons to a material is the driving force behind most spacecraft charging. Faster, free electrons are passed into a solid where they are slowed down and trapped, thus giving that solid an electric charge [12]. This is, in part, due to the plasma...
environment that the spacecraft must pass through. Plasma is defined as “a gas of electrically charged particles in which the potential energy of attraction between a typical particle and its nearest neighbor is smaller than its kinetic energy.” [33] The great amount of kinetic energy contained in the plasma prevents the electrons from rejoining the ions and thus neutralizing the field. Any spacecraft and payload that pass through this plasma are subjected to surface charge buildup. When two unlike materials build up charge at different rates a potential is created between the two surfaces. If this potential is large enough, an arc discharge can occur. This not only presents the obvious hazard of physical damage, but also the difficulty of arc-related electromagnetic interference (EMI). Both of which can damage spacecraft subsystems and sensitive electronics during flight [33].

The other significant charge of static buildup is after the rovers have reached the surface. It is this same principle of one substance losing electrons and another picking them up, but it has nothing to do with plasma. The phenomenon is known as triboelectric charging. When rolling about the dry surface of a planet or moon two unlike materials meet and interact with each other. During this process electrons are passed from one material to another. This leads to a static buildup that can eventually arc causing the previously mentioned electrical difficulties.
On Mars, using very thin, sharpened needles exposed to the atmosphere can combat this charging. The needles act like reverse lightning rods, bleeding any static charge off into the atmosphere. This was done on both the NASA’s MER and Pathfinder missions. The conditions on the lunar surface are different, however. Due to the rarified atmosphere on the Moon, atmospheric static discharge is not possible [21]. For this reason, a ground to the surface must be utilized to dissipate any built up charge. Due to the conductive nature of most rover building materials, there are a couple ways that this could be done. The most obvious is to simply drag an exposed wire behind the rover giving the excess electrons a clear path to the Moon’s surface. This, however, presents the concern that the wire may at some point be snagged or run over and cut. Another option might be to have a grounding brush made from some conductive material from the suspension to the aluminum wheel rolling along the regolith. This would transfer any charge to the surface and neutralize the rover. In either case, more testing would need to be performed to improve the design’s resistance to triboelectric static buildup and dissipation. Because this is not the focus of this design experiment, it has been briefly mentioned but will not be explored further.
3.2 Design Considerations

After the material considerations have been made, the design characteristics must be examined. This includes the design focus, the methods for manufacturing the design, and the actual structure requirements. The focus of this design exercise was to decrease overall structural weight while maintaining integrity. To do this an innovative design was created which combined both lightweight materials and a weight saving structure. Because the materials used require a specific manufacturing process, the design must be capable of being produced in that way. For this reason, care was taken during design to maintain all manufacturing requirements. These requirements are things such as wall thickness and actual machineability. For the structural requirements to be met, FEA was performed. Knowing that the overall design goal is to create a lightweight rover, a theoretical weight can be assumed. For calculation and design simplification, it is assumed that the total rover system weight plus payload is 4 kg. Knowing this value, the theoretical force on each member of the rover’s suspension can be calculated for maximum strain. From Figure 8 the equation for the total force on each of the MLR’s suspension links can be derived.
Equations 5-6 show the relationship for rover mass, payload, and suspension link forces are developed.

\[
\text{System + Payload} = M \times g = N = \text{Normal Force} \quad (5)
\]

In this equation, the variable \( M \) is the overall system plus payload mass. The variables \( g \) and \( N \) are the acceleration due to gravity and normal force, respectively. Because the system design is symmetric, a single side of the suspension experiences only half the total force from the mass \( M \). Knowing that the total mass is 4kg, the normal force on each leg of the suspension is known.

\[
N = \frac{1}{2} \times M \times g = \frac{1}{2} \times 4 \times g = 2 \times g \quad (6)
\]
But, as is obvious from the above figure, each leg only experiences half the force per side of suspension. The normal force experienced on each leg is 1\(g\). But, because of suspension articulation, there may be times when the rover only has three legs experiencing the normal force. For this reason, it is safe to assume that the suspension legs may experience up to twice the normal force. Therefore, the force experienced in each leg, at least for analysis, will be 2\(g\).

It is important to mention at this point, something about the acceleration due to gravity. This variable often changes value. The value changes from the surface of Earth, to the launch, to the surface of the Moon. The greatest of these forces will be during launch. During human launch acceleration up to three times that of Earth’s gravity can be experienced [4]. For satellites, the forces can be much higher. Launch forces can easily be overcome by simply building a frame that supports the rover’s suspension links during takeoff. By taking launch force off the suspension by a frame support, nearly all launch forces can be avoided. On the Moon, the forces are less than those experienced on Earth, so for the analysis, the acceleration due to gravity experienced on Earth will be the value used.
Having calculated this value and knowing the physical properties of the selected material and the gravitational constant, the analysis can be performed. This process will be explained more thoroughly in the Design portion of this thesis.

3.3 Manufacturing Considerations

The major difficulties in machining a custom part, such as a single side of the Micro Lunar Rover’s suspension, are frequently accuracy and complexity. There are often little or no standard sizes or parts that can be used with the design. This forces each part of the design to be manufactured separately. Doing this, can become extremely costly, especially if the parts require a great deal of accuracy. The requirement of a tight tolerance can be a strong driving factor behind the high cost of a custom part.

The other cost driver is the complexity of a design. If the design calls for a mold that requires four sides, as opposed to two, the cost more than doubles. If a design must be machined on several sides, instead of just one or two, the time for machining increases greatly due to set-up of the work piece in the machine. If design complexity can be simplified, it can greatly reduce the amount of
machining and manufacturing time, and each largely influences prototype expense. While the cost of component manufacturing is important to most missions, it is not typically a limiting factor. For this project, however, the cost is a critical issue.

3.3.1 Possible Manufacturing and Design Conflicts

There are several areas of concern when planning the production of a prototype such as the Micro Lunar Rover that must be addressed. These issues must be attended to during the design phase to simplify and reduce possible future incompatibilities. These concerns include, but are not limited to, pockets or shapes that cannot be manufactured, wall thicknesses that are unrealistic with the materials that have been selected, and structures that are not strong enough with the given material. Any shape that cannot be easily manufactured into a two-piece mold using a 3-degree of freedom CNC Mill is one that should be omitted from the design. Because of the possible manufacturing methods, the minimum thickness of the material was another consideration that must be made. For instance, for a sheet of carbon fiber the minimum thickness was .076mm, where compression molds, the minimum thickness would be 1.1mm [1, 10].
The final consideration is the system structure. Before design finalization could begin, an analysis of the structure must be performed to optimize design and prevent any structural integrity inadequacies. To do this, the structural model was designed in Pro/E then analyzed in Pro/Mechanica. Any weak points or stress risers in the structure were eliminated or improved. Again, this process will be further explained in the Design Chapter of this thesis.

3.3.2 Carbon Fiber Varieties

There are currently a couple carbon fiber manufacturing techniques. Each has positive and negative aspects. The first is sheet carbon fiber. This fiber comes woven into a sheet form, sometimes with the resin “prepregged”, or prepregnated, into the fiber matrix, and sometimes without. It is extremely strong and resistive to tensile stress. This form of carbon fiber is great for simple shapes like tubes or wall sections. It can even be formed to slightly more complicated designs, but that’s about where its application ends. For a design like the MLR, another manufacturing method is needed. From Table 3, it should be noted that the Toray carbon fibers are both the sheet form.
The other kind of carbon fiber is called chopped fiber molded. A mold is defined as “a hollowed-out block that is filled with a liquid like plastic, glass, or metal. The liquid hardens or sets inside the mold, adopting its shape.” [41] There are several varieties of molding techniques, but for this project is has been determined that compression molding is the best [10]. The difference between a regular kind of mold and a compression mold is that the thermoplastic material, in this case carbon fiber/epoxy mix, is put into a mold. The mold is then compressed either with a top force or a plug, until the fiber has reached all segments of the mold. The mold and composite are then allowed to cool and set. The advantage that this process has is that it is the most capable to form to a more intricate design, like the Micro Lunar Rover [38].

3.4 And the Winner Is?

Because the design of the Micro Lunar Rover depends so much upon the use of lightweight, space safe materials, these materials must be carefully selected. All the previously discussed topics must be addressed and evaluated during the material selection. The concepts of density, strength, thermal expansion,
outgassing, and structural integrity must be considered for each material evaluated. Again, Table 3 shows a comparison of several materials that have been considered.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Material</th>
<th>Tensile Strength</th>
<th>Modulus of Elasticity</th>
<th>Compressive Strength</th>
<th>Density</th>
<th>Thermal Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>400 MPa</td>
<td>75 GPa</td>
<td>N/A</td>
<td>2700 kg/m³</td>
<td>23E-6/°C</td>
<td></td>
</tr>
<tr>
<td>Titanium</td>
<td>850 MPa</td>
<td>110 GPa</td>
<td>N/A</td>
<td>4500 kg/m³</td>
<td>9.5E-6/°C</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>750 MPa</td>
<td>200 GPa</td>
<td>N/A</td>
<td>7850 kg/m³</td>
<td>14E-6/°C</td>
<td></td>
</tr>
<tr>
<td>YLA, Inc.</td>
<td>MS-1A (CF)</td>
<td>290 MPa</td>
<td>130 GPa</td>
<td>1530 kg/m³</td>
<td>3.5E-7/°C</td>
<td></td>
</tr>
<tr>
<td>YLA, Inc.</td>
<td>MS-4F (CF)</td>
<td>48 MPa</td>
<td>48 GPa</td>
<td>1500 kg/m³</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Toray</td>
<td>M40J (CF)</td>
<td>4410 MPa</td>
<td>377 GPa</td>
<td>1770 kg/m³</td>
<td>8.3-7/°C</td>
<td></td>
</tr>
<tr>
<td>Toray</td>
<td>M55J (CF)</td>
<td>4020 MPa</td>
<td>540 GPa</td>
<td>1910 kg/m³</td>
<td>1.1-6/°C</td>
<td></td>
</tr>
</tbody>
</table>

All materials presented meet with the NASA guidelines to be considered “low outgassing” materials. A note should be made that MS-1A and MS-4F are not solely fibers. They are more accurately a “carbon fiber/epoxy resin compression system”. [3] Due to the nature of chopped fiber compression molding, the epoxy and fibers are treated as a single item during forming. For this reason, the selections of MS-1A or MS-4F do not require a resin selection also, as it has already been indicated.

It is important to remember the characteristics that are critical to this design.

For the concept of thermal expansion, it is desirable for the expansion rate to be
small; therefore the material fiber M40J was selected. To address the structural requirement for the material selection, the material with the highest tensile strength and lowest density should be selected. The purpose of this was to insure that the parts are as strong as they are supposed to be, without exceeding the mass limitations. For pure strength, fiber M40J is considered. There must, however, be a compromise between structure strength and manufacturability. For this reason, even though it has a lower tensile strength and higher coefficient of thermal expansion, the fiber MS-1A was chosen for the most complicated parts, while M40J remains the choice for easy to produce shapes and parts.

The epoxy, resin or cyanate must also be evaluated for tensile strength, but for matrix selection, outgassing must also be considered. For this portion of the composite, the CVCM and TML must meet the requirements set forth by NASA of being <.01% and <1%, respectively [19]. Table 4 shows the values for a few of the examined resins.

<table>
<thead>
<tr>
<th>Producer</th>
<th>Resin</th>
<th>Tensile Strength</th>
<th>Density</th>
<th>CVCM</th>
<th>TML</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexcel</td>
<td>M74</td>
<td>83 MPa</td>
<td>1300 kg/m³</td>
<td>&lt;.01%</td>
<td>0.40%</td>
</tr>
<tr>
<td>YLA, Inc.</td>
<td>RS-1</td>
<td>75 MPa</td>
<td>1250 kg/m³</td>
<td>&lt;.01%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>YLA, Inc.</td>
<td>RS-3</td>
<td>81 MPa</td>
<td>1200 kg/m³</td>
<td>&lt;.01%</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>
It can be witnessed that these resins have very similar characteristics such as density and tensile strength. The aspects in which these epoxies vary are in their curing times, temperatures, and also in their different actual chemical makeup. While the first two resins are epoxies, RS-3 is a cyanate ester. Therefore, the application and manufacturing method would determine the appropriate resin to select.

For this project, it has been determined that using compression molding best produces the design. Because of the required manufacturing method of complex parts, the chosen carbon fiber/epoxy composite system is MS-1A. It is believed that this compromise between strength, weight, and manufacturability will lead to the optimal prototype. For simple shapes like tubes and flat surfaces fiber M40J and resin RS-3 were chosen for their low densities and high strengths.

When making the overall material selection, a comparison like that made in 3.1.1. for aluminum and titanium needs to be made for the selected composite material also. For this comparison, Table 5 should be seen.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's Modulus</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>75 GPa</td>
<td>2800 kg/m^3</td>
</tr>
<tr>
<td>Titanium</td>
<td>110 GPa</td>
<td>4500 kg/m^3</td>
</tr>
<tr>
<td>MS-1A (CF)</td>
<td>130 GPa</td>
<td>1530 kg/m^3</td>
</tr>
</tbody>
</table>
Using the same logic, the ratio of MS-1A’s modulus over its density is .085. Because the strength to weight ratio of MS-1A is much higher than that of aluminum’s, MS-1A is the appropriate material for this design. The material selection of MS-1A is correct.
Chapter 4

Design

The Micro Lunar Rover is a four-wheeled rover utilizing two motors with a simple suspension system to decrease weight and complexity. Its mechanical design was based primarily on the design of the SRII [27]. Figure 9 shows another image of the SRII design.

![SRII Design](image)

**Figure 9: SRII Design**
Image used with permission from Matt Roman

The two sides of the suspension have been created and are separated by a differential that enables the rover to traverse normally difficult terrain. The Micro Lunar Rover is made up of lightweight materials combined with common “off the
shelf” components. The suspension has been scaled down with some weight to strength tradeoffs being made. A finite element analysis and optimization have been conducted to improve the design. Some design conclusions are based on the final results of this analysis and presented at the end of Chapter 5.

4.1 Component Design

Each component of the reduced scale SRII has been designed closely following the design of the SRII. The MLR has had significant further redesign. There were compromises made between the reduced scale SRII design and the MLR design. Where possible, the amount of fasteners was reduced in the design. All non-vital components have been removed, while the number of critical components has been reduced.

The most significant design variation between the small scale SRII and the MLR is that for the MLR, the tube covering the drive shafts that are connected to the upper and lower suspension knuckles. Figure 10 shows the original SRII suspension design.
In the above figure, the gray tubes cover the drive shafts, the green housings are the lower suspension knuckles, and the yellow cut-away housing at the top is the upper suspension knuckle. Figure 11 is an image of what the SRII suspension looks like when it is simply scaled down.

Figure 10: SRII Suspension
Image used with the permission of Matt Roman

Figure 11: Scaled SRII Suspension
For the MLR, the tube has been merged with the upper and lower knuckles, creating only two pieces, where there were eight in the SRII design. This was an attempt to reduce fasteners and integrate multiple pieces together in the design. Figure 12 shows the revised MLR suspension design. A transparent material appearance was selected for the carbon fiber housing to improve visualization.

![Figure 12: MLR Suspension](image)

Each of the different components of the design will now further be discussed. A comparison of vital system information is presented at the conclusion of this design chapter.
4.1.1 Lower Suspension Knuckles

One area of importance during design was the lower suspension knuckle. This is where the drive shaft meets the wheels. At this point, the drive shaft is connected to a small gear. This smaller gear drives a larger bevel gear at a 90° angle that is attached to the wheel hub. This wheel hub transfers torque to the wheels. Figure 13 is an image of the lower suspension knuckle design utilized on the SRII.

![Figure 13: SRII Lower Suspension Knuckle](image-url)

Image used with the permission of Matt Roman

The sizes of the gears relative to each other are important, because this gives the gearing reduction. If the drive shaft spins at 60 rpm, and the ratio of the larger to smaller gear is 3:1, then the wheel spins at 20 rpm, the drive shaft making three revolutions to the wheel’s single revolution. This transfer of energy from the
drive shaft to the bevel gear set to the wheel hub was mimicked in the design of
the scaled down SRII design, as seen in Figure 14.

![Figure 14: Scaled SRII Lower Suspension Knuckle](image)

This design was also carried through in the design of the MLR. This can be seen
in Figure 15.

![Figure 15: MLR Lower Suspension Knuckle](image)
The main difference that should be noticed between the two designs is that the MLR is designed out of what appears to be a single piece. It is in fact two parts mating together, the seam appears on top of the green bevel gear. An exploded view is shown for clarification purposes in Figure 16.

![Exploded View of MLR Lower Suspension Knuckle](image)

**Figure 16: Exploded View of MLR Lower Suspension Knuckle**

In both the reduced scale SRII and the MLR the gear reduction at the lower suspension knuckles was 3:1. The gear reduction at the lower gear knuckles for the SRII is 4:1.
4.1.2 Upper Suspension Knuckle

Another area of importance during component design was the upper suspension knuckle. This is where the power transmitted from the motor is distributed to the drive shafts in each leg of the suspension. Figure 17 shows the upper suspension knuckle for the SRII.

![Figure 17: SRII Upper Suspension Knuckle](Image used with permission from Matt Roman)

This is the second opportunity for gear reduction in the drive train. The SRII has a gear reduction of 3:2 at the upper knuckle. The motivation behind this gearing ratio was due to the rover’s size. To attain the desired maximum rover traveling velocity, the speed of the motor was decreased into the drive shafts. It also increases torque at the wheels. This was not the case in the scaled down SRII or
the MLR. Both these designs have a gear increase at the upper suspension knuckled, then a decrease at the lower knuckles. This gives the rovers a 1:1 gearing. The motivation for this was to maximize the rover’s traveling velocity and recover losses from the small wheel designs. Figure 18 shows the reduced scale SRII’s upper suspension knuckle.

![Scaled SRII Upper Suspension Knuckle](image_url)

**Figure 18: Scaled SRII Upper Suspension Knuckle**

It should be noted that there is a slight difference between the two designs. The SRII was designed with $120^\circ$ between the suspension legs. The reduced scale design’s angle was increased to $140^\circ$. The motivation for this was to reduce the rover’s center of gravity. This would also slightly reduce ground clearance, but the threat of tipping over was great enough that the change was made. This
dropped the rover’s center of gravity by 3cm. For this reason the same suspension angle of 140° was kept for the MLR. This can be seen in Figure 19.

![Figure 19: MLR Upper Suspension Knuckle](image)

### 4.1.3 Drive Shafts

The drive shafts of each of the rovers are nearly identical, except in the material used, their lengths, and slight differences at the ends to fit different sized bearings. For the SRII, the drive shaft was steel. For the reduced scale model, the shaft was aluminum. For the MLR, the drive shaft is made out of solid carbon fiber. Figure 20 shows the drive train of the Micro Lunar Rover.
Figure 20: MLR Drive Train

Figure 21 is a comparison of the ends of the two drive shafts.

Figure 21: Drive Shaft Comparison

The upper drive shaft is from the MLR, while the lower drive shaft is from the reduced scale design of the SRII.
4.1.4 Motor Mount

The motor mount is an extremely critical component of the overall system design because this, along with the differential is what allows the suspension to articulate. The motor is mounted to a round housing that is rigidly attached to the differential and the upper suspension knuckle. This motor housing rests in two bearings, one in the differential and the other in the rover body housing, that allow the entire mount to rotate freely. Figure 22 shows the motor mount for the SRII.

![Figure 22: SRII Motor Mount](Image used with permission from Matt Roman)

Because the designs were very similar, the reduced scale SRII design is not illustrated, only the MLR’s motor mount is shown in Figure 23.
4.1.5 Differential

The design of the SRII differential is simple and elegant. Its simplicity is matched only by its affectivity. The motor housing is attached to a bevel gear by an adaptor that rests inside a bearing. This bearing sits in a differential housing that also holds three spider gears in position. These spider gears separate the two sides of the rover suspension. When one bevel gear rotates clockwise, the other rotates counterclockwise. The differential housing is mounted to the rover’s body, so the body and whatever equipment contained within it only experience half the angle of inclination the suspension is subjected to [27]. Figure 24 shows the differential design for the SRII.
The differential design for the MLR is shown in Figure 25.
4.2 Design Comparisons

To gain a realistic perspective of the gains made by the redesign and new material selection, Table 6 presents much of the important rover data.

<table>
<thead>
<tr>
<th>Rover</th>
<th>Total System Mass</th>
<th>Size (cm)</th>
<th>Ground Clearance</th>
<th>Wheel Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRII</td>
<td>5.73 kg</td>
<td>84.2 x 42.1 x 68.1</td>
<td>23.1 cm</td>
<td>20.6 cm</td>
</tr>
<tr>
<td>sdSRII</td>
<td>1.18 kg</td>
<td>43.2 x 30.1 x 18.7</td>
<td>8.5 cm</td>
<td>8 cm</td>
</tr>
<tr>
<td>MLR</td>
<td>.81 kg</td>
<td>43.2 x 28.8 x 18.6</td>
<td>11.8 cm</td>
<td>8 cm</td>
</tr>
</tbody>
</table>

In this table it is important to note that the MLR saved .43kg compared to the scaled down SRII design. Considering this is nearly half the entire system mass of the reduced rover design, this is a remarkable gain, or loss as it may be. There are still unanswered questions like where exactly the mass was saved. Did the saving come from the material selection, or the new integration of components? Also, it is critical to realize that much of the system weight the MLR saves on is in fasteners, a mass not included in this calculation.

To answer the question about where the mass was saved, a comparison of components must be made. Table 7 shows this comparison.
There are several important details about this chart that need to be pointed out. First, the mass saved on the suspension alone is about 10% of the MLR’s total system mass. The suspension is defined as the outside structure of the suspension. It doesn’t include any gears, bearings, or other internal workings. This is a significant improvement for the suspension mass. This chart doesn’t, however, clarify if the savings were from material selection or redesign. The second thing to notice is that of the .43 kg saved, nearly all was saved by these four items in Table 7.

The most critical concept to notice on this chart is the savings from the body. The body was a non-critical design component and was shared between scaled SRII and the MLR. The material properties were not common between designs. For the scaled model of the SRII, the body was assumed to be made from

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
<th>Savings per Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspension</td>
<td>.121 kg</td>
<td></td>
</tr>
<tr>
<td>Differential</td>
<td>.020 kg</td>
<td></td>
</tr>
<tr>
<td>Drive Shaft</td>
<td>.008 kg</td>
<td></td>
</tr>
<tr>
<td>Body</td>
<td>.420 kg</td>
<td></td>
</tr>
<tr>
<td>Suspension</td>
<td>.049 kg</td>
<td>.072 kg</td>
</tr>
<tr>
<td>Differential</td>
<td>.009 kg</td>
<td>.011 kg</td>
</tr>
<tr>
<td>Drive Shaft</td>
<td>.004 kg</td>
<td>.004 kg</td>
</tr>
<tr>
<td>Body</td>
<td>.228 kg</td>
<td>.192 kg</td>
</tr>
</tbody>
</table>

Table 7
aluminum. For the MLR, the design was made from the carbon fiber MS-1A. This result was expected, due to the lighter density of the carbon fiber. If this result is closer analyzed, a ratio of body masses can be obtained. This ratio of aluminum body to carbon fiber body is 1.84. The ratio of aluminum density to carbon fiber density is exactly 1.84. This result proves that all gains in body mass were from material selection. To determine the benefits of redesign, ratios of each system component are examined. Table 8 shows this examination.

<table>
<thead>
<tr>
<th>Component</th>
<th>Ratio</th>
<th>Redesign Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspension</td>
<td>2.47</td>
<td>0.63</td>
</tr>
<tr>
<td>Differential</td>
<td>2.22</td>
<td>0.38</td>
</tr>
<tr>
<td>Drive Shaft</td>
<td>2.00</td>
<td>0.16</td>
</tr>
</tbody>
</table>

What this above table is displaying is the ratio of old verses new design. The redesign benefit is a value of the lost mass that was attributed to the redesign alone, not material selection. Comparing the MLR’s suspension design to the reduced scale SRII, the ratio of masses was 2.47, while it was expected to be 1.84 for material differences alone. This means that .63 of the 2.47 benefit was specifically from the redesign of the actual structure. That is an indication that due to the structural redesign there was nearly a 50% increase in total mass
savings from material selection alone. This chart proves that while the redesign of the Micro Lunar Rover was beneficial, the majority of the mass savings came from the material selection.

The rest of the rover components are shared between the MLR and the scaled down version of the SRII. Table 9 shows these values.

<table>
<thead>
<tr>
<th>Component</th>
<th>Vendor</th>
<th>Model Number</th>
<th>Material</th>
<th>Quantity</th>
<th>Individual Part Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>Faulhaber Group</td>
<td>1319012SR 14/1</td>
<td>Various</td>
<td>2</td>
<td>0.0390 kg</td>
</tr>
<tr>
<td>Body Bearing</td>
<td>SDP-SI</td>
<td>S99PS3121608</td>
<td>Aluminum</td>
<td>2</td>
<td>0.0038 kg</td>
</tr>
<tr>
<td>Spider Gear</td>
<td>SDP-SI</td>
<td>A1C3Y48018</td>
<td>Steel</td>
<td>3</td>
<td>0.0011 kg</td>
</tr>
<tr>
<td>Diff. Bevel Gear</td>
<td>SDP-SI</td>
<td>A1C3Y48036B</td>
<td>Steel</td>
<td>2</td>
<td>0.0047 kg</td>
</tr>
<tr>
<td>Diff. Needle Bearing</td>
<td>SDP-SI</td>
<td>S99NH2BN1612</td>
<td>Steel</td>
<td>2</td>
<td>0.0196 kg</td>
</tr>
<tr>
<td>Upper Knuckle Bevel</td>
<td>SDP-SI</td>
<td>A1C3Y48036B</td>
<td>Steel</td>
<td>4</td>
<td>0.0011 kg</td>
</tr>
<tr>
<td>Upper Knuckle Pinion Gear</td>
<td>SDP-SI</td>
<td>A1C3Y48018</td>
<td>Steel</td>
<td>4</td>
<td>0.0011 kg</td>
</tr>
<tr>
<td>Thrust Bearing</td>
<td>SDP-SI</td>
<td>A7Z7012</td>
<td>Steel</td>
<td>4</td>
<td>0.0033 kg</td>
</tr>
<tr>
<td>Leg Sleeve Bearing</td>
<td>SDP-SI</td>
<td>A7P6P0608E</td>
<td>Polymer</td>
<td>8</td>
<td>0.0003 kg</td>
</tr>
<tr>
<td>Lower Thrust Bearing</td>
<td>SDP-SI</td>
<td>A7Z7018</td>
<td>Steel</td>
<td>4</td>
<td>0.0041 kg</td>
</tr>
<tr>
<td>Lower Small Sleeve</td>
<td>MSC Direct</td>
<td>MSI-090706</td>
<td>Polymer</td>
<td>4</td>
<td>0.0006 kg</td>
</tr>
<tr>
<td>Lower Big Sleeve</td>
<td>MSC Direct</td>
<td>DRS-121604</td>
<td>Polymer</td>
<td>4</td>
<td>0.0045 kg</td>
</tr>
<tr>
<td>Diff. Adaptor</td>
<td>NA</td>
<td>NA</td>
<td>Aluminum</td>
<td>2</td>
<td>0.0017 kg</td>
</tr>
<tr>
<td>Motor Housing</td>
<td>NA</td>
<td>NA</td>
<td>MS-1A</td>
<td>2</td>
<td>0.0038 kg</td>
</tr>
<tr>
<td>Bevel Motor Adaptor</td>
<td>NA</td>
<td>NA</td>
<td>Aluminum</td>
<td>2</td>
<td>0.0011 kg</td>
</tr>
<tr>
<td>Wheel Assembly</td>
<td>NA</td>
<td>NA</td>
<td>Various</td>
<td>4</td>
<td>0.0333 kg</td>
</tr>
</tbody>
</table>

It will be important in the following chapter to mention something about the motor selection here. The motor chosen is a small motor with a large gear reduction or 246:1, giving a final speed out of 52.03rpm. The actual rover speed will be a percentage of this because this value is found for the no load speed of
the motor. This gear reduction not only slows the rover’s top speed, but also increases the motor’s torque. The MLR’s top speed can be determined by using the following equation, Equation 7.

\[
\text{Top Speed} = \frac{RPM}{60} \pi d
\]  

(7)

In this equation the variables \(RPM\) and \(d\) are the motor’s top speed and the diameter of the wheels, respectively. Because these values are known, the top speed can be calculated. The result of the calculation is 21.8cm/sec. This top speed will be used in calculations in the FEA section following.
Chapter 5

Finite Elemental Analysis

The Finite Elemental Analysis of the Micro Lunar Rover suspension is the final stage of the rover’s design. During this stage, the material properties of the selected carbon fiber, MS-1A, are input into Pro/Mechanica where the design can be analyzed. There are two analyses that must be performed, a static and a kinetic. The first is the static analysis.

5.1 Static Analysis

After inputting the required material consideration into the software, the assumed loads and constraints are then applied to the model. Figure 26 shows the image of the applied loads on the carbon fiber suspension design.
Figure 26: MLR Suspension with Load and Constraints

In the image, the blue text is an indication of a displacement constraint. The yellow arrows indicate the direction of the applied loads. The light blue scales are the design constraint of contact between the two halves.

For a complete analysis of the design, each side of a suspension half was first put through an analysis where it was subjected to half the calculated load. This means that the inner half of the suspension was subjected to 1kg on each lower suspension knuckle. The analysis was then run and a von Mises stress plot was created. Figure 27 shows the results for the multipass stress calculations of the Inner Half of the suspension.
Figure 27: Inner Half of the MLR Suspension von Mises Stress Plot

In this image it is important to note where the stress is concentrated. The maximum stress in the model appears to be around the upper suspension knuckle.

For a closer examination of the highest stress points in the system design, Figure 28 should be seen.
The maximum stress is located at the thinnest part of the tabs located on the high side of the upper suspension knuckle. This maximum value is around 224,000 mmkg/sec²/mm², or 224MPa. This value seems large but to get an indication of whether or not the material can withstand that amount of compressive stress, the failure index of the design must be examined. An image of this index result is seen in Figure 29.
Figure 29: Inner Half of MLR Suspension Failure Index Plot

The two previous images appear nearly identical with the exception of the values in the upper right hand corner. The maximum value in this legend is .7736. The failure index does is analyzes the design, along with specified values for ultimate tensile strength, and computes whether or not the model has a threat for failure, a value of 1 means that the component has failed. It is obvious from the maximum value that this component has not failed under this load. This means that this half of the suspension can withstand half of the applied force, 1kg per knuckle under Earth’s gravitation.
For the other half of the suspension, the Outer Half, the same tests were run. The first analysis was again the von Mises stress computation. Figure 30 shows the results from this analysis.

![Figure 30: Outer Half of MLR Suspension von Mises Stress Plot](image)

For the same load, 1kg per lower knuckle, the maximum stress on the legend is 79210mmkg/sec²/mm², or 79.2MPa. The coloration of the component indicates that the stress in this component is felt throughout the model. The highest stress location can be seen in Figure 31.
Figure 31: Close-up of Outer Half High Stress Points

The reason for this location is because of what is called a stress riser. This is a point on the component that has a sudden change in form, like a sharp corner, where the stress flow concentrates [31]. To determine if this stress is enough for the component to fail, again, the failure index must be examined. Figure 32 shows the failure index for the outer suspension housing.
The maximum value for this figure is 0.2735, under the required value of 1 for failure. This component has been determined to be able to withstand the applied force.

It can be observed from the previous analysis, that these two components individually have the ability to withstand the applied load of 1kg at each lower knuckle. Thus, it is intuitive that when the two sides are combined that the suspension would be able to withstand the summed forces. This is the case, as can be seen in Figure 33.
Figure 33: MLR Suspension von Mises Stress Plot

The maximum stress when the two sides of the suspension are combined is 199,500mm/kg/sec²/mm², or 199MPa. To determine if this causes component failure, the failure index is examined. This can be seen in Figure 34.
In the above figure the maximum value is .6890. While this value is close to the required value of 1 for failure, it still indicates that the structure can withstand the applied force quite easily.

To get a better idea just how much force the design can take, a test to failure is required. The purpose of this test is to determine exactly what the payload capacity of the MLR suspension is. To find out what the maximum force can be held by the suspension, the design will be loaded and analyzed until a failure index of 1 is reached. Figure 35 shows the results of this analysis.
Figure 35: MLR Suspension Test to Failure

In this image it can be seen that the failure index maximum for this analysis is 1.055. The loading that the system is experiencing at this point is 7kg. Due to the stress having a linear relationship with the force applied, if the applied 7kg is divided by 1.055, the maximum allowable force is found. It is found to be 6.64kg. Figure 36 shows the analysis performed with a load of 6.64kg.
Figure 36: MLR Suspension Failure Index for 6.64kg

The maximum value of 1.0 means that this component is just failing. The impact of this is that the system can hold 13kg of total system mass plus payload before suspension failure. This is the system’s total static mass capability under Earth’s gravity. But, because rovers don’t usually stay stationary on a surface, they rove over rough terrain; an analysis must be performed that takes this into account.
5.2 Dynamic Analysis

To truly understand the MLR’s full capabilities, an analysis must be performed that takes into account the forces that it will experience during surface roving. There are two specific cases that must be analyzed. The first is when the rover is moving along at its top speed, the calculated value of 21.8cm/sec, and then runs into a wall or rock that stops the rover’s forward progress. This is the first dynamic analysis that must be performed.

To begin, some assumptions must be made. The first is that there is some distance over which the wheel has been stopped. There are several factors that would lead to this distance; the most likely is flex in the wheels or spokes. For calculations this distance is assumed to be 5mm. Because the traveling velocity is known, 21.8cm/sec, the mass of the rover, 4kg, is known, and the stopping distance is known, 5mm, the force experienced by the MLR can be calculated. Equation 7 shows this equation.

\[ F = \frac{v^2 M_r}{8d} \]  

(8)
In the above equation, the variables $F$, $v$, $M_r$, and $d$ are the force on the rover, the traveling velocity, the rover mass, and the distance it took for the rover to stop, respectively. Using the known rover values in Equation 8, the force is calculated. The force is calculated to be 4.75N. This value is then input into the Pro/Mechanica software to be analyzed. A failure index of less than one means the rover can withstand the force. Figure 37 shows the failure index plot for the assembled suspension.

Figure 37: Stopping Force on MLR
Because this value was found to be less than 1, the stopping force can be applied safely at a mass of 4kg. This assumes worst-case scenario that the stopping force is applied on only one wheel, as might really be the case. Using the same linear calculations as before, the maximum mass that the rover’s suspension can withstand is calculated, and is found to be 69.27kg. Because this value is beyond the static loading capabilities of the suspension, this value does not affect the overall carrying capacity of the rover. Essentially, this is not a limiting case in the rover design.

The second analysis that must be completed is when the rover is covering terrain and rolls off a rock or washout, and drops a significant distance. To be considered a significant distance, half the wheel diameter of 4cm is assumed. The velocity with which the MLR strikes the surface again is a significant consideration that must be made. Again Equation 8 can be used to find the force the rover experiences when striking the ground. But to complete the calculation, a new equation must be introduced to determine the falling velocity. Equation 9 determines the velocity at which the rover is traveling after having fallen 4cm.

\[
    v = \sqrt{2g \times H}
\]  
(9)
The variables $g$ and $H$ in this equation are acceleration due to gravity and the height from which the rover fell, respectively. Because these values are known, the velocity is known. The value for velocity is found to be 88.6 cm/sec. A difference that will be assumed between the two analyses is that due to the suspension’s articulation, no single wheel would ever experience the entire force from the rover’s fall. The force would be split between both sides of the suspension. Therefore, for this analysis, only 2 kg will be assumed for the rover load. Plugging this value back into Equation 8 yields a force of 39.2 N. Figure 38 shows the results of this analysis.
In the above figure it can be seen that the index is over the required value of 1 for failure. This means that the component would fail as a result of this 4cm fall in Earth's gravity landing on two wheels. To address this problem, the maximum allowable force can be computed by using the failure index’s linear relationship to stress. For this index, the maximum allowable force is calculated to be 28.1N.

There are two realistic ways to reduce the force applied to the suspension.

The first possible way to reduce the force applied is to simply develop control software that prohibits the MLR from free falling off an object of that height.
This is one way to reduce the force experienced, just avoid it. But, that is not always possible. The other way to reduce the force applied to the MLR suspension to less than 28.1N is to create wheels that have a better shock absorption. For these calculations, the absorption of the wheels was assumed to be 5mm. If, the wheels absorbed 14mm, the force applied to the rover’s suspension would be 28.0N, less than failure. Future design iterations would need to have optimized wheels, to improve overall system performance.

With the current wheel design, it is obvious that this rover has limited capabilities. In Earth’s gravity, with the total mass at 4kg, the suspension cannot survive a freefall from 4cm. Because the Moon’s gravity is roughly a sixth of the Earth’s, a comparable freefall would be from nearly 24cm, much higher [15]. For the current wheel design, with the given properties, the maximum system and payload mass can be calculated. Using Equation 8, the maximum total mass can be found for the calculated maximum value of force. This value is found to be 1.43kg per suspension side, yielding a total mass of 2.86kg. While this is lower than the sought after 4kg total mass, the payload capacity to mass ratio is still good, 3.5:1. This can also easily be improved with a better wheel configuration. Until that point, the Micro Lunar Rover is limited to a 2.86kg total mass.
Chapter 6

Conclusions

The Micro Lunar Rover is an effective solution to the need for a lightweight lunar rover. While it is not the only possible design, the MLR is an effective compromise between size, mass, and traversability. Designs like the SRII and MER are well designed to carry science equipment and cover several kilometers. But, both these designs are too large to be considered for a mission of limited mass and volume. Designs such as the Minerva hopper and JPL Nanorover are good at limiting the size and mass, but not as effective traversing difficult terrain. A compromise like the MLR is an effective way to manage mass and traversability.

6.1 Results

After comparing the two designs, the SRII and the scaled down version, it was determined that further mass reduction could be performed. This mass reduction should come from a new design and material selection. The new design was created while trying to integrate critical components, remove non-critical
components, and reduce fasteners. This redesign proved to give as much as a 50% greater mass loss than just a new material selection alone. The choice of building materials is still the dominant force behind structural mass loss.

After looking at several possible materials including aluminum, titanium, and different varieties of composites, the selection of carbon fiber MS-1A was made. This material uses a manufacturing method called chopped fiber compression. This manufacturing process was determined to be most beneficial because of its ability to produce complex shapes with accuracy. However, due to this technique’s cost and this project’s budget limitations, a prototype was not produced. An analysis of the design was then performed to insure structural integrity.

To demonstrate that this redesign was capable of actually carrying the total system plus payload mass, a finite elemental analysis was performed. While the static analysis of the suspension yielded a total mass capacity of 13kg, the dynamic analysis showed that the mass was limited to 2.86kg. It also highlighted a current design flaw in the rover’s wheels. If these wheels were to flex as little as 13mm, rover mass capacity would increase to the desired 4kg.
6.2 The Future

If a rover were a scaled down version of the SRII, like the MLR, equipped with only a camera, communications, and the requirements for mobility, it could have multiple uses. This rover could be used for roving observations. Possible sites of interest could be scouted and visually evaluated before a more scientifically well-equipped rover made the journey. On a foreign surface, the more information that scientists have, the better decisions they can make. A scout rover could drastically improve this information.

The MLR could not only greatly increase a mission’s chances of success, but it could also aid in documenting the success. This smaller rover could simply record a larger rover while it was performing its specified task. Watching a rover work on a foreign surface is much better than simply seeing panoramic images of that surface. What would Neil Armstrong’s first steps on the moon have been like without a video of it? The effect a mission has on the public can be greatly improved if they have something they can see and relate to. The benefits of a reduced scale, but still capable rover, such as the Micro Lunar Rover, are numerous.
For this design, there are several steps that should be made in the future to improve total mass capacity. The suspension design should be reiterated, eliminating all possible stress risers. A new wheel design should be created to allow for several millimeters of flex. Also, newer materials should be considered. Because, while at the time of the this thesis was written, most materials were as up to date as possible, technological breakthroughs happen regularly. The design reiteration process is never completely finished.
Bibliography


