USE AND SIZING OF ROCKET HOPPERS FOR PLANETARY SURFACE EXPLORATION

BY

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ABSTRACT
The utilization of rocket hoppers can provide a valuable means of obtaining enhanced mobility for planetary surface exploration missions. Hoppers offer higher exploration versatility than landers, rovers, or other surface exploration systems through their ability to quickly traverse difficult terrain in a variety of planetary environments. Furthermore, using a hover hop rather than a ballistic hop can provide many operational advantages. As the distance between target sites increases, the advantages of a single hopper compared to multiple landers decreases. However, in certain cases, in-situ resource utilization could overcome this problem. A detailed seven-phase hover hop model, simplified approximation formulas for lunar hops, and an optimization tool are presented in this thesis. With these, it becomes possible to quickly obtain optimized values for the vehicle mass, engine mass, and other mission parameters for a specified hopper mission. Results obtained from the application of a lunar hover hop model to realistic mission scenarios demonstrate the utility of hoppers for tasks relevant to future robotic and human exploration of the Moon.

Thesis Supervisor: Jeffrey A. Hoffman
Title: Professor of the Practice of Aerospace Engineering
I. INTRODUCTION

In the quest to explore the surfaces of the bodies of our solar system, spacecraft typically face the challenge of a single landing at a specific site. In order to explore several sites or a larger area than is possible from a stationary lander, either multiple landings need to be performed, or mobility across the surface needs to be employed. One such mobility system involves the use of hoppers, i.e. vehicles that traverse the surface without being in contact with it. In this study, hoppers specifically refer to vehicles that take off vertically, traverse above the surface, and perform a soft landing, all by using rocket propulsion.

I.1 SURVEY OF PLANETARY EXPLORATION SYSTEMS

Planetary landers have proven successful in the surface exploration of the Moon, Mars, Venus, Titan, and two asteroids. Several landers on missions to the lunar surface have also included ascend stages. Rovers have added mobility to exploration missions on the surfaces of the Moon and Mars. Hoppers however have not been utilized – except for a 2.5 m test hop of the Surveyor 6 lunar lander. Yet, hoppers may be able to overcome many of the current limitations of planetary surface exploration. Rocket hoppers will be able to traverse longer distances and access rougher terrain than is possible with current approaches. Just as landers and rovers, hoppers are applicable to a wide range of exploration missions, both robotic and human, across a wide range of planetary bodies, spacecraft sizes, and system architectures.

I.1.1 PLANETARY LANDERS

There have been 38 successful soft landings on the extraterrestrial bodies of our solar system. Most of these were stationary landers, which could only explore the immediate environment. Still, the knowledge gained from planetary landers is vast. And to date, for Venus and Titan, images transmitted from fixed cameras on stationary landers as shown in Figure I-1 and Figure I-2 remain the only impressions of the respective planetary surfaces.
Figure I-1: Image of the surface of Venus, created from Venera 9 data

Figure I-2: Image of the surface of Titan, transmitted by the Huygens probe
Tables I-1 and I-2 summarize the key characteristics for all successful soft landings on other planetary bodies to date, including the Apollo human landings, and excluding four pure rover missions discussed in the next section. Table I-1 lists lunar landings and Table I-2 those on other bodies. A successful landing is one where data was transmitted and received on Earth after the landing. The years refer to the landing, and the mission durations refer to the time spans on the surface from which data was received. Mass values denote mass landed on the surface.

<table>
<thead>
<tr>
<th>Name</th>
<th>No.</th>
<th>Year</th>
<th>Mission duration</th>
<th>Mass</th>
<th>Power</th>
<th>Descent</th>
<th>Ascend module</th>
<th>Rover</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOON:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luna</td>
<td>9</td>
<td>1966</td>
<td>3 d</td>
<td>80 kg</td>
<td></td>
<td></td>
<td>no</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>1966</td>
<td>5 d</td>
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<tr>
<td></td>
<td>16</td>
<td>1970</td>
<td>3 d</td>
<td>1880 kg</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>1972</td>
<td>3 d</td>
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<td></td>
<td></td>
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<tr>
<td></td>
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<td></td>
<td>24</td>
<td>1976</td>
<td>3 d</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Surveyor</td>
<td>1</td>
<td>1966</td>
<td>42 d</td>
<td>300 kg</td>
<td></td>
<td>solar cells</td>
<td></td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1967</td>
<td>13 d</td>
<td></td>
<td></td>
<td>rockets</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1967</td>
<td>97 d</td>
<td></td>
<td></td>
<td></td>
<td>no</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1967</td>
<td>14 d</td>
<td></td>
<td></td>
<td></td>
<td>no</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1968</td>
<td>41 d</td>
<td></td>
<td></td>
<td></td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Apollo Lunar Module</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LM-5</td>
<td>1969</td>
<td>21.5 h</td>
<td>16498 kg</td>
<td>batteries</td>
<td>yes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LM-6</td>
<td>1969</td>
<td>31.5 h</td>
<td>15235 kg</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>LM-8</td>
<td>1971</td>
<td>33.5 h</td>
<td>15264 kg</td>
<td></td>
<td>yes</td>
<td></td>
<td></td>
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<tr>
<td>LM-10</td>
<td>1971</td>
<td>66.9 h</td>
<td>16430 kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>LM-11</td>
<td>1972</td>
<td>71 h</td>
<td>16445 kg</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>LM-12</td>
<td>1972</td>
<td>75 h</td>
<td>16456 kg</td>
<td></td>
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<td></td>
<td>yes</td>
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</tbody>
</table>

Table I-1: Lunar lander missions overview
The two landings on the asteroids Eros and Itokawa were not planned as part of the respective missions. NEAR Shoemaker’s landing was improvised at the end of the mission, while Hayabusa’s landing happened accidentally during a sample collection maneuver.

<table>
<thead>
<tr>
<th>Name</th>
<th>No.</th>
<th>Year</th>
<th>Mission duration</th>
<th>Mass</th>
<th>Power</th>
<th>Descent</th>
<th>Ascend module</th>
<th>Rover</th>
</tr>
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<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Venera</td>
<td>7</td>
<td>1970</td>
<td>23 min</td>
<td>495 kg</td>
<td></td>
<td>Telescopes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1972</td>
<td>50 min</td>
<td></td>
<td>660 kg</td>
<td>Batteries</td>
<td>parachutes</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>1975</td>
<td>53 min</td>
<td></td>
<td></td>
<td>no</td>
<td>no</td>
<td></td>
</tr>
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<td></td>
<td>10</td>
<td>1975</td>
<td>65 min</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>1978</td>
<td>95 min</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>1978</td>
<td>110 min</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>1982</td>
<td>127 min</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>1982</td>
<td>57 min</td>
<td>760 kg</td>
<td></td>
<td></td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td><strong>Vega</strong></td>
<td>2</td>
<td>1985</td>
<td>56 min</td>
<td></td>
<td>855 kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MARS:</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mars</td>
<td>3</td>
<td>1971</td>
<td>15 sec</td>
<td>358 kg</td>
<td>Batteries</td>
<td></td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>Viking</td>
<td>1</td>
<td>1976</td>
<td>6 yrs</td>
<td>572 kg</td>
<td>RTG</td>
<td>parachutes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1976</td>
<td>3.5 yrs</td>
<td></td>
<td></td>
<td>rockets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mars Pathfinder</td>
<td>1997</td>
<td>3 mo</td>
<td>275 kg</td>
<td></td>
<td>solar cells</td>
<td></td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>Phoenix</td>
<td>2008</td>
<td>5 mo</td>
<td>350 kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>no</td>
</tr>
<tr>
<td><strong>433 EROS:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEAR Shoemaker</td>
<td>2001</td>
<td>16 d</td>
<td>487 kg</td>
<td></td>
<td>solar cells</td>
<td>rockets</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td><strong>25143 ITOKAWA:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hayabusa</td>
<td>2005</td>
<td>30 min</td>
<td>510 kg</td>
<td></td>
<td>solar cells</td>
<td>rockets</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td><strong>TITAN:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Huygens</td>
<td>2005</td>
<td>90 min</td>
<td>319 kg</td>
<td></td>
<td>Batteries</td>
<td>parachutes</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

Table 1-2: Planetary lander missions overview
I.1.2. PLANETARY ROVERS

To date, there have been eight rovers in use on the surfaces of the Moon and Mars. They have traveled a total of 138 km on the Moon and more than 25 km on Mars, and have provided valuable means of extending the exploration radii around the landing sites of the respective missions. Figure I-3 and Figure I-4 show two of the rovers used in the past.

Figure I-3: Lunokhod rover

Figure I-4: Sojourner rover operating on Mars
Table 1-3 gives an overview of historical rovers and some of their key system and mission characteristics. LRV 1, 2, and 3 landed on the Moon with the Apollo LM-10, 11, and 12 landers, respectively. Sojourner landed on Mars with the Mars Pathfinder lander. Preliminary characteristics of the planned Mars Science Laboratory mission are also included in the table.

<table>
<thead>
<tr>
<th>Name</th>
<th>No.</th>
<th>Year</th>
<th>Mission duration</th>
<th>Distance traveled</th>
<th>Mass</th>
<th>Power</th>
<th>Wheel diameter</th>
<th>Max. speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOON:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lunokhod</td>
<td>1</td>
<td>1970</td>
<td>1 yr</td>
<td>10.5 km</td>
<td>800 kg</td>
<td>Solar electric + radioisotope heaters</td>
<td>51 cm</td>
<td>0.56 m/s</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1973</td>
<td>4 mo</td>
<td>37 km</td>
<td>700 kg</td>
<td>Non-rechargeable batteries</td>
<td>82 cm</td>
<td>5 m/s</td>
</tr>
<tr>
<td>Lunar Roving Vehicle (LRV)</td>
<td>1</td>
<td>1971</td>
<td>3 d</td>
<td>27.8 km</td>
<td>700 kg</td>
<td>Solar electric + radioisotope heaters</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1972</td>
<td>3 d</td>
<td>26.6 km</td>
<td>700 kg</td>
<td>Non-rechargeable batteries</td>
<td>82 cm</td>
<td>5 m/s</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1972</td>
<td>3 d</td>
<td>35.9 km</td>
<td>700 kg</td>
<td>Solar electric + radioisotope heaters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MARS:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sojourner</td>
<td>1997</td>
<td>3 mo</td>
<td>0.1 km</td>
<td>10.5 kg</td>
<td>10.5 kg</td>
<td>Solar electric + radioisotope heaters</td>
<td>13 cm</td>
<td>0.01 m/s</td>
</tr>
<tr>
<td>Spirit</td>
<td>2004</td>
<td>&gt; 5 yr</td>
<td>7.8 km</td>
<td>185 kg</td>
<td>185 kg</td>
<td>Solar electric + radioisotope heaters</td>
<td>25 cm</td>
<td>0.05 m/s</td>
</tr>
<tr>
<td>Opportunity</td>
<td>2004</td>
<td>&gt; 5 yr</td>
<td>17.2 km</td>
<td>185 kg</td>
<td>185 kg</td>
<td>Solar electric + radioisotope heaters</td>
<td>25 cm</td>
<td>0.05 m/s</td>
</tr>
<tr>
<td>Mars Science Laboratory (planned)</td>
<td>2012</td>
<td>&gt; 2 yr</td>
<td>&gt;19 km</td>
<td>900 kg</td>
<td>900 kg</td>
<td>RTG</td>
<td>50 cm</td>
<td>0.04 m/s</td>
</tr>
</tbody>
</table>

Table 1-3: Rover missions overview

Even though the mission characteristics have been quite different among the historical rovers, there is a clear trend towards larger ranges with increasing wheel diameter. It appears that with current technology, the required wheel size poses a limit to the use of rovers for long-range surface exploration.

Additional limitations in the use of rovers arise from their difficulties in navigating rough terrain, and from their complex mechanical design which is prone to failure in long
missions and in difficult situations. While their scientific value has been extraordinary, the systems were not designed for covering large areas of the respective surfaces. Thus, our close-up knowledge of the surfaces of the Moon and Mars is still limited to fairly small areas. Furthermore, these areas have tended to feature rather smooth terrains, in order to minimize the risk involved in roving across the surface.

1.2 PLANETARY SURFACE EXPLORATION VERSATILITY ANALYSIS

There exists a large variety of other possible designs for planetary surface mobility systems beyond landers, rovers, and hoppers. Walkers, rollers, crawlers, and mechanically actuated hoppers can be used for traversing a planetary surface. Atmospheric exploration vehicles such as airplanes, helicopters, balloons, and airships can be suitable for traveling across surfaces on bodies with atmospheres. Boats and submarines could be used where surface or subsurface liquids are present. Diggers and ice-melters could be used for subsurface exploration.

The suitability of any such system will ultimately depend on the specific target and mission goals. However, when comparing system architectures, higher versatility across different mission scenarios will make a given architecture more useful when specific mission goals are not yet defined, or when a system is to be used for different missions. Thus, the development of a high versatility system likely offers a greater return on investment.

1.2.1. ESTABLISHING A MEASURE OF EXPLORATION VERSATILITY

To establish the planetary surface exploration versatility of a system, I propose a 1 to 5 scale with 1 being least versatile and 5 being most versatile. I furthermore propose 10 equally weighted sub-categories of versatility. These categories are:

Range: How far can a given vehicle travel across the surface?
System complexity: How high is the mechanical and electronic component complexity of the exploration system?

Technological maturity: How developed and proven are the required technologies?

Energy requirement: How much fuel and/or electricity has to be spent while traversing the surface?

Speed: How fast can the surface be traversed?

Rough terrain suitability: How well can the system operate in rough terrain (including take-off/landing where applicable)?

In-traverse exploration: How well is the exploration system suited for exploring the surface during traverses?

Requirement of high gravity: How important is high gravitational pull for operating the system on a planetary surface?

Requirement of atmosphere: How important is the presence of an atmosphere for the operation of the exploration vehicle?

Requirement of liquid or ice: How important is the presence of a liquid or of ice for operating the system?
1.2.2. VERSATILITY COMPARISON

Table 1-4 shows a comparison of different planetary surface exploration systems. I have assigned versatility measures to them for each sub-category, as I found appropriate considering anticipated typical usage scenarios for a given system. Versatility measures are meant to be relative measures with respect to the other systems’ versatilities.

For a better visualization, darker cell backgrounds in the table refer to higher versatility values. The rightmost column gives the versatility averages of the ten sub-categories, while the bottom row gives the versatility averages of the different exploration systems.

<table>
<thead>
<tr>
<th>VERSATILITY:</th>
<th>ROCKET HOPPER</th>
<th>LANDER</th>
<th>WALKER</th>
<th>ROVER</th>
<th>BALLOON</th>
<th>AIRSHIP</th>
<th>ROLLER</th>
<th>CRAWLER</th>
<th>AIRPLANE</th>
<th>HELICOPTER</th>
<th>MECH. HOPPER</th>
<th>SUBMARINE</th>
<th>BOAT</th>
<th>DIGGER</th>
<th>ICE-MELTER</th>
<th>AVERAGE</th>
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<tbody>
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<td>RANGE</td>
<td>HIGH 5</td>
<td>LOW 1</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>2.5</td>
</tr>
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<td>HIGH 5</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<td>2.6</td>
</tr>
<tr>
<td>TECHNOLOGICAL MATURITY</td>
<td>HIGH 4</td>
<td>LOW 5</td>
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<td></td>
<td></td>
<td></td>
<td>2.6</td>
</tr>
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<td>ENERGY REQUIREMENT</td>
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<tr>
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<tr>
<td>Requires atmosphere</td>
<td>NO 5</td>
<td>YES 4</td>
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<td>3.7</td>
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<tr>
<td>Requires liquid or ice</td>
<td>NO 5</td>
<td>YES 4</td>
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Table 1-4: Versatility comparison of planetary surface exploration systems
Rocket hoppers, the subject of this study, achieve the highest overall versatility rating among all surface exploration systems. They perform well across most sub-categories, with the notable exception of their energy requirement. Fuel consumption for a rocket hop is high and constitutes a limiting factor in the system’s usability. Thus, fuel consumption needs to be thoroughly analyzed and optimized in the design of rocket hopper systems.

1.3 HOPPERS VERSUS MULTIPLE LANDERS

The previous analysis focused on individual exploration vehicles. However, for most systems, a set of multiple vehicles, deployed at one or multiple landing sites, is possible. A special case that merits attention in the context of this study is the use of multiple landers. Performing multiple landings at different locations of a target body is similar to using a single hopper to explore multiple locations. Most subsystems of hoppers resemble those of landers. Both have similar descent and landing requirements, similar structural requirements, and similar communications, data handling, power, and thermal control subsystems. However, there are also important differences between the two approaches.

While for multiple landers, all subsystems have to be built and flown to the target body multiple times, for a hopper, one of each subsystem is sufficient for a given multiple-location mission.

However, historically, the initial landing on a planetary body has been the riskiest phase of surface exploration missions. With multiple chances of surviving the initial landing, multiple landers are more likely to return scientific value than a single hopper with only one chance of initial survival. Also, the development cost of multiple identical platforms for a multiple-lander mission might not be significantly higher than that of a single system.

Furthermore, due to more demanding propulsion, attitude control and navigation requirements, hoppers will be technologically more complex than landers.

A unique advantage of hoppers compared to multiple landers is their ability to perform relatively close-up surface exploration during traverses and to establish precise knowledge of the nearby surface that can aid in targeting subsequent landing sites.
Whenever these features are not important, and the previously mentioned differences are taken into account, the major tradeoff between multiple landers and a single hopper is the respective propellant requirement. While multiple landers require more propellant before reaching the surface, due to the increased overall system mass during transit and landing, they only require marginally more propellant to reach multiple sites far apart on the surface. A hopper on the other hand will require substantial additional propellant to traverse long distances on the surface. Hence, in general, mission scenarios with large site separations will favor multiple landers, while mission scenarios with sites closer together will favor individual hoppers.

1.4 RESEARCH GOALS FOR FUTURE PLANETARY SURFACE EXPLORATION

Many interesting exploration targets on the surfaces of planets and moons of our solar system lie in rough terrain. Cliffs, canyons, mountain ranges, valleys, boulder fields, craters, volcanoes, or ice shields offer some of the best access to study various geological processes.

Also, the search for occurrences of water on the surfaces of the Moon and Mars is an important research goal, as significant findings could help facilitate human presence and in-situ propellant production. Craters and similarly difficult to access surface features are currently the most promising targets for this search.

The most significant targets of past, present, and most likely future exploration of our solar system are the Moon and Mars. The Moon stands out as the most accessible large body beyond Earth. Mars stands out as the body that is most similar to Earth.

However, many more targets for surface exploration exist in our solar system. These include Venus, Mercury, the Moons of Jupiter, Saturn and Mars, as well as a large number of asteroids, comets, dwarf planets, and moons.

Especially on smaller bodies with low gravity, exploration with rovers is difficult due to very low surface traction. Hence, for these, hoppers can provide a unique option for surface mobility.
II. THE USE OF PLANETARY HOPPERS

II.1 HOPPER MISSION ARCHITECTURES

Mission architectures for hoppers are very flexible. This flexibility not only includes the applicability of hoppers to a wide range of target bodies, but also how hoppers can be adapted to different landing, payload, traverse and staging requirements.

Furthermore, hoppers are similar to landers in their overall system architecture. Many systems required for a precision soft landing on a planetary surface are similar to the systems required during the performance of a hop. Therefore, lessons learned from the past development of landers can be applied to the future development of hoppers.

Figure II-1: Artist's concept of lunar hopper (X PRIZE Next Giant Leap team)
II.1.1. LANDING SYSTEM

The initial landing of a hopper on a planetary body can impose system requirements that are distinct from those for subsequent landings after surface hops. This is especially true for target bodies with high gravity such as the Moon and Mars, where the initial soft landing requires a large expenditure of energy. On bodies with an atmosphere, such as Mars, Venus, and Titan, this energy requirement can be reduced by using the atmosphere for braking during atmospheric entry.

In case the requirements for the initial landing are distinct from the rest of the mission, it is beneficial to separate the two phases, and have a dedicated descent system that detaches from the hopper module. Thus, the mass of the hopper is reduced and its hop propulsion system can be optimized for the surface exploration phase. From here on, the mass of a hopper will generally refer to the mass after separation from the landing system, unless otherwise stated.

II.1.2. PAYLOADS

Hoppers and their associated payloads can be used in multiple ways. Hoppers can carry a single suite of instruments that is used throughout the mission to explore the different landing sites and make observations and measurements during the traverses. At the final site, the payload can be kept operational for an extended time, converting the hopper into a stationary platform.

In a different scenario, a hopper can drop payloads at multiple sites, for instance to establish a sensor network, to set up long-term experiments, or to deposit supplies for future missions. The two approaches can also be combined by having a main payload that stays on the hopper and one or more secondary payloads to be left behind during the mission.

II.1.3. TRAVERSSES

The traverses of hoppers can serve multiple purposes. In a mission scenario in known terrain, or with limited sensor equipment, they can be used solely for traveling to the next
destination. In other scenarios, the traverses can be used for remote exploration of the surface, or the atmosphere where applicable. Here, a bird’s eye view during a high-altitude traverse can enable wide-range observations to supplement narrow-range ground observations. In mission scenarios with unknown terrain and/or unknown exploration targets, the traverses can also be used for navigation and decision making with respect to the exact path to be taken to reach a next site of interest.

### II.1.4. STAGING

An interesting option for hopper missions it the use of staging. The previously mentioned separation from the descent module is one form of staging to reduce mass to be carried along subsequently. Another form of staging would be the dropping of empty propellant tanks, either while hopping, or at intermediate landing sites. The additional mass associated with dropping mechanisms and individual smaller tanks instead of a single large tank has to be taken into account when assessing the potential benefit of such an approach for a given mission scenario.

The dropping of propulsion, communication, and/or power generation modules could also be options, especially in mission scenarios with propulsion, communication and/or power requirements that change significantly throughout the mission.

### II.2 IN-SITU RESOURCE UTILIZATION FOR MARS HOPPERS

An interesting option for extending the range of hoppers in order to be able to explore larger areas or sites that are far apart is the use of in-situ resources for the hopper’s propulsion. This can also overcome the previously mentioned disadvantage of individual hoppers compared with multiple landers for mission scenarios with large separations between landing sites.

In-situ resource utilization (ISRU) is especially applicable for the exploration of Mars, where the supply of propellant from Earth is very expensive, and where the surface environment offers useful chemical compounds to enable locally-fueled propulsion systems.
Figure II-2 shows the relationship of required delta-V as a function of the hopper range for realistic Martian hops, which is applicable to potential Martian ISRU hoppers.

![Figure II-2: Delta-V requirements for Mars hoppers](image)

I will now present some of the potential options for in-situ resource utilization by rocket hoppers, as identified by previous research.

### II.2.1. HYBRID ISRU SYSTEMS

Hybrid ISRU systems are those that make use of local resources for fueling the propulsion system, but still partially depend on Earth-supplied fuel sources.

One option is to combust Earth-supplied powdered magnesium with carbon dioxide acquired from the Martian atmosphere. The carbon dioxide is acquired before each hop. Shafirovich et al\(^{10}\) estimate that a 200 kg hopper employing this approach could perform 10 to 15 hops with a total range of 10 to 15 km within 180 sols.

Another option is the production of ethylene from Martian carbon dioxide in a reverse water gas shift system, combined with an ethylene formation system. The required hydrogen can be supplied from Earth. Zubrin et al\(^{11}\) estimate that a lighter than 200 kg hopper utilizing
this technology, with 22 kg of Earth-supplied hydrogen could perform 7 hops of 1000 km each, with one hop every 200 sols.

II.2.2. FULLY AUTONOMOUS SYSTEMS

Fully autonomous ISRU systems solely rely on local resources for their propulsion requirements. Therefore, the mission duration, and possible ranges are not limited by the propellant requirements, and extended missions become possible.

One option for this approach is to combust carbon monoxide and oxygen, both produced from Martian atmospheric carbon dioxide. Landis et al\textsuperscript{12} estimate that a 20 kg hopper using this technology could perform one 0.5 km hop every 25 days.

Another option is the pressurization of Martian atmospheric carbon dioxide with a solar-electric powered pump. Zubrin et al\textsuperscript{13} estimate that a 55 kg hopper with this technology, with an added 30 kg of compressed carbon dioxide could perform a 15 to 20 km hop every 30 days.

A further option is to expel Martian carbon dioxide, heated by a nuclear thermal reactor system. According to Zubrin\textsuperscript{14}, a virtually unlimited operating range could be achieved with such a system.

II.3 BALLISTIC HOP VERSUS HOVER HOP

There are different ways of performing rocket-powered hops across planetary surfaces. The simplest hop is an ideal ballistic hop, with one short rocket firing at the beginning, to lift the hopper of the ground, an un-powered ballistic phase, and a second short rocket firing at the end to bring the hopper to a rest when landing on the surface.

Another option is to employ a hover hop, where the hopper lifts off the ground, and then stays at a constant altitude relatively close to the surface while traversing it, until descending to a soft landing. For a hover hop, continuous propulsion is required during traverses. While not energetically optimal, a hover hop offers several advantages over a ballistic hop:
- Lower engine thrust is required, because continuous propulsion rather than short engine firings are used.
- Less pointing accuracy for the direction of the engine firing is required, because course corrections are possible throughout the hop.
- Operations can be safer, because emergency landings are more feasible when staying close to the surface at all times.
- In unknown terrain, data collected of the surface during the traverse can be used in determining necessary course corrections while hopping.
- Finally, staying close to the surface enables better in-traverse surface exploration by enabling higher resolution observations.

These advantages of the hover hop over a ballistic hop are significant, and by analyzing and understanding the characteristics of hover hops, the utility of hoppers for planetary surface exploration can be improved significantly. Therefore, I will focus on the performance of hover hops for the remainder of this study.
III. HOVER HOP MODEL AND OPTIMIZATION

In order to perform a hover hop, a hopper requires at least one rocket engine to lift the vehicle off the ground, keep it at a constant altitude while propelling it sideways, and then bringing it back to the surface in a soft landing.

The lengths of the different phases of the hop, i.e. ascent, acceleration, coasting, deceleration, and descent are variable, and shall be optimized with respect to each other, in order to achieve minimum propellant consumption for a given hop distance and height.

For the purpose of this study, the simplest possible propulsion system with a single rocket engine is assumed. Different directions of thrust can be achieved by rotating the vehicle. This can be achieved by a separate attitude control system using small thrusters or reaction wheels. When performing multiple hops, reaction wheels can be easily desaturated while on the surface between hops.

III.1 HOPPER SUBSYSTEM MODELS

A rocket hopper contains subsystems that can be found in most spacecraft. These include the structures, thermal control, data handling, guidance, navigation, control, communications, and power systems. While it is beyond the scope of this study to provide any detail of the functionality and design of these systems, it is important to obtain estimates for the masses of these systems.

The mass for structural elements will be estimated as 15% of the total hopper mass, based on historical figures, and spacecraft mass estimation references\textsuperscript{15,16}.

The mass of the power generation and storage system, assuming a solar cell based design, and of the communications system will be included in my model, based on a spreadsheet developed by Benjamin Corbin\textsuperscript{17,18}. This model is based on a lunar scenario, but can be modified to allow for other missions. The spreadsheet can be seen in the appendix, in figure A-18.
Further subsystems, such as data handling, thermal control, and guidance systems will not be modeled explicitly, and have to be included in the payload mass of the hopper mass model.

Of special interest is the hopper’s propulsion system, which will be discussed in more detail in the following section.

III.2 PROPULSION SYSTEM

In the model presented here, the propulsion system consists of a single rocket engine, propellant tanks, and propellant. An optimized sizing of these components requires an integrated model, taking into account the details of the hopping. The goal is to obtain a minimized total mass given a limited set of input parameters.

The only input parameter directly related to the propulsion system is the engine’s specific impulse. We can vary this input to compare alternatives, but the analysis presented in this report is based on the use of hydrazine bipropellant systems, which are most common for high performance in-space propulsion.

III.2.1. SIZING THE ENGINE AND TANKS

The propulsion model that I propose introduces an optimized engine thrust level. To parametrically relate that to an engine mass, I looked at data from actual production engines. Figure III-1 shows mass versus thrust for a wide variety of in-space propulsion engines.

Over a wide range of thrust values, the engine masses approximately follow an exponential relationship of thrust versus mass. Figure III-1 shows the horizontal axis with the mass values on a logarithmic scale, such that the data points cluster around a straight line representing the estimated parametric relationship of engine thrust versus mass.
According to the analyzed engine data, I conservatively estimate the exponential relationship of engine thrust $T$ versus mass $m_E$, including required conversion units, as:

$$m_E = \frac{1}{10} \frac{s^2}{m T^3}$$  \hspace{1cm} (III-1)

Similarly, I looked at tank masses of actual satellites, compared with propellant masses, with propellant and oxidizer tank mass added where applicable.

Figure III-2 shows the propellant versus tank mass data points, and the estimated exponential fit.
The resulting estimated parametric relationship between propellant mass $m_p$ and tank mass $m_T$ is:

$$m_T = \frac{2}{3} m_p^{2/3}$$  \hspace{1cm} (III-2)

These two models fit actual data over large ranges of input values, such that I am confident in their applicability for a wide range of missions. The parametric mass relationships depend on the availability of arbitrarily sized tanks and engines. While this is not actually the case, for planetary exploration missions many components are typically custom-made, and thus it can also be possible to also custom manufacture arbitrarily sized engines and tanks.
III.3 MODELING A HOVER HOP

In order to obtain a propulsion system model that incorporates propellant expenditure, we have to model a hop profile. I will model this profile in seven phases. For multiple hops, several seven-phase hop sequences can be added in series.

The phases are, in sequence, a vertical ascent phase, a phase of horizontal acceleration, a constant-height hover phase with forward acceleration, a constant-height horizontal coasting phase, a constant-height hover phase with deceleration, a full horizontal deceleration phase, and a vertical descent phase. These are shown in Figure III-3.

![Figure III-3: Seven-phase hover hop model](image)

In all but the horizontal coast phase, a constant engine firing at maximum thrust is assumed, where only the direction of the firing is varied. This will be achieved by an attitude control system not included in the model.

The engine canting angle is measured from the vertical with positive angles corresponding to forward acceleration. During the coast phase we assume variable throttling of the engine, which can be achieved by either employing a throttleable engine or by constantly pulsing the engine.

In the current model, there are discontinuities in the engine cant angles between the different phases. As this is not actually achievable, it introduces inaccuracies to the model. However, these will be small for sufficiently long hops.
III.4 FUNDAMENTAL EQUATIONS OF A HOVER HOP MODEL

I will now list some of the fundamental equations governing a hover hop, based on the principles of classical mechanics. The formulas describing the hover hop phases, as shown in subsequent sections, can be derived using these and the constraints set by the model.

With engine thrust $T$ and effective engine exhaust velocity $v_E$, the mass flow of a rocket engine is:

$$\frac{dm}{dt} = \frac{T}{v_E}$$  \hspace{1cm} (III-3)

Therefore, with constant thrust and effective exhaust velocity, after integration, the time-dependent mass of the vehicle with initial mass $m_0$ becomes:

$$m(t) = m_0 - \frac{Tt}{v_E}$$  \hspace{1cm} (III-4)

Then, with backward engine cant angle $\theta$ and local gravity $g$, the vertical acceleration becomes:

$$a_v = \frac{T \cos \theta}{m(t)} - g = \frac{\cos \theta}{\frac{m_0}{T} - \frac{t}{v_E}} - g$$  \hspace{1cm} (III-5)

Accordingly, the horizontal acceleration becomes:

$$a_h = \frac{T \sin \theta}{m(t)} = \frac{\sin \theta}{\frac{m_0}{T} - \frac{t}{v_E}}$$  \hspace{1cm} (III-6)
### III.5 INPUT PARAMETERS

Input parameters for the hover hop model are local gravity $g$, specific impulse of the engine $I_{sp}$, number of hops $n$, fixed payload mass $m_F$, hover height above the surface $h_H$, individual hop distance $d_H$, and dropped payload mass at each site $m_D$. This setup allows for a variety of mission scenarios. By setting $m_F$ or $m_D$ to zero, fixed only and dropped only payload scenarios can be analyzed.

Total payload mass $m_Y$ is:

$$m_Y = m_D (n + 1) + m_F$$  \hspace{1cm} (III-7)

From the commonly used specific impulse $I_{sp}$, the effective engine exhaust velocity is calculated as follows:

$$v_E = g_{Earth} I_{sp}$$  \hspace{1cm} (III-8)

Earth gravity $g_{Earth}$ will be approximated with 9.807 m/s².

### III.6 SUBSYSTEM MODELS

As derived earlier, engine mass $m_E$ as a function of engine thrust $T$ is estimated as:

$$m_E = \frac{1}{10} \frac{s^2}{m} T^{\frac{2}{3}}$$  \hspace{1cm} (III-1)

And tank mass $m_T$ as a function of propellant mass $m_p$ is estimated as:

$$m_T = \frac{2}{3} m_p^{\frac{2}{3}}$$  \hspace{1cm} (III-2)
Furthermore, as mentioned above, structural mass $m_X$ as a function of total hopper mass $m_H$ is estimated as:

$$m_X = \frac{3}{20} m_H$$

(III-2)

III.7 DESCRIPTION OF THE HOPPER STATE

At each point in time during the hover hop, the hopper is described by the following parameters:

Time passed since beginning of the hop, $t$, mass of the hopper, $m$, height above ground, $h$, vertical velocity, $v$, horizontal distance traveled since beginning of hop, $d$, ground speed, $s$, and backward engine cant angle, $\theta$.

Subscripts will be added to these parameters, with $..._0$ designating the value before phase 1 of the hop, $..._1$ designating the value between phase 1 and 2 of the hop, etc.

The lengths of the phases of the hop are designated with letter subscripts by $t_A$ to $t_G$, with $t_A = t_1$, $t_B = t_2 - t_1$, $t_C = t_3 - t_2$, $t_D = t_4 - t_3$, $t_E = t_5 - t_4$, $t_F = t_6 - t_5$, and $t_G = t_7 - t_6$. The time passed since the beginning of the current phase is designated with $\tau$.

For multiple subsequent hops, the number of the current hop is denoted by superscripts. For instance, with this notation, $d^2_4$ will denote the horizontal distance traveled since the beginning of the second hop, after the fourth phase of the second hop. Superscripts $...^0$ denote initial states before the first hop. Variables without subscripts and/or superscripts apply to all hop phases and/or hops, respectively. A subscript $...^C$ represents a value at the current hop.

In the hover hop model described here, several variables are calculated twice by using different equations. Subsequently, the calculated values are matched by varying the inputs to the calculations. When variables occur in this fashion, one of the two instances is differentiated by adding a prime superscript $...'$.
III.8 PHASE 1 – VERTICAL ASCENT

During phase 1, the hopper takes off vertically with $\theta = 0$, until it reaches a height at which it will just reach the desired hover altitude $h_H$ after cutting off the vertical engine thrust component.

Initially, we have mass and height defined as the final mass and height at the end of the previous hop:

$$m_0 = m_f^{C-1} - m_D$$  \hspace{1cm} (III-3)

$$h_0 = h_f^{C-1}$$  \hspace{1cm} (III-4)

For the first hop we define:

$$m_i^0 = m_i^H$$  \hspace{1cm} (III-5)

$$h_f^0 = 0$$  \hspace{1cm} (III-6)

$m_i^H$ is the initial hopper mass, which will be minimized later.

After phase 1, we have:

$$m_1 = m_0 - \frac{T}{v_E} t_A$$  \hspace{1cm} (III-7)

$$h_1 = h_0 + t_A v_E + v_E \left( \frac{v_E m_0}{T} - t_A \right) \ln \left( 1 - \frac{T t_A}{v_E m_0} \right) - g \frac{(t_A)^2}{2}$$  \hspace{1cm} (III-8)

$$v_1 = -v_E \ln \left( 1 - \frac{T t_A}{v_E m_0} \right) - g t_A$$  \hspace{1cm} (III-9)
III.9 PHASE 2 – HORIZONTAL ACCELERATION

In the second phase, the engine is oriented sideways with $\theta = 90^\circ$. The hopper accelerates horizontally until it reaches hover altitude $h_H$.

After phase 2, we have:

$$m_2 = m_1 - \frac{T}{v_E}(t_2 - t_A)$$ (III-10)

$$h_2 = h_1 + \frac{(v_1)^2}{2g}$$ (III-11)

$$d_2 = v_E \left( (t_2 - t_A) + \left( \frac{v_E m_1}{T} - (t_2 - t_A) \right) \ln \left( 1 - \frac{T(t_2 - t_A)}{v_E m_1} \right) \right)$$ (III-12)

$$s_2 = -v_E \ln \left( 1 - \frac{T(t_2 - t_A)}{v_E m_1} \right)$$ (III-13)

$$t_2 = t_A + \frac{v_1}{g}$$ (III-14)

III.10 PHASE 3 – HOVER WITH ACCELERATION

In the third phase, the engine is oriented in such a way that its vertical thrust component just offsets the acceleration due to gravity, keeping the vehicle on its hover altitude. With continuous expenditure of propellant and decreasing vehicle mass, the engine has to swivel through an angle $\theta$ as follows:

$$\theta(t) = \arccos \left( g \left( \frac{m_2}{T} - \frac{t}{v_E} \right) \right)$$ (III-15)

The length of this phase will be optimized.
After phase 3, we have:

\[ m_3 = m_2 - \frac{T t_c}{v_E} \]  \hspace{1cm} (III-16)

\[ \theta_3 = \arccos \left( \frac{g m_3}{T} \right) \]  \hspace{1cm} (III-17)

We now define the following value:

\[ A_1 = \sqrt{1 - \left( \frac{m_2 g}{T} \right)^2} \]  \hspace{1cm} (III-18)

Then:

\[ d_3 = d_2 + s_2 t_c \]

\[ + \frac{v_E^2}{2g} \left[ \frac{m_2 g A_1}{T} - \arctan \sqrt{\left( \frac{g m_2}{T} \right)^2 - 1} \right] - \arctan \left( \frac{1}{g m_2} \right) - 1 + \theta_3 \]

\[ + \cos \theta_3 \left[ \sin \theta_3 - 2 A_1 - \ln \left[ \frac{2}{1 - \frac{1}{\sin \theta_3}} - 1 \right] \right] \]

\[ s_3 = s_2 + v_E \left[ A_1 + \frac{1}{2} \ln \left[ \frac{2}{1 - \frac{1}{\sin \theta_3}} - 1 \right] - \frac{1 - \frac{1}{A_1}}{1 + \frac{1}{A_1}} - \sin \theta_3 \right] \]  \hspace{1cm} (III-20)

\[ t_3 = t_2 + t_c \]  \hspace{1cm} (III-21)
III.11 PHASE 4 – HORIZONTAL COAST

In the fourth phase, the engine is oriented vertically and throttled in such a way that it just offsets the gravitational acceleration throughout the coast phase. The length of this phase will be optimized.

After phase 4, we have:

\[ m_4 = m_3 e^{\frac{g t_D}{v_E}} \quad \text{(III-22)} \]

\[ d_4 = d_3 + s_4 t_D \quad \text{(III-23)} \]

\[ s_4 = s_3 \quad \text{(III-24)} \]

\[ t_4 = t_3 + t_D \quad \text{(III-25)} \]

III.12 PHASE 5 – HOVER WITH DECELERATION

Similarly to phase 3, in phase 5, the engine orientation is continuously varied to offset gravity, keeping the vehicle at its hover height while decelerating.

After phase 5, we have:

\[ m_5 = m_4 - \frac{T t_E}{v_E} \quad \text{(III-26)} \]

\[ \theta_5 = - \arccos \left( g \left( \frac{m_4}{T} - \frac{t_E}{v_E} \right) \right) \quad \text{(III-27)} \]
We now define the following value:

\[
A_2 = \sqrt{1 - \left(\frac{m_4 g}{T}\right)^2}
\]  

(III-28)

Then:

\[
d_5 = d_4 + s_4 \tau_E
\]

\[
- \frac{v_E^2}{2g} \left[ \frac{m_4 g A_2}{T} - \arctan \left( \frac{1}{g m_4} \right) \right] - 1 - \theta_5
\]

\[
+ \cos(-\theta_5) \sin(-\theta_5) - 2A_2 - \ln \left[ \frac{1}{\sin(-\theta_5)} - 1 \right] \left[ \frac{1 - \frac{1}{A_2}}{1 + \frac{1}{A_2}} \right]
\]

(III-29)

\[
s_5 = s_4 - v_E \left[ A_2 + \frac{1}{2} \ln \left[ \frac{2}{1 - \frac{1}{\sin(-\theta_5)}} - 1 \right] \frac{1 - \frac{1}{A_2}}{1 + \frac{1}{A_2}} \right] - \sin(-\theta_5)
\]

(III-30)

\[
s'_5 = v_E \ln \left( 1 + T \frac{t_5 - t_s}{v_E m_5} \right)
\]

(III-31)

\[
t_5 = t_4 + \tau_E
\]

(III-32)

### III.13 PHASE 6 – HORIZONTAL DECELERATION

In the sixth phase, the engine is oriented with \( \theta = -90^\circ \), giving full horizontal deceleration, while the vehicle falls down under the influence of gravity until it reaches a height at which a continuous vertical engine firing will land the hopper on the ground with no remaining vertical velocity.
After phase 6, we have:

\[
m_6 = m_5 - T \frac{t_6 - t_5}{v_E}
\]

\[
v_6 = v_E \ln \left(1 - \frac{T t_6}{v_E m_5}\right) + g t_6
\]

\[
d_6 = d_5 + (s'_5 + v_E)(t_6 - t_5) + v_E \left(\frac{v_E m_5}{-T} - (t_6 - t_5)\right) \ln \left(1 + T \frac{t_6 - t_5}{v_E m_5}\right)
\]

\[
t_6 = t_5 - \frac{v_6}{g}
\]

Furthermore, we can express the height before phase 6 as follows:

\[
h'_5 = \left(\frac{v_E \ln \left(1 - \frac{T t_6}{v_E m_6}\right)}{2 g}\right)^2 - v_E \left(t_6 + \left(\frac{v_E m_6}{T} - t_6\right) \ln \left(1 - T \frac{t_6}{v_E m_6}\right)\right)
\]

III.14 PHASE 7 – VERTICAL DESCENT

In the seventh phase, the engine fires vertically until the hopper lands with zero vertical velocity.

After phase 7, we have:

\[
t_7 = t_6 + t_G
\]

\[
m_7 = m_6 - T \frac{t_G}{v_E}
\]

\[
h_7 = 0
\]
III.15 HOVER HOP OPTIMIZATION REQUIREMENTS

In the hover hop model described here, the system mass as a whole, including engine, tanks, and propellant, is minimized. The mathematical relationships governing the hover hop do not always resolve the desired input variables, such that an optimization process has to be employed in which model outputs are matched to desired values by varying model inputs. Hover height and hop distance appear as outputs, and the desired values have to be obtained by varying free parameters. The varied parameters are engine thrust and engine burn times in hop phases 1, 3, 4, 5, and 7. The engine burn times are optimized for each individual hop in a multi-hop scenario. The engine size is optimized globally, as the engine stays constant throughout the mission.

All relationships in the model are given analytically. Therefore, even though we require numerical optimization, we do not require numerical simulation of the hover hop. This results in good performance and usability of the model.

Figure III-4: Propulsion system mass fraction dependencies for a single hop
Figure III-4 shows how optimized propulsion system and engine mass fractions vary with hop distance and hopper mass. While the propulsion system mass fraction increases with longer hops, mainly due to more required propellant, the fraction of the engine within the propulsion system decreases. Also, with increased hopper mass, both of these fractions decrease.

III.16 OPTIMIZATION OF HOPPER MASS

Using the equations from the previous section, we can now calculate the total spent propellant mass:

\[ m_p = m_H' - (m_T^0 - m_D) - (n + 1) m_D \]

(III-41)

Then, the total initial hopper mass is:

\[ m_H = m_p + m_T + m_E + m_X + m_Y + m_C \]

(III-42)

\( m_C \) is the total mass of the communication, avionics, power, and thermal systems.

Now, \( m_H \) is minimized,

- by varying for all hops: \( T, m_H' \)
- and varying for each hop: \( t_A, t_C, t_D, t_E, t_G \)
- while for all hops, setting equal: \( m_H, m_H' \)
- and for each hop, setting equal: \( s_5, s_5', \) and \( h_2, h_5, h_H \) and \( d_6, d_H \)
The optimization problem presented above will be automatically solved using a software tool.

III.17 DESCRIPTION OF A HOPPER OPTIMIZATION TOOL

The optimization as described above is implemented in a Microsoft Excel workbook called the HOVER HOPTIMIZER. The tool instantly minimizes for the hopper mass as specified above when the required parameters are entered. The output includes the optimized engine thrust and mass as well as the engine burn times for the individual phases of the hops. Also, the mass of several individual landers for an equivalent mission profile can be calculated. Plots with data series can be created automatically, varying one or two of the parameters as specified by the user.

The documentation of the HOVER HOPTIMIZER is provided in the appendix. A copy of the tool is provided electronically with select copies of this thesis.

III.18 DESCRIPTION OF THE HOP ANALYSIS SPACE

The parameters required for performing a hopper optimization with the model presented in this study are: local gravity, specific impulse, number of hops, fixed payload mass, hover height, single hop distance, and payload dropped per site. Therefore, we have a seven-dimensional parameter space that can be analyzed for relationships between the individual parameters. Furthermore, the results can be compared to equivalent lander missions.

In the next chapter, the hop parameter space for lunar hop scenarios will be analyzed in detail, and the results will be applied in example mission planning problems.
IV. LUNAR HOP ANALYSIS

In this section, the seven-dimensional parameter space for the hopper optimization is constrained for a typical lunar hop scenario.

The goal is to find patterns in the lunar hop optimization results, to find a closed-form estimation formula for the optimization results, and to then apply these findings to give system design recommendations for realistic mission scenarios.

Lunar gravity of $1.624 \, \text{m/s}^2$ remains fixed, a specific impulse of 300 s is assumed, and the hover height is constrained to 10 m. This leaves us with four free parameters, i.e. number of hops, fixed payload mass, single hop distance, and payload dropped per site, creating a four-dimensional parameter space for the following analysis.

IV.1 DEPENDENCY ON FIXED PAYLOAD MASS

When varying the fixed payload mass $m_F$, for wide ranges of the other free parameters, we can observe linear relationships between fixed payload mass $m_F$ and hopper mass $m_H$.

Figure IV-1 illustrates this: The four data points are each the result of an optimization of hopper mass for the given set of parameters. A single hop with hop distance 100 m, and a dropped payload mass per site of 200 kg is performed. The fixed payload mass is plotted on the x-axis, the hopper mass is plotted on the y-axis. A linear fit is added to the plot, which gives a relationship of $y=1.2242x+527.67$, i.e. $m_H=1.2242m_F+527.67$. The coefficient of determination $R^2$ for the linear fit is 1.0000.
Similar plots were created for 42 representative combinations of the free parameters. For all plots, a linear fit with $R^2=1.0000$ could be obtained.

### IV.2 SINGLE-HOP EQUIVALENT DISTANCE AND PAYLOAD

To further simplify the parameter space, it is desirable to reduce it to fewer dimensions. When analyzing the optimization results, as will be discussed in the next subsection, it becomes apparent that the number of hops $n$ can be eliminated from the parameter space by defining single-hop equivalents of the payload dropped per site $m_D$, and the single-hop distance $d_{hr}$, respectively.
Given \( n \) and \( m_D \), we define a single-hop equivalent payload mass dropped per site, \( \mu \), as follows:

\[
\mu = m_D \frac{n + 1}{2}
\]  

(IV-1)

For all \( \mu \), the model behaves similarly to a single-hop case with \( m_D = \mu \). For \( n=1 \), \( \mu \) becomes \( m_D \). Figure IV-2 shows the dependency of \( \mu \) on \( n \) and \( m_D \).

![Figure IV-2: Single-hop equivalent dropped payload per site](image)

Given \( n \) and \( d_H \), we define a single-hop equivalent single hop distance, \( \delta \), as follows:

\[
\delta = (n\sqrt{d_H} + n^2 - 1)^2
\]  

(IV-2)
For all $\delta$, the model behaves similarly to a single-hop case with $d_{H}=\delta$. For $n=1$, $\delta$ becomes $d_{H}$. Figure IV-3 shows the dependency of $\delta$ on $n$ and $d_{H}$.

IV.3 EQUIVALENT DISTANCE AND PAYLOAD VARIATION

The 42 plots created with the variations of $m_{F}$ mentioned above are presented in Figure IV-4, a table spread over several pages. In the rows of the plot table, decreasing values of $\mu$ are given, in the columns, increasing values of $\delta$ are given. Series with fixed $\mu$ are designated with letters A through E, series with fixed $\delta$ are designated with numbers 1 through 12. As presented in the plot table, the linear fits for the $m_{F}$ variations increase in their slope value from bottom to top, i.e. with increasing $\mu$, and in their $y$-intercept value from left to right, i.e. with increasing $\delta$. 
Now, when we plot the slope and y-intercept values of the linear fits from the plot table on the horizontal and vertical axes of a secondary plot, respectively, the data points appear in the same horizontal and vertical order as in the plot table. In fact, we can observe linear relationships with good fits for all series, A through E, and 1 through 12. This behavior justifies the previous definitions of μ and δ.

Two differently scaled versions of the secondary plot are shown in Figure IV-5 and Figure IV-6. Linear fits for the letter-designated μ series and for the number-designated δ series, respectively, are shown in these two plots.
In a next step, the obtained slopes and y-intercepts of the secondary plot are plotted on tertiary plots. The plot in Figure IV-7 shows the letter-designated μ series, with their slope given on the horizontal axis and y-intercept given on the vertical axis.
Again, a good linear fit can be obtained for the data points. The closest points from the data points on the line were added to the plot, marked with crosses and with their respective x and y values.

From this, we can obtain an alternative plot with the x and y values of the closest points on the line from the tertiary plot given on the vertical axis, and the values of $\mu$ for the respective series given on the horizontal axis. Linear fits with $R^2=1.0000$ can be made to the x and y value data points, respectively. This is shown in Figure IV-8.

![Figure IV-8: X and Y values of the data points in the secondary letter-series plot](image)

Let us designate the slopes and intercepts of the different plots presented so far by $S_i$ and $l_i$, respectively, with $i=1$ for the primary plots presented in the plot table, and $i=2$ for the secondary plots. This gives us:

$$m_H = S^1 m_F + l^1$$  \hspace{1cm} (IV-3)

$$l^1 = S^2 S^1 + l^2$$  \hspace{1cm} (IV-4)

$$S^2 = 1.2433\mu + 48.893$$  \hspace{1cm} (IV-5)

$$l^2 = 0.9065\mu - 17.425$$  \hspace{1cm} (IV-6)
Now we have a look at the tertiary plot for the letter-designated $\delta$ series, with their slope given on the horizontal axis and $y$-intercept given on the vertical axis. Again, a good linear fit can be obtained for the data points. Figure IV-9 shows this.

![Figure IV-9: Slopes and $y$-intercepts of series 1 through 12](image)

Because one of the data points, the one for series 9, is located far away from the others, and would disproportionately influence the values of the linear fit, we will omit it for the next step. A plot showing the remaining data points and the resulting linear fit is shown in Figure IV-10.
Figure IV-10: Slopes and y-intercepts of numbered series, with linear fit

Figure IV-11: Alternative plot of number-series data points
A further linear relationship can be obtained by plotting the number-designated δ series’ negative intercept-to-slope ratio on the vertical axis and \(1 + \sqrt{\delta}\) on the horizontal axis, as shown in Figure IV-11.

This gives us, for the number-designated δ series:

\[
\begin{align*}
m_H &= S^1 m_f + l^1 \\
l^1 &= S^2 S^1 + l^2 \\
l^2 &= -1.1763 S^2 + 8976.9 \\
\frac{-l^2}{S^2} &= 0.0023(1 + \sqrt{\delta}) + 1.1941
\end{align*}
\]

Solving for \(S^2\) and \(l^2\) gives:

\[
\begin{align*}
S^2 &= 3444.21 + 8.06524(1 + \sqrt{\delta}) \\
l^2 &= 4925.48 - 9.487(1 + \sqrt{\delta})
\end{align*}
\]

We can insert this and the previous solutions for \(S^4\) and \(l^3\) into Formula IV-4, to obtain:

\[
\begin{align*}
l^1 &= \left(3444.21 + 8.06524(1 + \sqrt{\delta})\right) S^1 + (4925.48 - 9.487(1 + \sqrt{\delta})) \\
l^1 &= (1.2433 \mu + 48.893) S^1 + (0.9065 \mu - 17.425)
\end{align*}
\]

Solving for \(S^1\) and \(l^1\) gives us:

\[
S^1 = \frac{8994.325 \sqrt{\delta} - 0.9065 \mu \sqrt{\delta} - 7.922021 \mu + 4669702}{48.893 \sqrt{\delta} + 1.2433 \mu \sqrt{\delta} + 10.86536 \mu + 3903427}
\]

\[
l^1 = (48.893 + 1.2433 \mu) \frac{8994.325 \sqrt{\delta} - 0.9065 \mu \sqrt{\delta} - 7.922021 \mu + 4669702}{48.893 \sqrt{\delta} + 1.2433 \mu \sqrt{\delta} + 10.86536 \mu + 3903427} + 0.9065 \mu - 17.425
\]
Inserting into Formula IV-3 yields:

\[ m_H = \frac{8994.325\sqrt{\delta} - 0.9065\mu\sqrt{\delta} - 7.922021\mu + 4669702}{48.893\sqrt{\delta} + 1.2433\mu\sqrt{\delta} + 10.86536\mu + 3903427}m_F \\
+ (48.893 + 1.2433\mu) \frac{8994.325\sqrt{\delta} - 0.9065\mu\sqrt{\delta} - 7.922021\mu + 4669702}{48.893\sqrt{\delta} + 1.2433\mu\sqrt{\delta} + 10.86536\mu + 3903427} \\
+ 0.9065\mu - 17.425 \]  

(IV-15)

After simplifying the equation, the result for \( m_H \) as a function of \( m_F, \mu, \) and \( \delta \) for the typical lunar hop scenario is:

\[ m_H = \]

\[ \frac{(m_F + 48.893 + 1.2433\mu)(8994.325\sqrt{\delta} - 0.9065\mu\sqrt{\delta} - 7.922021\mu + 4669702)}{48.893\sqrt{\delta} + 1.2433\mu\sqrt{\delta} + 10.86536\mu + 3903427} \]

\[ + 0.9065\mu - 17.425 \]

(IV-16)

Now, we have obtained a formula that allows us to analytically calculate an estimate of minimized hopper mass for a lunar hop scenario from given values of \( n, m_F, d_H, \) and \( m_D. \) In this approach, \( \mu \) and \( \delta \) are calculated from \( m_D \) and \( n, \) and \( d_H \) and \( n, \) respectively, in an initial step.

Figure IV-12 gives a three-dimensional plot showing the relationship between \( \mu, \delta, \) and \( m_H \) for several values of \( m_F. \) This plot gives us a good graphical overview of the lunar hover hop parameter space and the optimized hopper mass for various mission scenarios.
Substituting the definitions for $\mu$ and $\delta$ into the formula above, and simplifying, gives us the following result for $m_H$ as a function of $m_F$, $m_D$, and $n$ for the typical lunar hop scenario:

$$m_H = \left[ m_F + 48.893 + 0.62165m_D(n + 1) \right]$$

$$8994.325 - 0.45325m_D(n + 1) + \frac{4591099}{n\sqrt{d_H} + n^2 + 7.73913} \times$$

$$\frac{48.893 + 0.62165m_D(n + 1) + \frac{3903000}{n\sqrt{d_H} + n^2 + 7.73913}}{n\sqrt{d_H} + n^2 + 7.73913}$$

$$+ 0.45325m_D(n + 1) - 17.425$$

(IV-17)

Figure IV-12: Hopper mass plot created from closed-form formula
Formulas IV-16 and IV-17 are useful tools for quickly assessing the mass of a lunar hopper without having to perform a multi-variable optimization, especially when the input values are within the limits of the analysis space presented in Figure IV-4. A close match between the estimated optimized hopper mass and the actual optimized hopper mass as given by the HOVER HOPTIMIZER tool was confirmed for a range of input values.

**IV.4 COMPARISON OF HOVER HOP RESULTS WITH LANDERS**

An interesting comparison is the one between a single hopper and multiple landers performing an equivalent mission scenario. In the case of landers, we have $n+1$ individual landers to visit all sites, and the total payload per lander is given by $m_F + m_D$. The total mass of the landers $m_s$, with mass of the communication and avionics system $m_c$, structural mass $m_x$, and mass of an individual lander $m_l$ is given by the following equations for the lunar scenario:

\[
\begin{align*}
    m_s &= (n + 1)(m_F + m_D + m_x + m_c) \quad \text{(IV-18)} \\
    m_s &= (n + 1)(m_F + m_D + 0.15m_l + 32.03) \quad \text{(IV-19)}
\end{align*}
\]

Furthermore:

\[
    m_l = m_F + m_D + m_x + m_c \quad \text{(IV-20)}
\]

Solving for $m_s$ yields:

\[
    m_s = (n + 1) \frac{m_F + m_D + 32.03}{0.85} \quad \text{(IV-21)}
\]
The mass of the equivalent landers in terms of the variables used in the analysis above is given by:

\[ m_s = 2.35294\mu + 1.176470588(n + 1)(m_F + 32.03) \]  
(IV-22)

Now, we can set \( m_s = m_H \) to find the boundary between sets of input parameters for which one or the other of the two mission types gives a smaller overall mass landed on the lunar surface.

From this we obtain, after simplifying:

\[
m_F \frac{(48.893 + 1.2433\mu) \frac{8994.325\sqrt{\delta} - 0.9065\mu\sqrt{\delta} - 7.922021\mu + 4669702}{48.893\sqrt{\delta} + 1.2433\mu\sqrt{\delta} + 10.86536\mu + 3903427} - 1.44644\mu - 37.6823529n - 55.1073529}{1.176470588(n + 1) - \frac{8994.325\sqrt{\delta} - 0.9065\mu\sqrt{\delta} - 7.922021\mu + 4669702}{48.893\sqrt{\delta} + 1.2433\mu\sqrt{\delta} + 10.86536\mu + 3903427}}
\]  
(IV-23)

Looking at the surfaces created by this formula, all data sets with lower \( \delta \)-value, and/or higher \( m_F \) value represent cases where the mass of a single hopper is lower than that of a set of individual landers for an equivalent mission.

The plot in Figure IV-13 shows the resulting boundary surfaces, with a logarithmic scale on the vertical axis, and gives an easily understandable graphical overview of the parameter space in the context of a hopper versus landers comparison.
IV.5 APPLYING THE LUNAR HOPPER SIZING MODELS

In this section I will present several example mission scenarios, in order to show how the models derived above can be applied to solve mission planning problems.

I will show how problems can be solved both by using the HOVER HOPTIMIZER tool, and by using the closed-form estimation formulas derived in the previous section.
IV.5.1. EXPLORING THE LUNAR SOUTH POLE REGION

In the first scenario, our mission goal is to explore the region around the lunar South Pole. This region of the moon is of special interest to researchers, as it has locations in permanent sunlight, suitable for continuous solar-powered operations of a spacecraft or lunar base. Also, areas inside craters are never illuminated by sunlight, and therefore remain at frigid temperatures at all times. This enables water to remain frozen and to not evaporate. Such water deposits can then play a vital role in future human presence on the moon. Recently, the LCROSS mission has discovered deposits of water near the lunar South Pole. In a next step, a robotic rocket hopper could be used for exploring the region, and for finding well-suited locations for future human settlements.

Let us assume a hopper with a fixed payload package of 50 kg. Also, we want to drop small 5 kg instrument packages at each site visited. The individual sites will be separated by 10 km. Let us further assume that the choice of a launcher, including lunar transfer and landing stages is predetermined, with the capability of landing up to 800 kg on the lunar surface. This is similar to the mass of the Lunokhod rovers. Also, we can either use a single hopper or individual landers to meet the mission requirements.

Our goal is to determine the maximum number of sites that we can visit around the lunar South Pole. We will use the HOVER HOPTIMIZER tool with its hopper versus lander function and vary the number of hops from 1 to 9. With lunar gravity, an assumed hover height of 10 m, and specific impulse 300 s, the fixed hop parameters are: \( g = 1.624 \text{ m/s}^2 \), \( I_s = 300 \text{ s} \), \( m_f = 50 \text{ kg} \), \( h_H = 10 \text{ m} \), \( d_H = 10000 \text{ m} \), and \( m_D = 5 \text{ kg} \). The resulting plot generated by the software is shown in Figure IV-14.
Figure IV-14: Hopper versus landers analysis for lunar South Pole mission scenario

According to our launcher limits, we can only consider cases below the 800 kg line for the mass landed on the surface. We can easily see that individual landers could visit up to 7 sites, while a hopper could visit up to 9 sites (with 8 hops). Hence, we will choose a hopper for our further mission design, and we will assume 8 hops of 10 km each. Entering this scenario into HOVER HOPTIMIZER gives us the outputs shown in Figure IV-15 and Figure IV-16.
Figure IV-15: Optimized hopper mass for lunar South Pole mission

<table>
<thead>
<tr>
<th>hop number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>engine thrust (all hops) [N]</td>
<td>$T = 1526$</td>
<td>[\text{ascent burn time} [s] ] $t_A$</td>
<td>4.89</td>
<td>3.726</td>
<td>2.972</td>
<td>2.429</td>
<td>2.015</td>
<td>1.686</td>
</tr>
<tr>
<td></td>
<td>[\text{horiz. accel. time} [s] ] $t_B$</td>
<td>56.28</td>
<td>44.6</td>
<td>36.34</td>
<td>30.01</td>
<td>24.93</td>
<td>20.72</td>
<td>17.19</td>
</tr>
<tr>
<td></td>
<td>[\text{horizontal coast time} [s] ] $t_c$</td>
<td>50.29</td>
<td>59.35</td>
<td>66.38</td>
<td>72.08</td>
<td>76.99</td>
<td>81.38</td>
<td>85.22</td>
</tr>
<tr>
<td></td>
<td>[\text{horiz. decel. time} [s] ] $t_D$</td>
<td>48.72</td>
<td>39.38</td>
<td>32.41</td>
<td>26.9</td>
<td>22.4</td>
<td>18.63</td>
<td>15.45</td>
</tr>
<tr>
<td></td>
<td>[\text{descent burn time} [s] ] $t_E$</td>
<td>3.805</td>
<td>3.031</td>
<td>2.477</td>
<td>2.055</td>
<td>1.722</td>
<td>1.452</td>
<td>1.229</td>
</tr>
</tbody>
</table>

Figure IV-16: Optimized hopper mission parameters for lunar South Pole mission

Now, we already have an initial rough design for our hopper and its mission profile. The resulting values for $t_A$ through $t_E$ for the 8 hops can be used to program the engine ignition and shut-off times during each of the hops. The engine thrust value can be used to design an appropriate engine. The masses of the hopper’s subsystems and its overall mass can help when making considerations for the vehicle configuration.
Figure IV-17 shows a satellite map of the lunar South Pole region with a sample hop path for our 8-hop scenario. The hopper could start by exploring the interior and then the rim of De Gerlache crater, followed by a traverse to the South Pole and an exploration of the interior and rim of Shackleton crater. Finally, the hopper can traverse to a permanently sunlit location on the rim of Shackleton crater, where it can remain operational for an extended time using photovoltaic power.

The hopper’s payload package can not only explore the landing sites in detail, but also make observations of the lunar surface during traverses. The total distance covered during the mission will be 80 km, which compares favorably with the maximum of 37 km achieved in the past by the Lunokhod rovers with a similar vehicle mass. Furthermore, exploring a cratered region like the one around the South Pole would be extremely challenging for a rover.
IV.5.2. SUPPORTING HUMAN SURFACE OPERATIONS

In this scenario, let us assume that a permanently inhabited base has been established on the moon. The construction of a large telescope is planned, and a favorable site for the telescope is located 50 km away from the base. In order to regularly service the telescope, a hopper is to be designed that can fly astronauts from the base to the telescope and back and provide a habitat module to support the astronauts for a limited time. Using a rover is considered too difficult, due to the rough terrain along the traverse. The mass of the habitat module, the sole payload of the hopper, is estimated to be 10,000 kg.

![Image: Artist's concept of a lunar base](image)

Figure IV-18: Artist's concept of a lunar base

With a hover height of 10 m, and number of hops 2 for one return trip, I obtained the following results in HOVER HOPTIMIZER: The mass of the hopper without propellant will be 14,063 kg. The propellant mass per round trip is 9,631 kg, such that the total mass is 23,694 kg.

Now let us use this result to verify the simplified formulas derived earlier. When substituting the parameters of this scenario into formula IV-17, we obtain a hopper mass of 22,303 kg. This differs by 5.9% from the HOVER HOPTIMIZER result. The discrepancy can be
either due to a suboptimal solution of the HOVER HOPTIMIZER, or due to an inaccuracy of the simplified formula. Still, with this small deviation, the formula serves as a valid tool to quickly generate estimates for an optimized hopper mass.

Going back to the detailed results of the optimization, we can determine that a 74 kN engine, with a mass of 176 kg will be optimal. Each leg of the round trip will take approximately 5 minutes, with the return trip taking slightly less time due to the decreased mass of the vehicle after propellant expenditure during the first leg. With this traverse time, a quick response to malfunctions in the telescope will be possible.

This example shows that the hopper model developed here can also be applied to cases that it was not initially designed for. The results are likely not as accurate as for small robotic hoppers, which were the basis for the included subsystem models. However, the fundamental equations of the hover hop and the propulsion system still apply for large hoppers.

IV.5.3. DEPLOYING A LARGE SENSOR NETWORK

In the next scenario, a network of sensor packages is to be deployed across the entire surface of the moon. Let us assume 20 sensors, spaced equidistantly, such that the sensor sites are at the vertices of a dodecahedron. This configuration is shown in Figure IV-19.

Figure IV-19: Dodecahedral configuration of lunar sensor network

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According to spherical geometry, the length of the arc on the lunar surface between two adjacent sites is then 1.214 times the lunar radius of 1737 km, or 2109 km. Therefore, 19 hops of 2109 km are required to deploy the sensor network. Let us further assume a mass of 10 kg per sensor package with no further payloads, a hover height of 10 m, and a specific impulse of 300 s. With lunar gravity, the inputs to the model are: \( g = 1.624 \text{ m/s}^2 \), \( I_p = 300 \text{ s} \), \( n = 19 \), \( m_F = 0 \text{ kg} \), \( h_H = 10 \text{ m} \), \( d_H = 2109000 \text{ m} \), and \( m_D = 10 \text{ kg} \).

Now, instead of using HOVER HOPTIMIZER, we will use formula IV-17, which yields \( m_H = 5095 \text{ kg} \). The resulting hopper mass is a large number for such a mission. However, we can easily compare this with an equivalent mission of 20 landers. Formula IV-21 gives us a landed mass of 989 kg for these. Therefore, for this scenario, the hopper option can be disregarded quickly.

This example shows that hoppers are not a good choice for missions with destinations far apart on the surface of a planetary body. In these cases, the propellant required to traverse from one site to the next outweighs the mass savings of a single hopping vehicle compared with multiple individual landers.
V. LIMITATIONS, FUTURE WORK, AND CONCLUSIONS

V.1 LIMITATIONS AND FUTURE WORK

The hover hop model and optimization tool presented in this thesis are valuable tools for analyzing the performance of hover hops for planetary surface exploration for a wide range of mission scenarios. However, the model still has some shortcomings that limit its applicability. The current analysis is focused on lunar mission profiles. While the hover hop model is applicable to any gravitational environment, it does not include atmospheric effects that may become important on bodies with atmospheres. Also, surface conditions, important for take-off and landing are not currently modeled. Future work should address these issues by adding atmospheric models for all relevant bodies of our solar system. Also, surface effects should be studied and added to the model if necessary.

The degree of detail in the subsystem models is very low, and several subsystems of a realistic hopping vehicle are not included in the model. Furthermore, the power and communications subsystem model is based on a lunar scenario. Future work could significantly enhance the fidelity of the overall model by increasing the detail and flexibility in the subsystem models. Also, systems for the initial planetary landing should be included, and should be adaptable to various target bodies.

The hopping model itself is also not optimal. It contains discontinuities in engine canting angles, which should be addressed in future work. Also, the optimality of the hover hop model has not been proven, and should be addressed.
V.2 CONCLUSION

The utilization of rocket hoppers can provide a valuable means of providing enhanced mobility for planetary surface exploration missions. Hoppers can provide higher exploration versatility than landers, rovers, or other surface exploration systems through their ability to quickly traverse difficult terrain in a variety of planetary environments. Furthermore, using a hover hop rather than a ballistic hop can provide many operational advantages. For missions with widely separated target sites however, the utilization of multiple individual landers becomes more beneficial than that of a single hopper.

With the hover hop model, optimization tool, and approximation formulas presented in this thesis, it becomes possible to quickly obtain optimized values for the vehicle mass and other mission parameters for a specified hopper mission. With a limited set of parameters, defined early in the design of a given planetary exploration mission, it becomes possible to obtain an initial characterization of a mission. Thus, fundamental system architecture decisions on whether to use a hopper vehicle can be based on optimized results early in a mission design process.

Finally, the results obtained from the application of the lunar hover hop model to realistic mission scenarios demonstrate the utility of hoppers for tasks highly relevant to future robotic and human exploration of the Moon.
I have developed a hopper mass optimization tool, called HOVER HOPTIMIZER, which is implemented as a Microsoft Excel 2007 macro-enabled workbook. The latest version that accompanies select copies of this thesis is 8.0. The file name of the workbook is “HOVERHOP8.0.xlsm”. This documentation is meant to serve as a user guide, and will also provide an overview of how the different functions are implemented.

A.1 SYSTEM REQUIREMENTS

Using HOVER HOPTIMIZER requires an installation of Microsoft Excel 2007 for Windows, or fully compatible programs. Furthermore, the tool makes use of Microsoft Visual Basic and the Excel Solver. Both need to be installed on the system, but are included in typical installations of Excel.

The Excel Solver is a third-party product bundled with Excel, developed by Frontline Systems. Further information can be obtained from Frontline System’s website www.solver.com. If a higher performance optimization is required, more advanced versions of the solver can be purchased from Frontline Systems.

A.2 STARTING THE PROGRAM

It is important to note that the Excel workbook is editable by the user, and is also being edited automatically when running optimizations. Therefore, it is possible that the file becomes damaged when using it. In order to ensure continuous usability of the tool, it is strongly recommended to keep the original file unchanged, and to work with copies of this file. Whenever changes are made to the workbook, such as generating data plots, it is recommended to save the workbook in a new file that remains unchanged subsequently.
After opening the HOVERHOP8.0 file, it is necessary to enable the execution of macros. When Excel displays a security warning “Macros have been disabled” above the spreadsheet area, the user has to click the “Options...” button next to the message and select “Enable this content” in the Security Alert dialog box displayed thereafter.

![Image of Security Alert dialog box](image)

**Figure A-1: Enabling the execution of macros**

### A.3 PROGRAM OVERVIEW

After opening the workbook, initially the “Sheet1” worksheet will be displayed. This is where the user interface of the program is located. The worksheet can be selected with the “Sheet1” tab on the bottom of the screen. Figure A-2 shows the different fields that can be identified on the screen.
The “Sheet1” worksheet area contains the optimization inputs, the minimized mass outputs and mode selection, the plot generator inputs, the solver option, the hop optimization outputs, and some additional information.

Above the worksheet area, the content of the selected cell is displayed. It can only be edited if the cell is not protected. By default, many cells, not including input cells, are set to be protected, i.e. not editable. The workbook can be unprotected and re-protected in the review tab on the top of the screen if the user wants to edit workbook contents.

For viewing or editing the Visual Basic code of the workbook, the user has to select the developer tab on the top of the screen and open Microsoft Visual Basic by clicking the “Visual Basic” button.
On the bottom of the screen, the user can access the different worksheets by clicking on the respective tabs. The worksheets following “Sheet1” contain the subsystem models. New plots and their data are added as additional worksheets.

The status bar in the bottom left corner of the screen displays the current status of the program.

A.4 RUNNING AN OPTIMIZATION

HOVER HOPTIMIZER can find an optimized hop profile for one or more sequential hops, minimizing the mass of a hopper that needs to be landed on a planetary surface. In order to obtain such an optimized hop profile, the user has to enter the required input variables. There are seven input cells in the optimization inputs box. These can be seen in figure A-3.

After selecting an input cell, entering a value and hitting the Enter key, an optimization is executed, and the results are immediately displayed in the worksheet area of “Sheet1”. Optimizations for large values of the number of hops can take some time. Therefore, it is recommended to set the number of hops to 1 and change the number of hops field last, in order to avoid long recalculation times.

The maximum value that is supported for the number of hops is 33 when using the standard Excel Solver. This corresponds to almost 200 simultaneously optimized variables. More advanced versions of the Solver support higher values.

The reset button inside the inputs box resets the worksheet to a default set of values.

Figure A-3: Optimization inputs box
When an optimization is running, the Excel worksheet area is typically flickering, or a “Trial Solution” message is displayed in the status bar. While an optimization is running, the user shall not interact with the program, as this could result in errors or data loss. If during an individual optimization, the maximum calculation time or number of iterations as defined in the solver options is exceeded, an error message will be displayed, shown in figure A-4, where the user can choose to stop or continue with the optimization. It is not recommended to stop an optimization, as data loss can occur.

![Show Trial Solution](image)

**Figure A-4: Error message for exceeded iteration limit**

After an optimization, the minimized hopper mass, and the subsystem masses are shown in the mass outputs box. In addition, the bottom row of the output box displays the corresponding mass in lunar orbit, required for landing the hopper on the lunar surface. This mass only includes additional descent propellant, and does not include any additional required components.

![Mass outputs box](image)

**Figure A-5: Mass outputs box**
A detailed overview of the optimized hop profile can be seen in the outputs box on the right hand side of the worksheet area, as shown in figure A-6.

<table>
<thead>
<tr>
<th>hop number</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>engine thrust (all hops) [N]</td>
<td>&amp; T = 199</td>
<td></td>
<td></td>
</tr>
<tr>
<td>engine can angle (deg) a</td>
<td>&amp; a = 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>horizontal distance [m] d</td>
<td>&amp; d = 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>horizontal speed (m/s) s</td>
<td>&amp; s = 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vertical velocity [m/s] v</td>
<td>&amp; v = 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mass [kg] m</td>
<td>&amp; m = 86.91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>height [m] h</td>
<td>&amp; h = 78.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>horizontal coast time [s] t</td>
<td>&amp; t = 70.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vertical thrust (all hops) T_a</td>
<td>&amp; T_a = 199</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ascent burn time [s] t_a</td>
<td>&amp; t_a = 4.615</td>
<td></td>
<td></td>
</tr>
<tr>
<td>horizontal acceler. time [s] t_b</td>
<td>&amp; t_b = 3.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>horizontal burn time [s] t_f</td>
<td>&amp; t_f = 3.067</td>
<td></td>
<td></td>
</tr>
<tr>
<td>horizontal distance [m] d</td>
<td>&amp; d = 0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>horizontal speed (m/s) s</td>
<td>&amp; s = 0.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The optimized output values are colored in blue and shown on the top. These are the engine thrust and the engine burn times $t_a$ through $t_f$. The fitted model outputs, i.e. where model input values are varied in order to obtain a fit between the model output value and the desired user input value, are colored in red. These are shown on the bottom and are hover height and hop distance, individually fitted for each individual hop. As an artifact of the model setup, the hover height, as well as the horizontal speed $s_5$ occur twice per hop, and have to be fitted against each other. The minimized initial hopper mass is shown in pink. This value is both optimized and fitted.
The data columns on the right contain various hopper state parameters at the points in time between the seven hop phases. The columns are labeled with the number of the respective hop in a multi-hop profile. Only the values required for the worksheet calculations are shown. For the first hop, additional state parameters are shown in grey on the left of the outputs box.

After a successful optimization, the blue-colored optimized input values from the outputs box and the optimized mass values from the mass outputs box represent the result of the optimization. These values can then subsequently be used for a hopper and hopper mission profile design.

A.5 HOPPER MODE AND LANDER MODE

In addition to finding an optimized hop profile in the default “hopper mode”, the HOVER HOPTIMIZER tool can also be used in a “lander mode” to find an optimized combined mass of a set of individual landers that perform an equivalent mission profile. With n hops for a hopper mission, we have (n+1) landers to visit all sites, and the total payload per lander is given by \( m_F + m_D \).

Two buttons are located in the mass output box to switch between hopper and lander mode. Figure A-7 shows the mass output box in the lander mode. The output box on the right hand side of the worksheet area is to be disregarded when in the lander mode.

![Figure A-7: Mass output box in lander mode](image)
A.6 SOLVER OPTIONS AND OPTIMIZATION STRATEGIES

In the solver options box, the user can specify the parameters used by the Excel Solver when performing an optimization. Maximum calculation time and maximum iterations specify how long the Excel Solver will search for a solution before generating an error message. The precision for optimization specifies the step size of the optimization, and the convergence for solution specifies how closely an output value has to match a specified target value. The reset button reverts the solver options to a default set of values.

![Solver Options Table]

Figure A-8: Solver options

It is not always easy to obtain a solution for a hop optimization problem. When an inappropriate set of input values is chosen, it is possible to not obtain results, or to obtain erroneous results.

Since no error messages are created in these cases, it is important that the user checks for errors before using the generated data. Figures A-9 and A-10 show the output boxes after an optimization error. Clear signs for calculation errors are cells with “#NUM!”, with negative time or mass values, or with fitted outputs that do not match their target values. In such a case, any results should be disregarded. It is recommended to click the input reset button after an error, as this ensures that the worksheet reverts to a condition that is known to work correctly.
Table A-1: Mass outputs after an optimization error

<table>
<thead>
<tr>
<th>hop number</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>engine thrust (all hops) [N]</td>
<td>4600</td>
<td>4600</td>
<td>4600</td>
</tr>
<tr>
<td>height [m]</td>
<td>4063</td>
<td>4063</td>
<td>4063</td>
</tr>
<tr>
<td>horizontal distance [m]</td>
<td>2418</td>
<td>19.61</td>
<td>2418</td>
</tr>
<tr>
<td>horizontal speed [m/s]</td>
<td>5.27</td>
<td>5.27</td>
<td>5.27</td>
</tr>
<tr>
<td>time [s]</td>
<td>22.5</td>
<td>40.29</td>
<td>22.5</td>
</tr>
<tr>
<td>mass [kg]</td>
<td>91.9</td>
<td>91.9</td>
<td>91.9</td>
</tr>
<tr>
<td>height [m]</td>
<td>4063</td>
<td>4063</td>
<td>4063</td>
</tr>
<tr>
<td>upward velocity [m/s]</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>engine cant angle [deg]</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>engine cant angle [deg]</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>engine cant angle [deg]</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>engine cant angle [deg]</td>
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<td>0</td>
</tr>
<tr>
<td>engine cant angle [deg]</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>horizontal distance [m]</td>
<td>2418</td>
<td>19.61</td>
<td>2418</td>
</tr>
<tr>
<td>horizontal speed [m/s]</td>
<td>5.27</td>
<td>5.27</td>
<td>5.27</td>
</tr>
<tr>
<td>time [s]</td>
<td>22.5</td>
<td>40.29</td>
<td>22.5</td>
</tr>
<tr>
<td>mass [kg]</td>
<td>91.9</td>
<td>91.9</td>
<td>91.9</td>
</tr>
</tbody>
</table>

Figure A-10: Outputs after an optimization error
In order to avoid optimization errors, the user should try to approach the desired input values in small steps. After each change in an input value, the user should check for data errors in the outputs. The step size to be chosen for approaching the target set of values varies with each set of parameters. It can require some trial and error to determine the best way of approaching the target input values. Some optimization problems may be very difficult to solve, and some may even be impossible to solve. Especially problems with a large number of hops are hard, since many variables have to be optimized simultaneously.

Furthermore, it is possible that no data errors occur but the optimization result is not optimal. It is advisable to vary the input parameters around the target values and approach the target inputs in different ways. If the user observes that the optimization results vary, the result with the lowest hopper mass should be taken as the optimized output.

Furthermore, such cases can be identified when after analyzing the results of a series of optimizations, an outlying value is detected. A repeated optimization with a different approach to the input values may then generate a better result.

A.7 GENERATING PLOTS AND DATA SERIES

In addition to optimizing individual hopping scenarios, HOVER HOPTIMIZER can also generate series of optimization results and make plots of these. The plot generator box serves as the user interface for the generation of plots and data series. It is shown in figure A-11.

Figure A-11: Plot generator inputs box
In order to generate a plot, the user has to enter a name for the plot in the “name” cell. This name cannot be one that was used for a worksheet or plot before, or otherwise the plot function will not work.

In the “style” field, the user can select whether the data series will be plotted with a marker for each data point, with lines connecting the data points of a series, or with both.

In the “x axis values” field, there is a column of round selection buttons, which each correspond to the input variable in the same row, to the left of the plot generator box. By selecting one variable, and defining a start value, step size, and number of steps in the “x axis values” field, the selected variable will be automatically varied accordingly, with an optimization being performed for each value of the variable. The value entered in the inputs box for this variable will be disregarded, but the remaining input variables will be used. For each optimization of the series, the hopper mass will be recorded, and plotted on the vertical axis of a generated plot. The varied variable will be plotted on the horizontal axis.

The plot function enables the user to quickly find the minimized hopper masses for a number of scenarios. The hopper mass is the only result recorded for each performed optimization. Thus, the user has to manually re-optimize a given scenario if other optimization results are needed.

It is also possible to vary two variables. In this case, a data series as in the single variable variation case will be generated for each value of the second variable. All data series will be added to one resulting plot. The specification of the variation of the second variable is done analogously to the specification of the first variable, but inside the “data series” field of the plot generator box. In addition to the selection buttons for the input variables, there are the additional buttons “none” and “hopper vs. landers”. Selecting “none” corresponds to only varying one variable. “Hopper vs. landers” will generate two data series, one for a hopper case, and one for an equivalent lander case.

In addition to specifying a variable variation with fixed step size, it is also possible to enter an arbitrary sequence for the varied variable(s). To do this, the “explicit” checkbox has to be selected, as shown in figure A-12 for the “x axis values” variable. Now, the input field of the selected variable becomes pink, and a series of values can be entered, with the individual values separated by spaces.
After specifying all parameters, clicking the “Plot!” button initiates the optimization series and plot generation. Before clicking the button, the user should verify that not too many optimizations have to be performed, as that can take a long time. Normally, no user interaction is required when running a plot optimization sequence, but calculation time and iteration limit error messages can be displayed as mentioned above, which require user attention. Therefore, it is important to check that adequate solver options have been chosen.

As with individual optimizations, the user should watch out for data errors. These can be identified as described above, when viewing the “Sheet1” worksheet. In order to avoid data errors, appropriate step sizes and start values should be chosen. In some cases it might be helpful to manually approach the start value(s) in steps through data entry in the inputs box, before making a plot.

For each plot, two sheets will be added to the workbook, one containing the plot of the data, with the name specified in the plot generator box, and one containing the data, with its name being the corresponding plot name appended with “-data”. The resulting sheets can then be edited and utilized for further analyses. Sample plots and data sheets are shown in figures A-14 through A-16, with the first two corresponding to a hopper versus lander analysis, and the last two corresponding to a multi-series analysis.
Figure A-13: Hopper versus equivalent landers data

<table>
<thead>
<tr>
<th></th>
<th>g</th>
<th>lsp</th>
<th>n</th>
<th>mf</th>
<th>hH</th>
<th>dH</th>
<th>mD</th>
<th><em>mS</em></th>
<th>g</th>
<th>lsp</th>
<th>n</th>
<th>mf</th>
<th>hH</th>
<th>dH</th>
<th>mD</th>
<th><em>mS</em></th>
</tr>
</thead>
<tbody>
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<td>10</td>
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<td>0</td>
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<td>100</td>
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<td>10</td>
<td>10</td>
<td>200</td>
<td>0</td>
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<td>1.624</td>
<td>300</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>200</td>
<td>0</td>
<td>197.81</td>
</tr>
<tr>
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<td>1.624</td>
<td>300</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>300</td>
<td>0</td>
<td>60.111</td>
<td>1.624</td>
<td>300</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>300</td>
<td>0</td>
<td>197.81</td>
</tr>
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<td>4</td>
<td>1.624</td>
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<td>3</td>
<td>10</td>
<td>10</td>
<td>400</td>
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<td>60.905</td>
<td>1.624</td>
<td>300</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>400</td>
<td>0</td>
<td>197.81</td>
</tr>
<tr>
<td>5</td>
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<td>3</td>
<td>10</td>
<td>10</td>
<td>500</td>
<td>0</td>
<td>61.703</td>
<td>1.624</td>
<td>300</td>
<td>3</td>
<td>10</td>
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<td>500</td>
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</tr>
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<td>6</td>
<td>1.624</td>
<td>300</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>600</td>
<td>0</td>
<td>62.431</td>
<td>1.624</td>
<td>300</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>600</td>
<td>0</td>
<td>197.81</td>
</tr>
<tr>
<td>7</td>
<td>1.624</td>
<td>300</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>700</td>
<td>0</td>
<td>63.106</td>
<td>1.624</td>
<td>300</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>700</td>
<td>0</td>
<td>197.81</td>
</tr>
<tr>
<td>8</td>
<td>1.624</td>
<td>300</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>800</td>
<td>0</td>
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<td>300</td>
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<td>10</td>
<td>10</td>
<td>800</td>
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</tr>
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<td>9</td>
<td>1.624</td>
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<td>3</td>
<td>10</td>
<td>10</td>
<td>900</td>
<td>0</td>
<td>64.342</td>
<td>1.624</td>
<td>300</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>900</td>
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<td>10</td>
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<td>10</td>
<td>10</td>
<td>1000</td>
<td>0</td>
<td>64.915</td>
<td>1.624</td>
<td>300</td>
<td>3</td>
<td>10</td>
<td>10</td>
<td>1000</td>
<td>0</td>
<td>197.81</td>
</tr>
</tbody>
</table>

local gravity [m/s²] = 1.624  specific impulse [s] = 300  number of hops = 3
fixed payload mass [kg] = 10  hover height [m] = 10  payload dropped per site [kg] = 0

Figure A-14: Hopper versus equivalent landers plot
Figure A-15: Data of multiple data series (only first four series shown)

\[
\text{local gravity \([m/s^2]\) = 1.624 \quad \text{specific impulse \([s]\) = 300 \quad \text{number of hops} = 2 \quad \text{hover height \([m]\) = 10}
\]
\]

payload dropped per site \([kg]\) = 0

Figure A-16: Plot of multiple data series
A.8 SUBSYSTEM MODELS

The worksheets “Engine”, “Tank”, “Structures”, and “Landing” each contain a simple model for the respective subsystem. Figure A-17 shows these models. Engine mass is a function of the optimized engine thrust, tank mass is a function of the optimized propellant mass, and structures mass and mass in orbit are functions of the overall hopper mass. Mass in orbit is only applicable to a lunar orbit scenario.

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
<th>Formula/Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link Range</td>
<td>S</td>
<td>250,000 km</td>
<td></td>
<td>Moon’s Distance from Earth</td>
</tr>
<tr>
<td>Antenna Diameter</td>
<td>D</td>
<td>1 m</td>
<td></td>
<td>Given in Requirements</td>
</tr>
<tr>
<td>Frequency</td>
<td>f</td>
<td>8 GHz</td>
<td></td>
<td>Guess based on historical precedent</td>
</tr>
<tr>
<td>Bus Power</td>
<td>Pb</td>
<td>300 Watts</td>
<td></td>
<td>Assumed to be 0 but in the model anyway</td>
</tr>
<tr>
<td>Distance from Sun</td>
<td>AU</td>
<td>1.00 AU</td>
<td></td>
<td>Dependent on Destination</td>
</tr>
<tr>
<td>Required Data Rate</td>
<td>R</td>
<td>50 kbps</td>
<td></td>
<td>Given in Requirements</td>
</tr>
<tr>
<td>Radiator Area</td>
<td>Ar</td>
<td>0 m²</td>
<td></td>
<td>Given in Requirements</td>
</tr>
<tr>
<td>Eclipse Power Fraction</td>
<td>Fe</td>
<td>0.15</td>
<td></td>
<td>Emergency Situation Only</td>
</tr>
<tr>
<td>Eclipse Time</td>
<td>Te</td>
<td>3 hr</td>
<td></td>
<td>Emergency Situation Only</td>
</tr>
<tr>
<td>Gain</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td>λ</td>
<td>0.0377 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parabolic Antenna Gain</td>
<td>Gt</td>
<td>564.70212</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Path Loss</td>
<td>Ls</td>
<td>1.42483E-22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batteries</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery Capacity</td>
<td>Cb</td>
<td>500 Wh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission Power</td>
<td>Pt</td>
<td>36.04 Watts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Power</td>
<td>PT</td>
<td>329.04 Watts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Irradiance</td>
<td>W</td>
<td>1355.388069 Watts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Panel Area</td>
<td>A</td>
<td>0.881900039 m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communications Mass</td>
<td>Mc</td>
<td>19.36 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Panel Mass</td>
<td>Ms</td>
<td>3.43 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery Mass</td>
<td>Mb</td>
<td>8.33 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Mass</td>
<td>M</td>
<td>32.03 kg</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This worksheet was created by Ben Corbin.
The worksheet "Power&Comm", shown in figure A-18, contains a detailed model for the hopper's power and communication model. It only applies to a lunar scenario, and has been created by Benjamin Corbin.

The worksheet "Hover Hop" shows pseudo-code for the hop model contained in "Sheet1" and how the Excel Solver performs the hop optimization. This worksheet is not functional and only serves as a visualization of cell entries and Visual Basic code, which are otherwise hidden and difficult to understand. Figure A-19 shows the worksheet content.

```plaintext
inputs: g, h, n, r, mF, NH, dH, mD
vE=9.807-isp
mT[@]=mI
hT[@]=0

"x@y" means "x as evaluated at hop y"
for hop=1..n
  a=1
  b=3
  c=5
  t=T
  m=mT(hop=1-mD
  h=hT(hop=1)
  mI=m0(T/VE)TA
  vI=vE*(1-T*4(A/I(E*m0)) g*(TA*2)/2
  x2=vE*(1-T*4(A/I(E*m0)) g*TA
  mI=3*T(2-mA)/VE
  h2=H+3*V*2/BEG
  d2=vE*(1-T*4(A/I(E*m0)) g*(TA*2)/2
  mI=3*(T(2-A))/VE
  t2=A+1/2
  A1=sort(L[-(m2*m2)+/2)
  m=mI+(T(VE)+B
  B=acos(cos(m2/g7))
  d2=x2=cos(m2)*sin(m2)+sin(m2)*cos(m2)
  t2=2+1
  m4=m2*m2+t*2+CE
  d4=x4=2*CE
  s4=s
  t4=x4+C
  A2=sort(L[-(m4*m4)+/2)
  mI=m2+(T+T)/VE
  B=acos(cos(m4/g7))
  d5=x5=cos(m4)*sin(m4)+sin(m4)*cos(m4)
  t5=t4+D
  m6=m2+(T+T)/VE
  h=0
  h=2
  d6=d5
  d6=x5+sin(m4)+(T+T)/VE
  m6=m2+T+T/VE
  m6=m6+T+T/VE
  m6=m6+m6+CE

-- to minimize m6 by varying (for all hops) (T,m6), for each hop (TA,T1,T2,T3,T4,T5), while for all hops (m6=m6), for each hop (s5=s5, h2=nhl, h5=nhl, d6=nhl)

Figure A-19: Pseudo-code of the hover hop model
```
A.9 VISUAL BASIC CODE

In addition to the information contained in the worksheets, HOVER HOPTIMIZER also accesses Visual Basic code. In this section I will provide further information about this part of the software. However, during normal use it is not necessary to view the code.

In order to view and edit the code, the user has to open Microsoft Visual Basic by selecting the developer tab on the top of the screen and then clicking the “Visual Basic” button. On the left of the Visual Basic window is the Project Explorer, which can also be opened via the “View” menu, if not visible. Here, the individual sections of code contained in the project appear. The only items containing code for HOVER HOPTIMIZER are “ThisWorkbook” and “Sheet1” in the folder “Microsoft Excel Objects”, and “Module2” in the folder “Modules”, all contained in “VBAProject (HOVERHOP8.0.xlsm)”. Figure A-20 shows the Visual Basic screen with the Project Explorer and the three relevant pieces of code.

![Visual Basic Code](image)

Figure A-20: Overview of the Visual Basic code.

The “ThisWorkbook” code checks whether the Excel Solver is installed when opening the workbook. If it is not installed, it installs it or creates an error message. I have adopted
this code from Peltier Technical Services, Inc. I have slightly edited the code for recognition of the latest Microsoft Excel file extension, and for a new error message.

The “Sheet1” code enables the execution of an optimization immediately after changing an input cell, and without moving the selection to another cell. For cells containing explicit input, immediate optimization is disabled.

All other functions are contained in the “Module2” code. Figure A-21 shows a list of the functions in “Module2”.

<table>
<thead>
<tr>
<th>Members of Module2</th>
</tr>
</thead>
<tbody>
<tr>
<td>beginS</td>
</tr>
<tr>
<td>dataEntry</td>
</tr>
<tr>
<td>endS</td>
</tr>
<tr>
<td>hoppermode</td>
</tr>
<tr>
<td>hopsolve2</td>
</tr>
<tr>
<td>initExplicit</td>
</tr>
<tr>
<td>landermode</td>
</tr>
<tr>
<td>landersolve</td>
</tr>
<tr>
<td>makeChart</td>
</tr>
<tr>
<td>makeData</td>
</tr>
<tr>
<td>plot1</td>
</tr>
<tr>
<td>readExplicit</td>
</tr>
<tr>
<td>reset1</td>
</tr>
<tr>
<td>restoreExplicit</td>
</tr>
<tr>
<td>setUpDataSheet</td>
</tr>
<tr>
<td>solverOptionsReset</td>
</tr>
</tbody>
</table>

Figure A-21: Functions of the Module2 code

I will now briefly summarize the tasks performed by the functions of “Module2”:  

- “beginS” and “endS” unprotect and re-protect the worksheet “Sheet1” whenever the program needs to edit cell contents of protected cells.

- “dataEntry” prepares “Sheet1” for an optimization when data is entered. Hopper or lander mode is detected, and if necessary, additional columns are added for multi-hop scenarios.
• “hopsolve2" and “landersolve" reset and run the Excel Solver with the user specified values and solver options when in hopper or lander mode, respectively.

• “hoppermode” and “landermode” change “Sheet1” to the hopper mode or lander mode view, respectively.

• “reset1” resets “Sheet1” to a default set of values when the input reset button is clicked. “solverOptionsReset” resets the solver options when the solver options reset button is clicked.

• “initExplicit”, “readExplicit”, and “restoreExplicit” enable the activation, use, and deactivation of the explicit input feature, respectively.

• “setUpDataSheet” prepares a new worksheet for a newly generated data series. “makeData” then generates the data by varying the input values on “Sheet1” according to the user specifications.

• “plot1” and “makeChart” create a data plot from a given data sheet, including added labels and formatting.

A.10 LIMITATIONS AND FUTURE WORK

While the HOVER HOPTIMIZER in its current version has proven an invaluable tool to perform series of hover hop optimizations, it is still limited in many ways. For instance, the subsystem models for power and communication, as well as landing are limited to the lunar case. For analyzing hopping scenarios on other planetary bodies, these have to be manually modified. Also, detecting data errors, and creating results without errors is not automated, and thus requires much user attention. Additionally, the tool is not very robust in the case of
interrupted optimizations. Finally, the underlying hover hop model is not optimal. Most notably, it contains discontinuities in the engine cant angle between hop phases.

Future work on the HOVER HOPTIMIZER should address these issues, and could also implement new features, such as picked-up payload mass, unequal individual hop distances, and higher fidelity models for power, communication, engine, tanks, structures, and landing module.
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1 Image source: http://www.mentallandscape.com/C_Venera_Perspective.jpg


3 Data sources:
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   http://en.wikipedia.org/wiki/Apollo_16
   http://en.wikipedia.org/wiki/Apollo_17
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http://en.wikipedia.org/wiki/Viking_2
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http://en.wikipedia.org/wiki/Apollo_16
http://en.wikipedia.org/wiki/Apollo_17

Image source: http://www.googlelunarxprize.org/lunar/teams/next-giant-leap

Figure adapted from: Figure 12, Mars In-situ Resource Utilization Based on the Reverse Water Gas Shift: Experiments and Mission Applications, Zubrin, R., Frankie, B., Kito, T., AIAA 97-2767


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17 Benjamin Corbin, graduate student of aeronautics and astronautics at MIT

18 see reference 15

19 Data source: http://www.tudelft.nl/live/pagina.jsp?id=56438fe7-95c8-4c02-927c-82766a35721a

20 see reference 19


22 Background image adapted from: http://www.diviner.ucla.edu/gallery/figure_4b_full_res.jpg
23 Image source: http://www.nasa.gov/centers/goddard/images/content/208291main_lunar_outpost.jpg

24 Image source: http://en.wikipedia.org/wiki/File:Uniform_tiling_532-t0.png


26 See reference 17

27 Code adapted from: http://peltiertech.com/Excel/SolverVBA.html