PRELIMINARY DESIGN OF REUSABLE LUNAR LANDER LANDING SYSTEM

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Luleå University of Technology
Department of Computer Science, Electrical and Space Engineering
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Disclaimer

This project has been funded with support from the European Commission. This publication (communication) reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.
This thesis presents the methodology to design the landing system for the Reusable Lunar Resupply Vehicle (RLRV) for soft landing on the Moon surface. The landing gear preliminary design is based on the requirements of the stability distance and ground clearance.

Two-dimensional cantilever design lander model in the MATLAB/Simulink environment is used to analyse the landing dynamics of the lunar lander with honeycomb crushable absorber and metal bellow absorber to determine the preliminary design parameters. Two main case simulations are run with different touchdown conditions. Case simulation 1 analyses normal operations of the RLRV. Case simulation 2 analyses initial landing of the RLRV.

Results show that the honeycomb absorber has a more effective energy absorption than the metal bellow absorber. The landing system with honeycomb absorber has a smaller sizing as well. However, reusability of the honeycomb absorber is not possible.

The structural mass of the landing system is estimated based on the required design parameters and design requirements from the landing analysis. Aluminum alloy and carbon fiber reinforced plastic are both assessed. Carbon fiber reinforced plastic has much weight saving compared to aluminum alloy due to its high strength-to-weight ratio. Metal bellow absorber required more mass than the honeycomb absorber because of the stainless steel metal bellows required for the stroke of the shock absorber.
Acknowledgements

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Most of all, I had the love and support of my partner and my family throughout the two years of the master program.
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<td>Ns/m</td>
<td>Damping coefficient from ground contact</td>
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</tr>
<tr>
<td>$m$</td>
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<td>$m_i$</td>
<td>kg</td>
<td>Estimated mass of landing leg</td>
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<tr>
<td>$n$</td>
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<td>Heat capacity ratio of perfect gas</td>
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\( p_{\text{out}}(t) \) Pa Outer chamber pressure of metal bellow absorber
\( p_{\text{in}}(t) \) Pa Inner chamber pressure of metal bellow absorber
\( t_b \) m Thickness of metal bellow absorber
\( t_f \) m Thickness of footpad
\( t_p \) m Thickness of primary strut
\( t_s \) m Thickness of secondary strut
\( x_{fi}(t) \) m Horizontal displacement of footpad
\( y_{fi}(t) \) m Vertical displacement of footpad
\( \alpha_i(t) \) rad Angle between ground vertical and primary strut
\( \beta_i(t) \) rad Angle between ground vertical and secondary strut
\( \delta(t) \) m Deflection of the shock absorber
\( \tau_{pi}(t) \) rad Angle between primary strut and body vertical
\( \tau_{si}(t) \) rad Angle between secondary strut and body vertical
\( A_p \) m Cross sectional inner area of primary strut
\( A_s \) m Cross sectional inner area of secondary strut
\( CG \) m Center of gravity
\( C \) - Choke parameter of metal bellow absorber
\( D_s \) m Stability distance
\( D_b \) m Diameter of metal bellow absorber
\( D_c \) m Clearance distance
\( D_f \) m Diameter of footpad
\( D_p \) m Outer diameter of primary strut
\( D_s \) m Outer diameter of secondary strut
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<td>$E_s$</td>
<td>Pa</td>
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<td>Design crush force of honeycomb absorber</td>
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<td>Axial load in primary strut</td>
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<tr>
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<td>m</td>
<td>Length of primary strut lower section</td>
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<td>$L_{fp}$</td>
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<td>$S_a$</td>
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<td>$V_h$</td>
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<td>Volume of the inner chamber of metal bellow absorber</td>
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<tr>
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<td>Volume of the outer chamber of metal bellow absorber</td>
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<td>Stress due to bending moment in primary strut</td>
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<td>N/m$^2$</td>
<td>Stress subjected in primary strut</td>
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<td>$\sigma_s$</td>
<td>N/m$^2$</td>
<td>Stress subjected in secondary strut</td>
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<tr>
<td>$\Delta V$</td>
<td>m/s</td>
<td>Velocity increment</td>
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### Acronyms

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<td>ISPP</td>
<td>In–situ Propellant Production</td>
</tr>
<tr>
<td>LH2</td>
<td>Liquid Hydrogen</td>
</tr>
<tr>
<td>LM</td>
<td>Apollo Lunar Module</td>
</tr>
<tr>
<td>LOx</td>
<td>Liquid Oxygen</td>
</tr>
<tr>
<td>RLRV</td>
<td>Reusable Lunar Resupply Vehicle</td>
</tr>
<tr>
<td>ROBEX</td>
<td>Robotic Exploration under Extreme Conditions</td>
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Chapter 1
Introduction

In the past lunar missions, several landers had already landed successfully on the lunar surface. Missions such as the Apollo Lunar Program, Russian Luna mission and China Lunar Exploration Program made several attempts on both hard impact landings and soft landings since 1950s. The experiences of these landings from these lunar missions had contributed much to our current knowledge of the moon and also the successful design of the different landers. However, these missions were designed for a one way mission and the landers had not been intended for multiple missions or continuous operations.

1.1 Background

As part of the Robotic Exploration under Extreme Conditions (ROBEX) framework, a study of reusable lunar resupply system involving In–situ Propellant Production (ISPP) plant and Reusable Lunar Resupply Vehicle (RLRV) as a resupply vehicle between Moon surface and Low Lunar Orbit (LLO) or Earth-Moon Lagrange Point 1 (EML1) as rendezvous orbit has been proposed in [1]. This is categorised under the ROBEX work package which focus on reconfigurability, modularity and standardisation and also to ensure sustainability of the design.

The RLRV has tank capability to transport LOx and LH2. Depending on the possibility of producing LOx or LH2, this affects the tank capacity requirements of the resupply vehicle. The RLRV is also required to descent and ascent additional payloads between the rendezvous orbit and the lunar surface. This would also mean that the landing system of the RLRV would have to be cater to different payload masses with a single design. Since the RLRV will be used for continuous operations, reusability remains one important factor in this preliminary study of the landing system.

The initial landing of the RLRV is proposed to land with a payload of 10 tonnes on an unprepared moon surface. The mission of the first landing is to set up the basic infrastructure required to prepare for the lunar architecture. Once the initial landing site has been identified, the subsequent landings of the RLRV shall be carried out on a prepared landing site of payload up to 25 tonnes.
1.2 Motivation

Landing dynamics of a lander requires the understanding of the lander motion, contact dynamics and forces interactions within the multibody system. The challenges and uncertainties in the landing dynamics and landing environment could result in devastating outcome of the lander which could lead to a loss of mission.

The landing system plays an important role in defining the stability and safety of the lunar lander. During touchdown, it provides energy absorption during landing impact and attenuates landing loads to minimise load accelerations to the lander. This could effectively prevent damages on the lander structures as well as onboard electronics.

In the event of loss of control of the landing navigation system or the loss of engine control after touchdown, the landing system must be able to provide a passive method of landing the lunar vehicle without detrimental damage to the entire vehicle or toppling instability.

As part of any lunar lander, the landing system could contribute up to 5% of the mass budget. Inaccurate estimation of the landing system mass could result in additional ΔV in optimising the fuel mass for the mission of the lander.

1.3 Objective

The objective of this thesis is to develop a preliminary design of a landing system for the landing of the RLRV in all possible descent missions. Possibility of a reusable landing system shall be studied. The preliminary design shall be used to calculate the initial mass estimation of the landing system. The landing system must fulfil the requirements of landing performance and structural needs of the touchdown phase.

1.4 Structure

The thesis begins with an introductory chapter to let the reader understand the background, motivation and objective of the work.

Chapter 2 presents review of the literature on the lunar landings, planetary landers, reusability of lander and the different types of shock absorbers possible to be used in space environment.
Chapter 3 defines the requirements and definitions of the landing system and landing conditions required to analyse the simulation model and also address the landing problem.

Chapter 4 presents the dynamic model development to be used in the model and simulation. This section provides all the equations of motions, forces on each attachment of the model and forces output of the shock absorbers.

Chapter 5 shows the results and landing performance of the simulations of the different load cases and shock absorbers considered in the thesis.

Chapter 6 details the preliminary design and the subcomponent mass estimation based on structural requirements.
Chapter 2

Literature Review

To understand the landing dynamics of a lander on the moon, it is important to find out more about the past missions to the moon as well as other landers which had made it successfully to other planets. Landing systems used in these landers are reviewed and reusability of shock absorbers is looked into.

2.1 Lunar Landings

2.1.1 History

Mankind has attempted moon landing since the 1950s. Most landings of the early phases were to reach the surface of the moon despite the intentional hard impact landings. These successful landings eventually lead to attempts of soft landing of the spacecraft and to establish communications from the lunar surface.

In 1966, Luna 9, became the first spacecraft to achieve soft landing on the surface of the moon [2], following shortly by Surveyor 1 [3] which demonstrated our technology in soft landing a spacecraft on the celestial surface. Further successful soft landings by Surveyor program finally led to the Apollo 11 mission which landed the first human on the moon in 1969. This was followed by more Apollo missions and Luna robotics mission which further increase our landing capability and understanding of the moon. From the 1990s till date, many other missions continued to attempt landing on the moon with the last successful mission of Chang’e 3 in 2013.

2.2 Planetary Landers

2.2.1 Surveyor 7 Lander

Surveyor 7 lander was an unmanned vehicle with a landing mass of 305.7 kg under the American Surveyor programme to achieve successful soft landing on the moon in 1968 [3]. The surveyor landing legs consists of aluminum tubes attached to the corners of the main body structure. Landing leg configuration consisted of one primary strut and two secondary struts attached to the landing pad. This resembled an inverted tripod landing
gear design type for landers. The landing leg struts and footpads contained honeycomb crushable element for landing energy absorption. The 4.3 m footprint radius from the center of the spacecraft provides stability during landing.

Fig. 2-1 Surveyor 7 on Earth’s surface [3]

2.2.2 Apollo 11 Lunar Module

The Apollo 11 Lunar Module (LM) was the first manned spacecraft which successfully soft landed a crew on the Moon surface in 1969. It consisted of an ascent and descent stage, and separated from the Apollo Command/Service Module during the lunar parking orbit and was operated by the module commander to perform the soft touchdown.

The vehicle has a landing mass of 7327 kg [4]. The landing system was of a cantilever design with the primary struts attached to the footpads and two secondary struts was connected to each of the upper section of the primary struts. The primary struts were made of AL7178 and the secondary struts are made of AL2024. Two-staged honeycomb absorber elements are used in both the primary and secondary strut to absorb the landing impact energy. The footpad is made of AL7075 in a dish shape and the core was made of honeycomb type 2024 and 5052 [5].
2.2.3 Viking 1 Lander

The Viking 1 lander was the first spacecraft which successfully achieved soft landing on Mars’s surface as part of the NASA Viking program in 1976. The Viking program consisted of an orbiter and a lander. The lander soft landed onto Mars’s surface after separating from the orbiter during the Martian orbit.

The landing system of the Viking lander was of the inverted tripod design type. It had a three legged system which included a main strut assembly, secondary struts assembly and a footpad for each leg. The main strut assembly contained five stages of crushable honeycomb tube core for main energy absorption. The secondary strut inboard ends were attached to load limiters which deformed upon reaching the designed limit load to protect the main body structure and onboard electronics components [7].
2.2.4 Philae Lander

Philae was the first comet lander designed to land on comet 67/P Churyumov-Gerasimenko as part of ESA Rosetta mission. It was launched onboard Rosetta in 2004 and separated from Rosetta ballistically in 2014 to land on the comet surface. The lander touched down on the surface but bounced off the landing site as the harpoon system failed to anchor the lander and cold gas thrusters failed to fire upon landing. The lander came to rest in a reduced sun lit area and had short periods of communication with Rosetta [9].

The lander had a carbon fibre structure and weighed approximately 98 kg. The landing system consists of three legs connected to the cardanic joint and tilt limiter assembly at the center of the body structure. With a large footprint radius, the lander was designed for great stability and minimum clearance. The landing system energy absorber was a damping mechanism which drove an electric motor and dissipated the energy through resistor. The landing energy was also used for driving the ice screws onto the surface [13].
2.3 Reusability of Lander

Past missions’ lander design have not considered reusability in the use of the lander. The landing systems of the landers up till date were designed for a specific mission with no reusability in consideration. Most landers incorporated the honeycomb crushable energy absorber core within the cylindrical struts which were an irreversible energy absorption process. Even the load limiters on the Viking lander, which bends at a limit load, were designed for one time usage. Hence, landing technology for landers has not yet implement reusability in the design. In this section, possible shock absorber system application to space usage will be introduced.

2.3.1 Honeycomb Crushable Absorbers

For past landers, the honeycomb crushable absorbers had provided an effective and simple method of absorbing energy by crushing at a design load level. When the absorber
is subjected to load over the design load level, the honeycomb structure deforms plastically and causes the absorber to stroke until the load becomes insufficient to continue crushing the elements. This design load level is determined by the axial buckling or yield strength of the honeycomb cells. Fig. 2-5 shows the honeycomb cartridges and Fig. 2-6 shows the operation of the honeycomb crushable absorbers.

Fig. 2-5 Aluminum honeycomb cartridges with different stroked length [10]
2.3.2 Metal Bellows Shock Absorber

Metal bellow shock absorbers were proposed for application in space or harsh terrestrial conditions by University of Central Florida [11]. Stainless steel metal bellows are designed to operate from cryogenic to extreme temperatures of 400°C which are suitable for application in space environments [23]. This system consists of two gas chambers separated by an orifice and a piston connected to the metal bellow as shown in Fig. 2-7. The orifice between two pressurised gas chambers acts as the damper and the metal bellow with the gas chamber both act as the spring element of the shock absorber. Since the system is hermetically sealed, it eliminates the risks of leakage through seals.
Fig. 2-8 Simplified diagram of metal bellow shock absorber before compressing (left) and after compressing (right) design from [11]

2.3.3 Electromagnetic Absorber

Electromagnetic shock absorber was proposed by Boston University College of Engineering to be used in resettable landing gear for Mars hopper [12]. This system uses a passive electromagnetic system as damping and a spring for resetting. As the magnet core strokes through the coil section, the magnetic field induced by the coil opposed the movement of the magnet and creates a resisting damping force to slow the magnet core. Since the damping method is achieved through electromagnetic means, no hydraulic or pneumatic system is required, making it a possible solution as a reusable shock absorber in space applications. The use of magnets and coils add a considerable amount of mass to the shock absorber. Fig. 2-9 shows the simplified representation of the function of the electromagnetic shock absorber.

Fig. 2-9 Simplified diagram of electromagnetic shock absorber before compressing (left) and after compressing (right) design from [12]
2.3.4 Electromechanical Absorber

Electromechanical shock absorber was implemented in the Philae lander landing system to absorb kinetic energy by driving a damping motor. During landing, the electric motor converts kinetic energy into electrical energy. The electrical energy is thereafter dissipated by resistor [13]. Resettable method can be added by installation of a spring to reset the position of the landing system for reusability. The complexity and mass of the system must also be taken into account in selection of this shock absorber. A simplified representation of the electromechanical damping system is shown in Fig. 2-10.

![Simplified representation of electromechanical damping system of Philae lander landing system before compressing (left) and after compressing (right)](image)

2.4 Lunar Environment

During the past years, lunar science information has been accumulated all over journals and articles with databases across the world. These lunar parameters have been measured by different scientist groups and provided much insight about the lunar environment. In this section, certain parameters of the lunar environment which affects the landing dynamics are described briefly.
2.4.1 Lunar Atmosphere

The Moon has almost no atmosphere as compared to a dense atmosphere on Earth. The atmospheric density of Moon is approximately \(1 \times 10^4\) molecules/cm\(^3\) in the day and \(2.5 \times 10^5\) molecules/cm\(^3\) at night, which is about \(10^{14}\) times less than that of Earth [14]. This means that atmospheric influence on the surfaces of the lander could be considered negligible as compared to landing in Earth’s atmosphere.

2.4.2 Lunar Gravity

Gravitational acceleration has various effect on the landing dynamics during touchdown. The lower gravity effect on the Moon means that an equal mass on Earth would require less landing energy absorption. However, low gravitational acceleration also leads to lesser energy required to topple a lunar lander during touchdown. Due to its smaller size and mass, the gravity experienced on the moon is approximately one sixth that of the Earth. The gravitational acceleration of the Moon’s equator is \(1.62\) m/s\(^2\) [14].

2.4.3 Lunar Soil

The density of the lunar soil affects the amount of soil penetration of the landing system footpad. As the lunar soil is compressed by the footpad, the density increased as well as the bearing capability to prevent further depth penetration.

The lunar soil has an average bulk density of \(1.50 \pm 0.05\) g/cm\(^3\) for the top 0.15 m and an average bulk density of \(1.66 \pm 0.05\) g/cm\(^3\) [14]. These values have been referenced from the numerous source and references in the Lunar Source Book [14]. The values are tabulated in Table 2-1.

<table>
<thead>
<tr>
<th>Depth Range [m]</th>
<th>Bulk Density [g/cm(^3)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00 – 0.15</td>
<td>1.45 – 1.55</td>
</tr>
<tr>
<td>0.00 – 0.30</td>
<td>1.53 – 1.63</td>
</tr>
<tr>
<td>0.30 – 0.60</td>
<td>1.69 – 1.79</td>
</tr>
<tr>
<td>0.00 – 0.60</td>
<td>1.61 – 1.71</td>
</tr>
</tbody>
</table>
Chapter 3
Requirements and Definitions

It is important to define clearly the requirements and definitions before modelling and simulation of the landing model. The objective of this chapter discusses the RLRV lander configurations considered in this study, followed by the landing system parametric definitions and the drivers which are required to set the minimum requirements for the landing analysis.

3.1 Lander Configurations

In the paper presented in [1], different tank configurations of RLRV have been considered. Tank configurations of different fuel capability, together with different tank diameters and length were discussed during the preliminary sizing. Based on the structural index of the tanks plotted against the fuel capability in [1], tank with fuel capability of 20 tonnes has the lowest structural index and hence, selected for the lunar lander design.

For the 20 tonnes fuel capability tank configurations, design of LH2 tank of 3 m diameter with LOx tank of 3 m diameter is compared to the design of LH2 tank of 4 m diameter with LOx tank of 3 m diameter. The moment of inertia, height of center of gravity and total mass of four possible payload cases of each design are tabulated in Table 3-1 and Table 3-2.

Table 3-1 LH2 tank of 3 m diameter with LOX tank of 3 m diameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>No Payload</th>
<th>10 tonnes Payload</th>
<th>25 tonnes Payload</th>
<th>6800 kg Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>[kg]</td>
<td>0</td>
<td>10000</td>
<td>25000</td>
<td>6800</td>
</tr>
<tr>
<td>Inertia</td>
<td>[kgm^2]</td>
<td>36687</td>
<td>408352</td>
<td>645772</td>
<td>47929</td>
</tr>
<tr>
<td>CoG Height</td>
<td>[m]</td>
<td>6.90</td>
<td>15.20</td>
<td>17.32</td>
<td>7.26</td>
</tr>
<tr>
<td>Total Mass</td>
<td>[kg]</td>
<td>3043</td>
<td>13043</td>
<td>28043</td>
<td>9843</td>
</tr>
</tbody>
</table>
Table 3·2 LH2 tank of 4 m diameter with LOX tank of 3 m diameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>No Payload</th>
<th>10 tonnes Payload</th>
<th>25 tonnes Payload</th>
<th>6800 kg Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>[kg]</td>
<td>0</td>
<td>10000</td>
<td>25000</td>
<td>6800</td>
</tr>
<tr>
<td>Inertia</td>
<td>[kgm²]</td>
<td>27515</td>
<td>295007</td>
<td>502150</td>
<td>36500</td>
</tr>
<tr>
<td>CoG Height</td>
<td>[m]</td>
<td>6.50</td>
<td>13.02</td>
<td>14.97</td>
<td>5.97</td>
</tr>
<tr>
<td>Total Mass</td>
<td>[kg]</td>
<td>3043</td>
<td>13043</td>
<td>28043</td>
<td>9843</td>
</tr>
</tbody>
</table>

The mass and height of the RLRV are important parameters to consider for the landing performance. Compact, heavy and short tank design are much preferred as compared to slender, light and tall tank designs in optimising landing performance. A simple landing MATLAB/Simulink model, shown in Fig. 3·1, was carried out to determine the landing stability for each of the cases, similar to the case study in [15]. The model is simulated at initial horizontal velocity of 1.0 m/s and vertical downwards velocity of 1.5 m/s as in Section 3.5. The results are shown in Fig. 3·2 and Fig. 3·3.

Fig. 3·1 Simple MATLAB mathematical model

As expected, results show that the second tank design exhibits a better landing stability characteristics over the first tank design. The second tank design requires a smaller footprint radius given a certain height of the landing system required. Preliminary landing gear design will be analysed for the RLRV configuration with LH2 tank of 4 m diameter and a LOx tank of 3 m diameter.
Fig. 3-2 Required footprint radius required for different height of landing leg for LH2 tank of 3 m diameter with LOx tank of 3 m diameter

Configuration 1 represents the lander with 25 tons of payload and configuration 2 represents the lander with 10 tons of payload. Table 3-3 shows the details of configurations 1 and 2.

<table>
<thead>
<tr>
<th>Table 3-3 Configuration 1 and 2</th>
<th>Parameter</th>
<th>Unit</th>
<th>Configuration 1</th>
<th>Configuration 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Payload</td>
<td>[kg]</td>
<td>10000</td>
<td>25000</td>
</tr>
<tr>
<td></td>
<td>Inertia</td>
<td>[kgm²]</td>
<td>295007</td>
<td>502150</td>
</tr>
<tr>
<td></td>
<td>CoG Height</td>
<td>[m]</td>
<td>13.02</td>
<td>14.97</td>
</tr>
<tr>
<td></td>
<td>Total Mass</td>
<td>[kg]</td>
<td>13043</td>
<td>28043</td>
</tr>
</tbody>
</table>
3.2 Landing Gear Type

In order to design the landing system, it is important to choose a suitable landing gear type design. The landing gear type defines the types of loads in the landing gear struts, overall mass of the landing gear and efficiency of the energy absorption. Some of the past landers, which were introduced in Section 2.2, had used various types of landing gear design. The cantilever and the inverted tripod landing gear design remain the most common design for lunar lander. Simplified two dimensional representations of the cantilever design and the inverted tripod design are illustrated in Fig. 3-4.

The cantilever design has the secondary struts connected to the lower end of the primary strut upper section and to the main body structure. The upper section of the primary strut is fix in length and connects the secondary struts at the middle attachment point of the primary strut. Both the lower section of the primary strut and the secondary struts have energy absorber elements incorporated within the internal cylinder of the struts. The joints connecting the body structure and both primary and secondary struts are pivoted on ball joints for landing flexibility. The primary strut is subjected mainly to bending moment because of the secondary strut and compressive loading from the energy absorber element in the primary strut. The secondary strut is mainly loaded only in the axial direction.

![Cantilever design](image1)

![Inverted tripod design](image2)

Fig. 3-4 Cantilever design (left) and inverted tripod design (right)

The inverted tripod design has both the primary and secondary struts connected to the footpad. The primary strut and secondary strut both has energy absorbers, although in some cases, only the primary strut contains the absorbing elements. Similar to the cantilever design, the joints connecting the body structure and both primary and secondary struts are pivoted on ball joints to allow flexibility during landing. The primary and secondary strut are both subjected to axial loadings.
For the preliminary design of the RLRV landing system, the cantilever design is chosen over the inverted tripod design, primarily because of the lighter structure since the secondary struts are much shorter. The connection of the secondary strut to the primary strut also reduces the risk of interference with obstacles in the vicinity of the footpad as compared to the inverted tripod design. Additionally, choosing the cantilever design for the RLRV allow the mass to be compared to similar reference such as the Apollo LM.

![Diagram of landing gear configurations](image)

Fig. 3-5 Landing gear with three-legged (left) and four-legged (right) configuration

Most landers had three-legged or four-legged landing system. Consideration The difference in number of legs affect the landing dynamics shown in Fig. 3-5. For simplicity and symmetrical reasons, the four legged landing system shall be adopted for the preliminary design of the RLRV.

### 3.3 Design Parameters

In order to model and simulate the landing dynamics in the later sections, design parameters are identified to size the landing gear. These parameters, as shown in Fig. 3-6, are chosen to define the four-legged cantilever landing gear system and will determine the structural and mass sizing of the landing gear initial design.
Fig. 3-6 Design parameters of cantilever design model.

Height of the center of gravity, $L_{cg}$ is measured vertically from the bottom of the body structure to the location of the center of mass for the lander. Width of the body structure, $L_w$ is the horizontal distance from the center of gravity to the top attachment of the primary strut. Footprint radius, $L_{fp}$ is the horizontal distance from the center of gravity to the footpad. The vertical distance, $L_v$ is the vertical distance between the ground and the bottom attachment point of the landing system. Primary angle, $\tau_p$ is the angle between the primary strut with the body vertical reference. Secondary angle, $\tau_s$ is the angle between the secondary strut and the body vertical reference.

These parameters could all be varied to obtain the required optimal design for the landing system. However, some parameters are limited or defined by constraints which could be predetermined before the landing gear analysis. In the following sections, certain parameters shall be fixed for this preliminary design stage.

3.3.1 Height of Landing System

The initial height of the landing system is influenced by the length of the lander propulsion engine, the required lift-off engine clearance, available landing system absorption stroke and possible obstacles on the Moon surface. The initial parameters of the preliminary engine assembly design for the RLRV is given in Table 3-4.

Table 3-4 Engine parameters
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Engine Length</td>
<td>[m]</td>
<td>2.50</td>
</tr>
<tr>
<td>Chamber Length</td>
<td>[m]</td>
<td>1.68</td>
</tr>
<tr>
<td>Nozzle Exit Diameter</td>
<td>[m]</td>
<td>1.05</td>
</tr>
</tbody>
</table>

For engine performance during lift off from the Moon surface, an engine clearance below the exit nozzle must be available. There are slight concerns about the radially expanding exhaust after the exit stream from the nozzle impinges on the ground surface. The engine performance might be affected if this available clearance is too little. This clearance requirement is also not distinctly defined by any rocket engine’s manufacturer. However, using the conservation of mass approach, it is possible to estimate the height required for the preliminary design stage. The exhaust of the engine is illustrated in Fig. 3-7.

The exit surface area of the available clearance must be more than the nozzle exit surface area. The nozzle exit surface area is given by

$$S_{\text{nozzle}} = \frac{\pi d_{\text{nozzle}}^2}{4} \quad (3-1)$$

where $d_{\text{nozzle}}$ is the exhaust diameter. The cylindrical stream exit surface area, determined by the diameter of the exit nozzle and the height of the engine clearance available is given by

$$S_{\text{stream}} = 2\pi d_{\text{nozzle}} h_{\text{clearance}} \quad (3-2)$$

where $h_{\text{clearance}}$ is the height of the engine clearance. Using a stream exit area two times more than the diameter of the engine, the minimum required engine clearance is given by

$$h_{\text{clearance}} = \frac{d_{\text{nozzle}}}{2} \approx 0.60 \text{ m} \quad (3-3)$$

During landing, the landing gear absorbs energy by stroking through the shock absorbers which reduce the ground clearance further. Depending on the type of shock absorbers implemented, it is hard to determine the exact amount of stroke required. For a conservative approach at preliminary stage, vertical stroke is set to 1.0 m of vertical stroke allowance. Hence, the initial height is set at 4.0 m to allow adequate height clearance for energy absorption stroking.
3.3.2 Width of Lander Body Structure

The width of the lander is constrained by the size of the allowable payload of the launch vehicle. Since the RLRV was proposed to be launched with Ariane 5 launcher, the maximum diameter of the static volume is 4.570 m [16]. This is illustrated in Fig. 3-8. In the preliminary design of the RLRV landing system, the width, $L_w$, is set at 2.25 m.
3.4 Design Drivers

The landing system design type, lander configurations and design parameters have been determined in the previous sections. To determine results of the landing, methods of measuring the landing performance have to be determined. The main design drivers, which are considered in the preliminary stage, are the stability distance and ground clearance, as illustrated in Fig. 3-9.

Stability distance, $D_s$ is required to prevent toppling of the lunar vehicle and is measured by the minimum distance perpendicular to the gravity vector from the center of gravity to the position of the footpad during the entire landing period. If the stability distance is negative, it means that the lander has pivoted over the footpad and is considered instable. The higher the stability distance means a better stability measurement of the landing.

![Design drivers with stability distance (left) and clearance distance (right)](image)

Clearance distance, $D_c$ is measured from the bottom of the lander body to the ground. Sufficient ground clearance is necessary to allow for possible boulders or uneven surface during descent and engine performance during ascent. As explained in Section 3.3.1, the required minimum clearance distance is the total of the engine assembly length and engine clearance which is an approximate value of 3.1 m.

3.5 Touchdown Conditions

The touchdown conditions have a major impact on the landing dynamics which affect the design parameters of the landing system. These conditions are dependent on the possible
missions of the RLRV. Since the missions of the RLRV are different from those of the past landers, the touchdown conditions are not the same as the values which have been analysed for past landers such as Apollo lander or the Viking lander. This section describes the touchdown conditions of the RLRV missions.

3.5.1 Lunar Environment

The gravity on the Moon differs from that on the Earth. Earth acceleration is 9.81 m/s² at sea level while Moon gravity is 1.62 m/s² [14]. Because of the larger acceleration gravity on Earth, landing on Earth's surface has more stability because it requires more energy to topple a landing vehicle as compared to landing on the Moon surface.

Atmosphere on the moon is almost non-existent. The density of the Moon atmosphere is approximately $10^4$ molecules/cm³ compared to that of Earth which is $2.5 \times 10^{19}$ molecules/cm³, is an order 15 times smaller [14]. Hence, the effect of atmosphere acting on the surface of the RLRV will not be considered in this preliminary design.

3.5.2 Terrain Slope

The mission of the RLRV is to descent an initial payload of 10 tons during the first landing on the moon surface to deliver the necessary logistics equipment to set up the essential infrastructure. The first landing is predicted to be landing on unprepared Moon surface and terrain slope estimated to be at a maximum steepness of 5 °.

Since the purpose of the RLRV is to transport propellant from the ISPP plant, the landing site shall be a familiar area near to the plant. The normal landing operations of the RLRV shall be carried out on a prepared platform. The steepness of the landing platform is set at maximum value of 2 °.

3.5.3 Touchdown Velocities

The touchdown velocities, both horizontal and vertical, are the velocities at which the footpad of the landing system comes into contact with the Moon surface. Depending on the time at which the engine thrust is cut-off and controls of the landing navigation system has ceased, these velocities can range from a pessimistic point of view for a heavy landing or a controlled landing even after touchdown for a near-zero velocity landing. It is a more conservative approach to assume the worst-case scenario in designing the landing system as it acts as a passive system to ensure the safety of the landing vehicle.
In this preliminary design, horizontal velocity of 0.5 ± 0.5 and vertical velocity of −1.0 ± 0.5 are specified as the touchdown velocities.

3.5.4 Ground Forces

During the touchdown of the RLRV, the footpads penetrate the lunar soil to a certain depth before the compressed soil gain enough bearing strength to hold the lunar touchdown energy. Since the normal operations of the RLRV are performed on a prepared platform, the footpad to soil contact dynamics is not of importance during the preliminary design stage. Friction force can be modelled by a coefficient factor to the normal force reacting from the landing impact as explained later in Chapter 4.

3.5.5 Landing Orientation

The landing orientation affects the stability and ground clearance of the landing. For a four-legged landing system, there are two main critical orientations in which landing could occur. The 2-2 landing orientation touchdown on two leading legs before the two trailing legs. The 1-2-1 landing orientation lands on first leading leg, followed by two landing legs and lastly the trailing leg.

Fig. 3-10 Landing orientations with 2-2 landing orientation (left) and 1-2-1 landing orientation (right)
Referring to Fig. 3-10, the 2-2 landing orientation has a much smaller two-dimensional footprint radius which is a critical factor to stability. On the other hand, 1-2-1 landing orientation is more critical to leg loading and stroke which can occur to either the leading leg or trailing leg.

3.5.6 Load Cases

To simulate the landing dynamics of the different RLRV configurations with different touchdown conditions explained in the previous sections, two load cases were designed to represent the two touchdown conditions which represent the two possible missions of the RLRV. Load case 1 represents the initial mission to the Moon to set up first area surveying and infrastructure deployment. Load case 2 represents the normal operations of the RLRV on familiarised landing platform. The load cases values are shown Table 3-5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Load Case 1</th>
<th>Load Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>[m/s²]</td>
<td>1.62</td>
<td>1.62</td>
</tr>
<tr>
<td>Terrain Slope</td>
<td>[°]</td>
<td>0 ± 2</td>
<td>0 ± 5</td>
</tr>
<tr>
<td>Horizontal Velocity</td>
<td>[m/s]</td>
<td>0.5 ± 0.5</td>
<td>0.5 ± 0.5</td>
</tr>
<tr>
<td>Vertical Velocity</td>
<td>[m/s]</td>
<td>-1.0 ± 0.5</td>
<td>-1.0 ± 0.5</td>
</tr>
<tr>
<td>Friction Coefficient</td>
<td>[-]</td>
<td>0.3 – 0.9</td>
<td>0.3 – 0.9</td>
</tr>
</tbody>
</table>
Chapter 4
Dynamic Model Development

To analysis the landing dynamics of a multibody landing system, a MATLAB/Simulink mathematical model is developed to understand the environmental variables and lander parameters effect on the landing dynamics and performance. The landing model is simplified as two–legged and two–dimensional systems. The analysis of motion is computed in three degree of freedom: vertical translational, horizontal translational and pitch rotational motions. In this chapter, the model topology, model equations, method implementation and model validation are explained.

4.1 Model Topology

The landing simulation consists of a lunar lander dynamic model and landing ground model. The model of the lander includes the main body structure and the landing gear system. Fig. 4-1 illustrates the lander model topology.

As discussed in Chapter 3, the landing gear system is of the cantilever type design with two primary struts connected to two secondary struts at the middle attachment points.
The upper section of the primary strut is attached between the top attachment of the body structure and the middle attachment of the primary strut. The secondary strut is attached between the bottom attachment point of the body structure and the middle attachment of the primary strut. Energy absorbers are located in the lower section of the primary strut and in the secondary strut.

4.2 Lander Model

To model the lander model, equations of motion of the system are derived and forces acting on the elements are analysed in details. The mathematical model is illustrated in Fig. 4-2. $x_p$ and $y_p$ are the horizontal and vertical distances between the COG and top attachment point of the primary struts respectively. $x_s$ and $y_s$ are the horizontal and vertical distances between the COG and attachment point of the secondary struts respectively. The slope of the terrain with the horizon is denoted by $\theta$ and the angle of the lander body with the horizon is denoted by $\varphi$. Angles of the primary strut and secondary with respect to the vertical are $\alpha$ and $\beta$ respectively. From this point onwards, subscript 1 denotes the left-hand side landing leg, subscript 2 denotes the right hand side landing leg and subscript $i$ denotes both landing legs.

Fig. 4-2 Mathematical model of two-dimensional lunar lander
The contact forces acting on the footpad between the footpads of the lunar lander and soil are derived using the simple damper model. Normal force is a function of the penetration depth and penetration rate of the footpad. Horizontal friction forces is proportional to the normal force friction by a factor of friction coefficient, \( \mu \) and in a direction opposite to that of the horizontal motion of the footpad. These perpendicular force, \( f_{cn} \) and parallel ground force, \( f_{ct} \) are given by

\[
f_{cn}(t) = -k_c y_f(t) - c_c \dot{y}_f(t) \tag{4.1}
\]

\[
f_{ct}(t) = -\mu f_{cn}(t). \text{sign}(\dot{x}_f(t)) \tag{4.2}
\]

where \( k_c \) and \( c_c \) are the stiffness and damping constants of the ground contact respectively. \( y_f \) is the vertical penetration of the foot in the ground. \( \dot{y}_f \) is the vertical penetration rate of the foot. \( \dot{x}_f \) is the horizontal velocity of the foot. Forces acting on the footpad from the ground contact depend on the angle between the leg and ground normal. The axial force, \( f_{in} \) in the lower primary strut is the force from the absorber element in the primary strut which will be further discussed in Section 4.3. The tangential force, \( f_{lt} \) in the lower primary strut is contributed by the ground normal forces and friction forces.

\[
f_{in}(t) = f_{lat}(t) \tag{4.3}
\]

\[
f_{lt}(t) = -f_{cn}(t) \sin \alpha_i(t) + f_{ct}(t) \cos \alpha_i(t) \tag{4.4}
\]

Since the upper section of the primary strut is considered rigid in this model, the length of the upper section remains constant during the landing impact. The equation of motion in the tangential direction is given by

\[
\ddot{\tau}_{p1}(t) = -\frac{1}{L_u m_1} \left[ f_{lt1}(t) - f_{sn1}(t) \sin (\tau_{s1}(t) - \tau_{p1}(t)) \right] \tag{4.5}
\]

\[
\ddot{\tau}_{p2}(t) = -\frac{1}{L_u m_2} \left[ -f_{lt2}(t) - f_{sn2}(t) \sin (\tau_{s2}(t) - \tau_{p2}(t)) \right] \tag{4.6}
\]

where \( \tau_p \) and \( \tau_s \) are the angles between the body vertical and primary and secondary struts. \( \ddot{\tau}_p \) is the angular acceleration between the body vertical and primary struts. \( L_u \) is the length of the upper section of the primary strut. \( f_{sn} \) is the axial force in the secondary strut. \( m_1 \) and \( m_2 \) are the estimated mass of the landing legs. Hence, the axial forces acting on the upper section of the primary strut are given by

\[
f_{um1}(t) = f_{in1}(t) - f_{sn1}(t) \cos (\tau_{s1}(t) - \tau_{p1}(t)) \tag{4.7}
\]

\[
f_{um2}(t) = f_{in2}(t) - f_{sn2}(t) \cos (\tau_{s2}(t) - \tau_{p2}(t)) \tag{4.8}
\]
The normal and tangential forces, acting on the top attachment of the lander body, \( f_{bpn} \) and \( f_{bpt} \) respectively, are resolved from the axial forces of the upper section of the primary strut. These forces are functions of the upper primary strut axial forces and the angle between the ground vertical and primary strut.

\[
f_{bpi}(t) = f_{uni}(t) \cos \alpha_i(t) \quad (4\cdot9)
\]
\[
f_{bti}(t) = f_{uni}(t) \sin \alpha_i(t) \quad (4\cdot10)
\]

The normal and tangential forces acting on the bottom attachment of the body, \( f_{bsn} \) and \( f_{bst} \) respectively, are functions of the secondary actuator force, \( f_{sn} \) and the angle between the ground vertical and secondary strut.

\[
f_{bsni}(t) = f_{sni}(t) \cos \beta_i(t) \quad (4\cdot11)
\]
\[
f_{bsti}(t) = f_{sni}(t) \sin \beta_i(t) \quad (4\cdot12)
\]

Finally, the lander body is subjected to the normal and tangential forces from the top and bottom attachments. These equations of motion will define the position of the center of gravity in the next time step. The new calculated center of gravity will then define the position of the geometry of the landing legs position and the whole process is iterated.

\[
\ddot{x}(t) = \frac{1}{m} [f_{bpt1}(t) + f_{bpt2}(t) + f_{bst1}(t) + f_{bst2}(t)] - g \sin \theta \quad (4\cdot13)
\]
\[
\ddot{y}(t) = \frac{1}{m} [f_{bpi1}(t) + f_{bpi2}(t) + f_{bsni1}(t) + f_{bsni2}(t)] - g \cos \theta \quad (4\cdot14)
\]
\[
\ddot{\phi}(t) = \frac{1}{I} [f_{bpi1}(t)x_{p1}(t) + f_{bpi2}(t)x_{p2}(t) + f_{bsni1}(t)x_{s1}(t) + f_{bsni2}(t)x_{s2}(t) + f_{bst1}(t)y_{p1}(t) + f_{bpt2}(t)y_{p2}(t) + f_{bst2}(t)y_{s1}(t) + f_{bst2}(t)y_{s2}(t)] \quad (4\cdot15)
\]

where \( \ddot{x} \) is the horizontal acceleration of the COG, \( \ddot{y} \) is the vertical acceleration of the COG and \( \ddot{\phi} \) is the angular acceleration of the lander attitude. \( I \) is the inertial of moment of the lander and \( m \) is the total mass of the lander.

### 4.3 Energy Absorber Model

The energy absorber elements are located in the lower section of the primary strut and in the secondary strut. The function of the energy absorber element is to absorb energy by stroking and it depends on the load stroke curve of the shock absorber. In this section, the
model of the honeycomb shock absorber and the model of the metal bellow shock absorber will be explained in details.

4.3.1 Honeycomb Crushable Element

The energy absorption of the crushable element is based on the designed crushing force and the stroke of the crushed length. The output of the honeycomb absorber model is shown in Fig. 4-3.

![Fig. 4-3 Honeycomb absorber model load stroke curve](image)

During stroking, the strut force is limited at the designed crush load limit of the honeycomb element. Before the strut force exceed the designed crush load limit, the output force of the absorber is given by

\[ f_a(t) = -k_a \delta(t) - c_a \dot{\delta}(t) \]  \hspace{1cm} (4-16)

where \( \delta \) is the deflection of the absorber and \( \dot{\delta} \) is the deflection rate of the absorber. \( k_a \) and \( c_a \) are the stiffness and damping constants of the absorber. When the output force of the absorber exceed the design crush force, \( F_{\text{crush}} \) of the honeycomb absorber, the output force of the absorber is

\[ f_a(t) = F_{\text{crush}} \]  \hspace{1cm} (4-17)
When the stroke exceeds its available honeycomb material, the absorber will not be able to absorb additional energy and the output force of the absorber will be the input force.

\[ f_a(t) = -k_a \delta(t) - c_a \dot{\delta}(t) \]  

(4-18)

4.3.2 Gas Pressurised Metal Bellow

The following equations of the gas pressurised metal bellow shock absorbers are derived from the normalized equations presented in paper [11]. The output force is defined as a function of the area of the piston, the pressure in the outer chamber, \( p_{out} \) and the spring force by the metal bellow.

\[ f_a(t) = S_a p_{out}(t) - k_b \delta(t) \]  

(4-19)

\( S_a \) is the cross sectional area of the absorber. \( \delta \) is the deflection of the absorber and \( k_b \) is the stiffness of the metal bellow. The orifice has a tendency to be choked when the flow in the orifice is sonic. It depends on the ratio of the upstream pressure over downstream pressure. This is defined by choke parameter, \( C \) and equation is given in [11].

The pressure in both chambers are determined by the rates of change of the chamber pressure which are functions of the deflection and deflection rate, \( \dot{\delta} \), of the absorber. The outer chamber pressure rate of change, \( \dot{p}_{out} \), during extension stroke is given by

\[ \dot{p}_{out}(t) = \frac{1}{-V_{out} + S_a \delta(t)} \left[ -S_a n \dot{\delta}(t)p_{out}(t) - CS_a p_{out}(t) \frac{3n-1}{2n} \right] \]  

(4-20)

\[ \dot{p}_{in}(t) = \frac{CS_a}{V_{in}} \left[ p_{out}(t)^{\frac{n+1}{2n}} p_{in}(t)^{\frac{n-1}{n}} \right] \]  

(4-21)

The pressure rate of change during compression stroke is

\[ \dot{p}_{out}(t) = \frac{1}{-V_{out} + S_a \delta(t)} \left[ -S_a n \dot{\delta}(t)p_{out}(t) - CS_a p_{out}(t) \frac{n-1}{n} p_{in}(t) \frac{n+1}{2n} \right] \]  

(4-22)

\[ \dot{p}_{in}(t) = -\frac{CS_a}{V_{in} p_{in}(t)} \frac{3n-1}{2n} \]  

(4-23)

where \( p_{in} \) is the pressure of the inner chamber of the absorber. \( V_{out} \) is the outer chamber volume of the metal bellow absorber. \( n \) is the heat capacity ratio of a perfect gas. Fig. 4-4 and Fig. 4-5 show the load stroke curve of the metal bellow absorber and the chamber pressures in the absorber. Outer pressure is represented by the red curve and inner pressure is represented by the blue curve.
Method Implementation

The implementation of the equations in the previous section is performed in MATLAB/Simulink environment. The initial parameters are input in MATLAB and the non-linear equations are solved in Simulink. The output is plotted and simulated in MATLAB. Fig. 4.6 illustrates a general algorithm flow of the model implementation in Simulink.
Initial conditions and parameters are provided to the lander position and attitude. When the foot of the landing system contact ground, the ground event is executed. The forces in the landing system acts on the lander center of gravity. This will determine the landing system geometry and this sequence repeats until the final simulation time is reached.

4.5 Model Validation

In order to validate the simulation model, landing experiments are usually carried out to compare the experimental results and the simulation results. In this preliminary design stage, building a prototype of the lunar lander would not be suitable as parameters are still constantly varying. Hence, the full scale Apollo lunar lander presented in [Full Scale] is modelled in MATLAB and the drop test of the vertical landing on a flat ground, similar to that in [17] will be simulated. Geometry of the full scale model and design parameters are abstracted from [17] and detailed into the model.

Dimensions of footprint radius, primary angle, secondary angle, height of landing system are kept similar to the full scale Apollo model. Two stage honeycomb absorber elements are implemented into the primary strut and secondary struts. Vertical velocity of -3 m/s is initiated at touchdown with no horizontal velocity. Fig. 4-7 shows the illustration of the drop test to obtain a vertical velocity of 3 m/s at touchdown. Fig. 4-8 shows the vertical acceleration acting on the center of gravity of the model. Maximum acceleration of +21.5 m/s² acts on the simulation model during landing phase, as compared to +21.58 m/s² for the full scale experimental model.
Fig. 4-7 MATLAB Apollo model drop test simulation in Simulink

Fig. 4-8 Vertical Acceleration of Apollo model drop test simulation

Fig. 4-9 and Fig. 4-10 show the stroke in the primary strut absorber and the secondary strut absorber respectively. Primary stroke value is at approximately 0.3 m and the secondary stroke value is at 0.072 m. The experimental values in [17] are average value of 0.2955 m for the primary stroke and 0.0775 for the secondary stroke. The results of the simulation model, thus, are within 10% accuracy of the experiment. Therefore, the model is validated.
Fig. 4-9 Apollo lander simulation primary absorber load-stroke curve

Fig. 4-10 Apollo lander simulation secondary absorber load-stroke curve
Chapter 5

Case Simulation

A two dimensional simple lander model and cantilever type lander model is modelled and simulated in the MATLAB/Simulink environment to assess the touchdown dynamics and determine the required design parameters. Design parameters were optimised for the two load cases to analyse the touchdown performance based on the stability and ground clearance.

5.1 Rigid Model

To find out how terrain conditions influence the landing stability requirement, a simple rigid lander model is simulated landing on a sloped terrain with horizontal velocity of 1 m/s and vertical velocity of -1.5 m/s illustrated in Fig. 5-1. Two scenarios simulated are the effect of landing direction on stability and the effect of friction on stability. In the simulations, the measured stability distance is plotted against increasing footprint radius.

Fig. 5-2 shows the effect of the landing direction on stability. It shows that lesser stability distance is measured when landing away from the slope as compared to landing towards the slope. Landing away from the slope contributes to the tendency of toppling over of the landing vehicle. Hence, it would be a conservative approach to simulate the load cases for landing direction away from the sloped terrain.

![Simulation](image1.png)

![Simulation](image2.png)

Fig. 5-1 Rigid lander model simulation landing away from slope
Fig. 5.3 shows the effect of friction coefficient on stability distance. Lesser stability distance is measured for friction coefficient of 0.6 and 0.9 as compared to the friction coefficient of 0.3. The effect of friction coefficient for the model seems to have a negligible effect for coefficient more than 0.6. Higher friction coefficient leads to instability as friction on the ground tends to lead to toppling over of the lander during touchdown.

5.2 Cantilever Model

The cantilever landing system has various parameters as described in Chapter 3. The width of the body, height of the landing system and height of the center of gravity is predetermined but the primary and secondary angle has not been discussed. To understand how the primary and secondary angles influence the landing dynamics, a
cantilever models of both configuration 1 and 2 are simulated with varying primary angles and secondary angles on flat landing platform. Fig. 5.4 shows the graphical results of the cantilever model landing on a flat ground.

In this case, footprint radius is kept constant as no toppling over is expected for landing on a flat ground. Fig. 5.5 and Fig. 5.6 show the results for configuration 1. Fig. 5.7 and Fig. 5.8 show the results for configuration 2.
Primary angle does not affect the ground clearance and stability distance until when it increased to a value when the secondary angle attached to it is insufficient to resist the landing legs from spreading. The overspreading of the landing legs lead to low ground clearance and possibly instability. Secondary angle of $50^\circ$ performs poorly in this study. The higher secondary angles have a better landing performance with primary angles of $25^\circ$ and less. Furthermore, the primary angle directly affects the length of the primary strut, which suggest that a larger primary angle will correspond to shorter length, leading to a lower mass of the primary struts. For the preliminary design, a primary angle of $25^\circ$ with secondary angle of $80^\circ$ shall be used for further case studies.
5.3 Simulation Test Plan

Due to the number of parameters and conditions which can be varied in simulating the landing dynamic, it is appropriate to simulate the worst case scenario to reduce the number of simulation data and focus on important parameters which affects the preliminary design of the landing system. From the previous discussions, simulating landing away from slope has lesser stability than landing towards the slope. A higher friction coefficient leads to toppling instability and lower friction coefficient leads to lower ground clearance. Table 5.1 tabulates the simulations to be carried out for the honeycomb absorber case study and metal bellow case study.

Table 5.1 Landing case simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Flat Ground</th>
<th>Case Simulation 1</th>
<th>Case Simulation 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration</td>
<td>1 and 2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Load Case</td>
<td>N/A</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Landing Direction</td>
<td>N/A</td>
<td>Away Slope</td>
<td>Away Slope</td>
</tr>
<tr>
<td>Landing Orientation</td>
<td>N/A</td>
<td>1·2·1</td>
<td>2·2</td>
</tr>
<tr>
<td>Friction Coefficient</td>
<td>0.3 – 0.9</td>
<td>0.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>
5.4 Honeycomb Crushable Absorber

This case study is based on the honeycomb crushable absorber. The absorbing elements are implemented in the mathematical model of the RLRV which is analysed for landing on flat ground, load case 1 and load case 2.

5.4.1 Case Simulation 1

RLRV configuration 1 is simulated to land on a terrain slope of 2 degree of steepness with the lander model landing away from the slope. Touchdown velocities are 1 m/s horizontal and -1.5 m/s vertical. Primary angle is 25 ° and secondary angle is 80 °. Primary load level ranges from 20 kN to 80 kN and secondary load level ranges from 10 kN to 30kN. Footprint radius were varied from 5.0 m to 7.0m to study the effects on stability distance and ground clearance during landing phase. The results are presented in Fig. 5·9 and Fig. 5·10.

![Graph showing the effect of footprint radius with varying primary and secondary crush forces on stability for honeycomb absorber landing system in load case 1](image)

**Fig. 5·9** Effect of footprint radius with varying primary and secondary crush forces on stability for honeycomb absorber landing system in load case 1
Increasing the footprint radius increases the stability distance as expected but have negligible effect on the ground clearance. Higher load level of the primary absorber elements contributes to lower stability distance but higher ground clearance. This is because a lower load level allows better energy absorption but leads to larger strocking of the shock absorber. Higher secondary load level has slightly better stability distance and significantly better ground clearance. Primary force level of 20 kN is insufficient to maintain the required ground clearance.

5.4.2 Case Simulation 2

RLRV configuration 2 is simulated to land on a terrain slope of 5° to represent an initial landing on an unprepared platform. Touchdown velocities are 1 m/s horizontal and -1.5 m/s vertical. Primary angle is 25 ° and secondary angle is 80 °. Primary load level ranges from 20 kN to 80 kN and secondary load level ranges from 10 kN to 30kN. Footprint radius were varied from 5.0 m to 7.0m to study the effects on stability distance and ground clearance during landing phase. Results of the simulations are presented in Fig. 5·11 and Fig. 5·12.
Fig. 5-11 Effect of footprint radius with varying primary and secondary crush forces on stability for honeycomb absorber landing system in load case 2

Fig. 5-11 shows that the curves corresponding to primary load levels of 60 kN and 80 kN are not displayed on the graph. This means that these primary load levels are of a value too high for stability of configuration 2 on load case 2. Primary load level of 20 kN seems to meet the minimum requirement for stability in this simulation. Lower secondary load level provides a slightly better stability but worse ground clearance. Fig. 5-12 shows that ground clearance is not an issue with the range of primary and secondary load levels simulated for case simulation 2.

Fig. 5-12 Effect of footprint radius with varying primary and secondary crush forces on ground clearance for honeycomb absorber landing system in load case 2
5.4.3 Performance

From the study of case simulation 1 and 2, we can determine the preliminary design parameters of the landing system for the honeycomb crushable absorber. It might be obvious that selecting a larger footprint radius and smaller primary angle will provide great stability and ground clearance. However, the mass of such configuration would increase tremendously which would not be desirable. As a result, preliminary design parameters values are selected based on a compromise between the landing performance and configuration mass. Robustness and adequate design margins are also taken into account in the selection to allow changes to be altered when further details are added to the landing gear design in the future. Table 5-2 shows the parameters values of a selected design for landing system with honeycomb absorber element.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of Footprint</td>
<td>[m]</td>
<td>6.0</td>
</tr>
<tr>
<td>Height of Landing Leg</td>
<td>[m]</td>
<td>4.0</td>
</tr>
<tr>
<td>Primary Angle</td>
<td>[°]</td>
<td>25</td>
</tr>
<tr>
<td>Secondary Angle</td>
<td>[°]</td>
<td>80</td>
</tr>
</tbody>
</table>

Since the requirements of the honeycomb absorber elements required for landing of configuration 1 and 2 are different, a two stage honeycomb absorber is necessary to be implemented into the landing system. The load-stroke curves of the primary and secondary absorber elements are re-designed to accommodate both landing load cases. Load levels are derived from previous study and stroke values are adjusted to meet the stability and clearance requirements. Adequate stroke must be available for energy absorption without bottoming of the honeycomb absorber. The chosen preliminary design of a two stage load level curve, defined in each primary and secondary absorber element is shown in Table 5-3.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Load Stage 1</td>
<td>[kN]</td>
<td>20.0</td>
</tr>
<tr>
<td>Primary Stroke Stage 1</td>
<td>[m]</td>
<td>0.5</td>
</tr>
<tr>
<td>Primary Load Stage 2</td>
<td>[N]</td>
<td>80.0</td>
</tr>
<tr>
<td>Primary Stroke Stage 2</td>
<td>[m]</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Secondary Load Stage 1 [kN] 20.0
Secondary Stroke Stage 1 [m] 0.2
Secondary Load Stage 2 [kN] 40.0
Secondary Stroke Stage 2 [m] 0.6

With this honeycomb crushable absorber element load-stroke curve design, the new parameters values are implemented into the mathematical model of the RLRV. The load cases are re-simulated and the landing performance is tabulated in Table 5-4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Load Case 1</th>
<th>Load Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability Distance</td>
<td>[m]</td>
<td>5.81</td>
<td>1.60</td>
</tr>
<tr>
<td>Clearance Distance</td>
<td>[m]</td>
<td>3.12</td>
<td>3.49</td>
</tr>
</tbody>
</table>

Both results from the load cases show that stability distance and ground clearance satisfy that of the requirements.

Appendix A and Appendix B show the full results of the landing performance for the honeycomb absorber landing system. Fig. 5-13 and Fig. 5-14 show the graphical results for the preliminary landing system with honeycomb absorbers.

Fig. 5-13 Simulations graphical results for preliminary landing system with honeycomb absorbers in case simulation 1
5.5 Metal Bellow Absorber

This case study is based on metal bellow absorber implemented into the mathematical model of the RLRV in MATLAB/ Simulink environment. The metal bellow absorber is controlled by a few parameters as explained in Section 4.3.2. Orifice size, initial chamber pressures, volumes of chamber, stiffness of bellow, diameter of cylinder. In this case simulations, only the chamber pressures will be varied to determine the necessary required design parameters while the rest of the parameters are fixed.

5.5.1 Case Simulation 1

RLRV configuration 1 is simulated landing away from the terrain slope of 2°. Touchdown velocities are 1 m/s horizontal and -1.5 m/s vertical. Primary angle is 25° and secondary angle is 80°. In this case study, footprint radius ranges from 5.0 m to 7.0 m, initial primary chamber pressure varies from 700 kPa to 1000 kPa and initial secondary chamber pressure varies from 200 kPa to 400 kPa. Bottoming of the metal bellow shock absorber is taken into account. If bottoming occurs during landing, the stability distance is set to -1 and ground clearance is set to 3.0 m to indicate non acceptance of results. The simulation results are shown in Fig. 5·15 and Fig. 5·16.
Fig. 5-15 Effect of footprint radius, primary pressure and secondary pressure on stability distance for metal bellow absorber landing system in load case 1

Fig. 5-16 Effect of footprint radius, primary pressure and secondary pressure on ground clearance for metal bellow absorber landing system in load case 1

From the results, minimum footprint radius of 6.0 m is required for the stability of the landing system. Lower primary pressure contributes to better stability but lower ground clearance. Secondary pressure of 300 kPa seems to provide better stability among the other secondary pressure values. Larger secondary pressure provides better ground clearance.

5.5.2 Case Simulation 2

RLRV configuration 2 is simulated landing away from the terrain slope of 5 °. Touchdown velocities are 1 m/s horizontal and 1.5 m/s vertical. Similar to case simulation 1, footprint radius ranges from 5.0 m to 7.0 m, initial primary chamber pressure varies from 700 kPa
to 1000 kPa and initial secondary chamber pressure varies from 200 kPa to 400 kPa. Results are shown in Fig. 5-17 and Fig. 5-18.

Fig. 5-17 Effect of footprint radius, primary pressure and secondary pressure on stability distance for metal bellow absorber landing system in load case 2

Fig. 5-18 Effect of footprint radius, primary pressure and secondary pressure on ground clearance for metal bellow absorber landing system in load case 2

Fig. 5-17 and Fig. 5-18 show that a minimum of 6.5 m footprint radius is required for stability and clearance requirements. Primary pressures and secondary pressures variation does not seem to affect the landing on load case 2 as much as load case 1. However, it might be possible to see some differences as the footprint radius increases.
5.5.3 Performance

From the study of case simulations 1 and 2, possible preliminary design parameters of the landing system with metal bellow absorber design could be defined. As bottoming has already been considered in the output results of the load cases, the preliminary parameters can be obtained directly from the results. The parameters are tabulated in Table 5-5.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of Footprint</td>
<td>[m]</td>
<td>6.5</td>
</tr>
<tr>
<td>Height of Landing Leg</td>
<td>[m]</td>
<td>4.0</td>
</tr>
<tr>
<td>Primary Angle</td>
<td>[°]</td>
<td>25</td>
</tr>
<tr>
<td>Secondary Angle</td>
<td>[°]</td>
<td>80</td>
</tr>
</tbody>
</table>

Since the RLRV will be using the same landing system for different payloads, the metal bellow shock absorber, unlike the two stage honeycomb crushable element, has to support both landing configuration 1 and 2 with one specific design. Additionally, the value of the initial pressure chamber must ensure that the shock absorber does not bottom during landing impact which has been factored into the simulation results. The chosen initial pressures for primary and secondary shock absorbers are shown in Table 5-6.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Pressure</td>
<td>[kPa]</td>
<td>900</td>
</tr>
<tr>
<td>Secondary Pressure</td>
<td>[kPa]</td>
<td>300</td>
</tr>
</tbody>
</table>

The selected initial pressure values are implemented into the lander model and the analysis is simulated for both load case 1 and 2. The performance of the RLRV preliminary landing gear design with metal bellow shock absorber is shown in Table 5-7.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Load Case 1</th>
<th>Load Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability Distance</td>
<td>[m]</td>
<td>5.3</td>
<td>2.2</td>
</tr>
<tr>
<td>Clearance Distance</td>
<td>[m]</td>
<td>3.8</td>
<td>4.0</td>
</tr>
</tbody>
</table>
The landing system with metal bellows of the chosen parameters is able to land the RLRV in the two load cases without compromising on the stability or the ground clearance. Results of the simulations are shown in Appendix C and Appendix D. Fig. 5-19 and Fig. 5-20 illustrate the graphical results for the preliminary landing system with metal bellows absorbers.

**Fig. 5-19** Simulations graphical results for preliminary landing system with metal bellows absorbers in case simulation 1

**Fig. 5-20** Simulations graphical results for preliminary landing system with metal bellows absorbers in case simulation 2
Chapter 6
Preliminary Design

The design of the landing system consists of the sub components in the assembly of the landing system. Structural requirements of each component of the landing system are also assessed to determine the dimensions necessary for the sizing of the components to ensure that no structural failure occur during landing.

6.1 Configuration

The landing gear has a configuration of the cantilever type design. Fig. 6-1 shows an overall configuration of the RLRV with the landing legs deployed. The primary strut on each landing gear assembly consists of an upper outer cylinder with a lower inner cylinder for compression stroking. It is connected the footpad, middle attachment to the secondary strut and the top attachment of the lander body structure with ball joint attachment.

![Fig. 6-1 Overall view of the RLRV landing gear system](image_url)

The footpad is attached to the lower end of the primary strut with a ball joint attachment. Similarly, two secondary struts, each consisting of an outer cylinder and inner cylinder, connect the middle attachment of the primary strut to the deployment mechanism. The
absorber elements are implemented within the cylinder of the primary and secondary struts.

6.2 Design Requirements

In the preliminary stage, the sub components are simplified into geometries for structural and mass estimations. Complex geometries are not required at this stage of the design. In this section, the geometry as well as design requirements of the components is explained.

6.2.1 Primary Strut

The geometry of the primary strut is simplified as an annulus cylinder geometry shown in Fig. 6-2. The primary cylinder is defined by the outer diameter, $D_p$, thickness, $t_p$ and length, $L_p$. $L_{pl}$ is the length of the lower section of the primary strut.

![Fig. 6-2 Simplified geometry of primary strut](image)

The primary strut is mainly subjected to compressive stresses from the compressive load of the primary energy absorber. However, since the secondary strut is connected to the middle attachment point of the primary strut, the primary strut is additionally subjected to bending moment induced by the tension or compression of the secondary strut. The moment due to the secondary strut is given by

$$M_p = F_s \sin (\tau_s - \tau_p) L_t \frac{(L_p - L_t)}{L_p}$$  \hspace{1cm} (6-1)

where $F_s$ is the force from the secondary strut acting on the middle attachment of the primary strut, $L_p$ is the total length of the primary strut, $L_{pl}$ is the length of the lower
section of primary strut. The compressive or tensile stress due to the bending moment is given by

$$\sigma_m = -\frac{M_p D_p}{2I_p} \quad (6.2)$$

where $D_p$ is the outer diameter of the primary strut and $I_p$ is the moment of inertia about the neutral axis. Compressive load, $F_a$ from the primary absorber element contribute to compressive stress in the primary strut.

$$\sigma_a = \frac{F_a}{A_p} \quad (6.3)$$

where $A_p$ is the cross sectional area of the primary strut. This increases the risk of buckling failure in cylinder structure. The total compressive stress in the primary strut is given by

$$\sigma_p = \sigma_m + \sigma_a \quad (6.4)$$

In our case, the buckling equation is governed by Johnson Parabolic Formula for short column tube. The critical buckling stress is given by

$$\sigma_c = \sigma_f - \frac{\sigma_f \left( \frac{L_e}{\rho_p} \right)^2}{4\pi^2 E_p} \quad (6.5)$$

where $\rho_p$ is the radius of gyration, $L_e$ is the effective buckling length which is about half the total length of the primary strut and $E_p$ is the Young’s modulus of the primary strut material. $\sigma_f$ is the strength of the material of strut at failure. Local buckling in the primary strut is also considered in this structural sizing. The critical local buckling stress of the primary strut is given by [18].

$$\sigma_c = \frac{K_c E_p}{D_p / t_p} \quad (6.6)$$

where $K_c$ is a theoretical factor due to imperfection [18], $D_p$ is the outer diameter of the primary strut and $t_p$ is the thickness of the primary cylinder. Structural safety factor of 1.50 shall be applied to the calculation of the primary strut cylinder diameter and thickness.
6.2.2 Secondary Strut

The secondary struts provide lateral resistance to the primary strut and resist the spread of the primary struts during landing. Two secondary struts connect to the middle attachment point of each primary strut at an approximate angle of 45°. The secondary strut is represented by an annulus cylinder strut similar to that of the primary strut.

![Diagram of Secondary Strut](image)

Fig. 6-3 Simplified geometry of secondary strut

$D_s$ is the outer diameter of the secondary strut. $t_s$ is the thickness of the secondary strut. $L_s$ is the length of the secondary strut. The secondary struts are subjected to either compressive or tensile loads. In most landing scenarios, the secondary struts experience only tensile loads. The tensile or compressive stress in the secondary struts depends on the force of the secondary absorber element and is given by

$$\sigma_s = \frac{F_a}{A_s} \quad (6.7)$$

where $F_a$ is the force exerted from the shock absorber and $A_s$ is the cross sectional area of the secondary strut. Since buckling failure mode is considered in the secondary strut, the critical buckling stress is also given by the Johnson Parabolic equation [18]

$$\sigma_c = \sigma_f - \frac{\sigma_f (\frac{L_e}{\rho_e})^2}{4\pi^2E_s} \quad (6.8)$$

where $\rho_e$ is the radius of gyration, $L_e$ is the effective buckling length which is about half the total length of the secondary strut and $E_s$ is the Young’s modulus of the secondary strut material. $\sigma_f$ is the strength of the strut material at failure. Local buckling is also be considered in the secondary strut because of its thin wall cylinder structure under compressive loads. The equation, similar to primary strut, governing this is given by

$$\sigma_c = \frac{K_cE_s}{D_s/t_s} \quad (6.9)$$
where $K_c$ is a theoretical factor due to imperfection [18], $D_s$ is the outer diameter of the secondary strut and $t_s$ is the thickness of the secondary cylinder. Structural safety factor of 1.50 is accounted for in the structural sizing of the secondary strut diameter and thickness.

6.2.3 Footpad

The footpad supports the mass of the lander against the lunar regolith. Large footpad surface area would prevent deep penetration of the ground as compared to smaller footpad surface area. The shape of the footpad also affects the friction force acting on the footpad. However, to avoid detailed designing of the footpad in the preliminary stage, general spherical shape is selected for the footpad. $D_f$ is the diameter of the footpad. $L_f$ is the height of the footpad and $t_f$ is the thickness of the footpad. A simplified geometry of the footpad is shown in Fig. 6-4.

Fig. 6-4 Simplified representation of footpad (left) and interaction with lunar soil (right)

In this preliminary stage, the spherical-dish footpad is designed to penetrate within the top 0.15 m layer of the lunar regolith for static landing of the lunar lander. Hence, the maximum penetration depth of unprepared lunar regolith is 0.15 m which has an average bulk density $1.50 \pm 0.05$ g/cm$^3$ [14]. The average static bearing strength at this bulk density is estimated to be approximately 10000 N/m$^2$ as interpolated exponentially from [14] and shown in Table 6-1. Bearing capacity at 1.50 g/cm$^3$ bulk density is 10000 N/m$^2$

| Table 6-1 Typical average lunar bulk density [14] |
|-----------------|-----------------|
| Bulk Density    | Bearing Strength|
| [g/cm$^3$]      | [N/m$^2$]       |


With a payload of 25 tons, the RLRV can weigh up to 28 tons during landing. The force acting on each footpad is 11.36 kN due to the lunar gravity. With a structural safety factor of 1.50, a planar surface area of 1.135 m\(^2\) is required of each footpad to maintain soil static bearing capability of 10000 N/m\(^2\).

### 6.2.4 Deployment Mechanism

The deployment mechanism hold the landing legs stowed during launch and in space fuelling operation. Before landing, the deployment of the landing system must be carried out. However, the detailed design of the deployment mechanism is not available during the preliminary design phase. Since the axial loadings on the deployment truss are similar to that of the secondary struts during landing, the structural design requirements are regard as similar to that of the secondary struts.

### 6.2.5 Thermal Insulation

Thermal insulation is required to protect the landing gear from thermal induced damage and minimise changes to the mechanical properties of the subcomponents due to thermal variations. Deployment and landing mechanism can also be affected due to thermal expansion or contraction of the joints and interfaces. The plume heating of the engine can cause a significant thermal problem near the lunar surface.

The thermal insulation is required to cover the external surface areas of the primary struts, secondary struts and footpads which are exposed to the lunar environment. The detailed analysis of the required thermal insulation is not available in the preliminary phase and shall be considered similar to that of the Apollo Lunar Module.

### 6.2.6 Honeycomb Crushable Absorber

To provide the necessary design crush force, the honeycomb structure must be of a density, material and cell design structure. Referring to [22], the honeycomb crushable absorber is chosen to be made of aluminum alloy 3003 expanded material. The required crush
strength is dependent on the design crush force and the cross section surface area of the struts. The strength of the absorber can be calculated by

\[ \sigma_a = \frac{F_h}{A_h} \]  \hspace{1cm} (6-10)

where \( F_h \) is the design crush force of the honeycomb and \( A_h \) is the cross-sectional area of the honeycomb cartridge which correspond to the core space of the struts. The density of the absorber element can then be obtained with the calculated crush strength from [22].

6.2.7 Gas Pressurized Metal Bellow Absorber

The design requirements of the metal bellow absorber implemented within the primary strut and secondary strut can be estimated by hoop stress and longitudinal stress based on the maximum pressure reached in the pressure chambers during the landing. Stress in the radial direction is given by

\[ \sigma_{bt} = \frac{P_b D_b}{2 t_b} \]  \hspace{1cm} (6-11)

where \( t_b \) is the thickness of the bellow chamber, \( P_b \) is the pressure in the bellow and \( D_b \) is the diameter of the bellow chamber. Since the pressure is contained in a closed chamber, the longitudinal stress can be estimated by

\[ \sigma_{bn} = \frac{P_b D_b}{4 t_b} \]  \hspace{1cm} (6-12)

The maximum stress required of the struts from the metal bellow shock absorbers is dependent on the force, \( F_b \) from the absorber and the cross sectional area of the metal bellow chamber, \( A_b \) given by

\[ \sigma_a = \frac{F_b}{A_b} \]  \hspace{1cm} (6-13)

Metal bellow design is determined by the diameter of the shock absorber and the length of the stroke required. The selection of suitable metal bellows can be directly chosen from the off the shelf manufacturer's data shown in [23]. The mass of the bellow can be determined by calculating the number of capsules required to achieve the length of the stroke.
6.3 Materials

Materials are considered an important factor for the structural and overall mass estimation for the landing system. Similar to materials for aerospace applications, the key driving force for the selection of material for the landing system is the strength-to-weight ratio. Two of the materials to be considered in this preliminary design of the landing system are aluminum alloy and carbon fibre reinforced plastics.

6.3.1 Aluminum Alloy

Aluminum alloy has been widely used in aerospace applications, both in aviation and space industry, and is known for its corrosion resistance, density and high strength-to-weight ratio. The composition of the elements in the alloy determines the specific mechanical properties. Additionally, aluminum alloy can be further strengthened by heat treatment or cold working.

Among all the series of aluminum alloy, the 7000 series aluminum alloy is considered to be the highest strength aluminum alloy. These alloys can be strengthened by solution heat treatment and precipitation hardening. For Apollo LM, aluminum alloy 7178 was used for the primary struts and aluminum alloy 2024 was used for the secondary struts [5]. However, due to its susceptibility to stress corrosion cracking, the aluminum alloy has been obsolete from the Metallic Materials Properties Development and Standardization (MMPDS) handbook [19]. In this preliminary design analysis, reusability remains one of the important factors and hence aluminum alloy 7075 is chosen for primary struts, secondary struts, deployment truss and footpad for the RLRV landing system. The typical mechanical properties of aluminum alloy 7075 is tabulated in Table 6-2.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic Modulus</td>
<td>[GPa]</td>
<td>71.7</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>[MPa]</td>
<td>503</td>
</tr>
<tr>
<td>Density</td>
<td>[kg/m³]</td>
<td>2810</td>
</tr>
</tbody>
</table>

6.3.2 Fibre Reinforced Plastic

Fibre reinforced plastics is currently widely used in aerospace, automotive and marine applications. This composite material consists of a polymer matrix reinforced with fiber
materials. The mechanical strength and toughness are enhanced by the high-strength and stiffness fibres embedded in the polymer matrix. This combination allows the material to achieve high stiffness and strength with low density properties. Among the common industrial fibres such as glass fibres and aramid fibres, carbon fibre reinforced plastics (CRFP) offer higher tensile strength and higher stiffness. In regards to space applications, CRFP inhibits high thermal conductivity, low coefficient of thermal expansion and low density. In this preliminary design, CFRP material is used for the primary struts, secondary struts and deployment truss as a comparison to aluminum alloy. The typical mechanical properties of CFRP provided in Table 6-3.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic Modulus</td>
<td>[GPa]</td>
<td>70.0</td>
</tr>
<tr>
<td>Strength</td>
<td>[MPa]</td>
<td>608</td>
</tr>
<tr>
<td>Density</td>
<td>[kg/m]</td>
<td>1605</td>
</tr>
</tbody>
</table>

### 6.4 Mass Estimation

The overall mass estimation depends on the design requirements of each individual sub component discussed in the previous sections. These requirements are dependent on the materials of the component and the stresses of which the components are required to withstand. The structural components are assumed to have simplified geometry for the preliminary design stage. The primary strut and secondary struts are hollow cylinders with annulus cross-sectional area. The footpad is designed of a spherical dish shape.

Structural factors and additional mass margin factors are factored into the mass estimation on top of the structural sizing to account for the additional fittings, details and unaccounted mass at this stage of mass estimation. Because of the lack of available lunar lander references, the Apollo lunar lander is studied closely for these margins.

#### 6.4.1 Mass Margin Estimation

From the study of the Apollo lander landing system [5], the nominal diameter and thickness of the primary strut and secondary strut can be recalculated based on the design requirements and loads from the honeycomb absorbers. Additional mass factor can be derived from the difference in estimation of calculated mass. These are shown in Table 6-4.
The maximum compressive load acting on the primary strut is 42.2 kN from the maximum crush force of the second stage honeycomb absorber element. The secondary strut tension of 28.3 kN force at the middle attachment point of the primary strut, lead to a bending moment of 25.8 kNm on the primary strut. This differs from the bending moment of the Apollo LM which has a value of 33.9 kNm because there might be unaccounted bending moments from the deployment of the landing legs. With a predetermined primary strut diameter of 0.140 m, a thickness of 0.00576 m is required to withstand the compressive stress contributing from both the bending moment and compressive load with a structural factor of 1.50. The estimated mass of the primary strut is 20.89 kg which 1.10 times lower than the actual mass because of the fittings and joints. A mass marginal factor of 1.1 shall be accounted for in the mass estimation of primary struts.

The secondary strut is subjected to a maximum load of 20.0 kN compression and 22.2 kN tension [5]. The diameter is predetermined at 0.115 m and thickness calculated at 0.000662 m with a structural factor of 1.50. The estimated mass of the secondary strut is 0.804 kg. This is about twice lower than the actual mass of 1.597 kg because of the fittings and joints. Mass marginal factor of 2.00 shall be accounted for in the mass estimation of secondary struts.

The footpad was designed for a static bearing capability of 6.90 kN/m² [5]. With a touchdown landing mass of 7252 kg, the static force acting on each footpad is 2.94 kN. The calculated footpad diameter is 0.902 m and footpad height is given at 0.178 m. The footpad design is assumed to be in a thin dish shape and its estimated mass is 2.64 kg with a mass margin factor of 1.93 lower than the actual mass.

Thermal insulation for the Apollo Lunar Module had a mass of 7.76 kg which covered an estimated surface area of the primary and secondary strut at 14.775 m². The thermal mass surface density is calculated to be 0.5252 kg/m².

The deployment truss of the Apollo Lunar Module was 9.117 kg. As explained in Section 6.2.4, the design requirements of the deployment truss are similar to that of secondary struts. It is assumed that the deployment mass is an additional mass margin factor of the secondary struts mass. Since the secondary struts weighed 3.19 kg per leg assembly, this mass margin factor can be estimated to be 2.85.
6.4.2  Honeycomb Absorber Landing System Mass Estimation

The mass estimation of the subcomponents of the landing systems are based on the design requirements in the Section 6.2 and the materials selection in Section 6.3. Structural factor of 1.5 is considered in sizing of the primary and secondary struts. The estimated required dimensions of the primary and secondary struts are shown in Table 6.5.
Table 6.5 Primary and secondary strut dimensions for honeycomb absorber element landing system

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Unit</th>
<th>AL7075</th>
<th>CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Strut Diameter</td>
<td>[m]</td>
<td>0.300</td>
<td>0.300</td>
</tr>
<tr>
<td>Primary Strut Thickness</td>
<td>[m]</td>
<td>0.00509</td>
<td>0.00473</td>
</tr>
<tr>
<td>Secondary Strut Diameter</td>
<td>[m]</td>
<td>0.150</td>
<td>0.150</td>
</tr>
<tr>
<td>Secondary Strut Thickness</td>
<td>[m]</td>
<td>0.000561</td>
<td>0.000568</td>
</tr>
</tbody>
</table>

To ensure that the selected dimensions of the struts are of appropriate value, the safety margins of each failure mode is obtained according to design requirements in Section 6.2 and above the structural safety factor of 1.50. The results are presented in Table 6.6. From the results, the sizing of the primary strut is limited by the short buckling failure mode and secondary strut is limited by the local buckling failure mode.

Table 6.6 Safety margin of failure modes for landing system using honeycomb absorber element

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>AL7075</th>
<th>CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Strut Local Buckling</td>
<td>43.1</td>
<td>36.26</td>
</tr>
<tr>
<td>Primary Strut Buckling</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Secondary Strut Local Buckling</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Secondary Strut Buckling</td>
<td>4.04</td>
<td>4.75</td>
</tr>
<tr>
<td>Secondary Strut Tension</td>
<td>5.00</td>
<td>5.73</td>
</tr>
</tbody>
</table>

For mass estimation of the overall landing system, additional mass margins calculated in Section 6.4.1 are factored into the structural mass to account for the uncertainties, additional fittings and connections within the landing gear system. Mass estimation of RLRV landing gear system with honeycomb absorber element is shown in Table 6.7.

Table 6.7 Overall mass estimation using honeycomb absorber element

<table>
<thead>
<tr>
<th>Sub Components</th>
<th>Unit</th>
<th>AL7075</th>
<th>CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Struts</td>
<td>[kg]</td>
<td>517.8</td>
<td>273.9</td>
</tr>
<tr>
<td>Secondary Struts</td>
<td>[kg]</td>
<td>34.9</td>
<td>20.1</td>
</tr>
<tr>
<td>Footpads</td>
<td>[kg]</td>
<td>76.9</td>
<td>77.0</td>
</tr>
<tr>
<td>Deployment Mechanism</td>
<td>[kg]</td>
<td>49.8</td>
<td>28.7</td>
</tr>
<tr>
<td>Thermal Insulation</td>
<td>[kg]</td>
<td>34.9</td>
<td>34.9</td>
</tr>
</tbody>
</table>
6.4.3 Metal Bellow Absorber Landing System Mass Estimation

The mass estimation of the landing system with metal bellow absorber is similar to that of the honeycomb absorber. However, the maximum forces in the struts depends on the simulated maximum forces during landing. These forces are used in a similar way to meet the design requirements explained in Section 6.2 and the materials selection in Section 6.3. The dimensions required for the primary strut and secondary strut is shown in Table 6-8. Margins of the failure modes are computed in Table 6-9.

Table 6-8 Primary and secondary strut dimensions for metal bellow absorber element landing system

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Unit</th>
<th>AL7075</th>
<th>CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Strut Diameter</td>
<td>[m]</td>
<td>0.300</td>
<td>0.300</td>
</tr>
<tr>
<td>Primary Strut Thickness</td>
<td>[m]</td>
<td>0.00413</td>
<td>0.00408</td>
</tr>
<tr>
<td>Secondary Strut Diameter</td>
<td>[m]</td>
<td>0.150</td>
<td>0.150</td>
</tr>
<tr>
<td>Secondary Strut Thickness</td>
<td>[m]</td>
<td>0.000435</td>
<td>0.000440</td>
</tr>
</tbody>
</table>

Table 6-9 Margin of landing system using metal bellow absorber element

<table>
<thead>
<tr>
<th>Sub Components</th>
<th>Unit</th>
<th>AL7075</th>
<th>CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Strut Local Buckling</td>
<td>[-]</td>
<td>20.13</td>
<td>19.31</td>
</tr>
<tr>
<td>Primary Strut Buckling</td>
<td>[-]</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Secondary Strut Local Buckling</td>
<td>[-]</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Secondary Strut Buckling</td>
<td>[-]</td>
<td>4.71</td>
<td>5.37</td>
</tr>
<tr>
<td>Secondary Strut Tension</td>
<td>[-]</td>
<td>6.05</td>
<td>7.40</td>
</tr>
</tbody>
</table>

Mass estimation of RLRV landing gear system with metal bellow absorber element is shown in Table 6-10.

Table 6-10 Overall mass estimation using metal bellow absorber element

<table>
<thead>
<tr>
<th>Sub Components</th>
<th>Unit</th>
<th>AL7075</th>
<th>CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Struts</td>
<td>[kg]</td>
<td>476.7</td>
<td>269.1</td>
</tr>
<tr>
<td>Component</td>
<td>[kg]</td>
<td>Value 1</td>
<td>Value 2</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>Secondary Struts</td>
<td>34.3</td>
<td>19.8</td>
<td></td>
</tr>
<tr>
<td>Footpads</td>
<td>77.0</td>
<td>77.0</td>
<td></td>
</tr>
<tr>
<td>Deployment Mechanism</td>
<td>48.9</td>
<td>28.2</td>
<td></td>
</tr>
<tr>
<td>Thermal Insulation</td>
<td>39.3</td>
<td>39.3</td>
<td></td>
</tr>
<tr>
<td>Absorber Element</td>
<td>71.2</td>
<td>67.80</td>
<td></td>
</tr>
<tr>
<td><strong>Total Landing System</strong></td>
<td>747.3</td>
<td>501.1</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 7

Discussion

7.1 Assumptions

The preliminary design for the RLRV landing system provides the initial study on its landing dynamics and design requirements. Various assumptions have been made through this process and it is important to state them in order not to misunderstand the values obtained in this study.

Driving factors in this study are the stability distance and ground clearance. Other landing performance factors such as settling time, maximum overshoot of the elastic bouncing of the landing system or damping coefficient are not taken into account at this design stage.

Geometries of the components are simplified to represent the main affecting parameters. Detailed design of the connecting fittings, ball joints and internal features are not considered. Especially for the shock absorbers elements, only additional mass contributed by the difference of the shock absorbers is added. In any of these cases, mass marginal factors are considered to account for these additional mass.

Failure modes of the CFRP strut are studied in a similar way to that of the aluminum strut. The CFRP tensile and compressive strengths are assumed to be similar to the tensile yield strength and compressive yield strength of aluminum. In practical cases, the failure modes of CFRP such as delamination, debonding and fiber breakage is much more complicated and has to be studied in details.

7.2 Discussion

The landing performance, size of landing system, mass of landing systems and materials used for the RLRV landing systems were shown in the previous sections.
7.2.1 Landing Performance

The landing performance of the landing system with honeycomb absorbers displayed an effective method of energy absorption for landing. The honeycomb absorbers crush at a predetermined force level and strokes through the absorber with minimum elastic energy stored within the absorber. It is relatively simple to design the honeycomb absorber as the predetermined crush is proportional to the energy absorption.

The landing performance of the landing system with metal bellow shock absorbers seems to have a more elastic effect. The gas chambers and orifice in the absorber provides damping but also provides an elastic air spring effect to the landing. The stiffness metal bellows contribute directly to the elasticity of the absorber. There are other parameters of the metal bellow shock absorbers which could be further optimised to provide a better damping which could improve the landing performance.

In this study, the landing system with metal bellow absorbers is a less effective means of energy absorption as compared to the honeycomb absorbers.

7.2.2 Design Parameters of Landing System

The primary angles and secondary angles of the cantilever design were studied with a simple cantilever model. Results shown in Section 5.2 show that primary angle of 20 to 25 ° provides a good choice for the cantilever design. Secondary angle of about 80 ° show a relatively good effect on keeping the spread of the primary struts for stability distance and ground clearance.
The primary angle, in this study, has also a significant effect on the length of the primary strut which influences the mass of the landing system. Fig. 7-1 shows an illustration of the difference in primary angle. The secondary angle, on the other hand, has minimum effect on the mass of the landing system.

The footprint radius requirement for the RLRV landing system with honeycomb absorbers is 6.0 m minimum to meet the landing performance requirements as shown in Section 5.4.3. The footprint radius for the landing system with metal bellow absorber has a minimum of 6.5 m as shown in Section 5.5.3. This is because the honeycomb absorbers have a better energy absorption than the metal bellow absorbers. Hence, leading to a smaller footprint radius required for the honeycomb absorbers.

7.2.3 Mass of Landing System

Comparison of the mass of the RLRV landing system with honeycomb absorber with the Apollo LM is shown in Table 7-1. The percentage of the total mass for the RLRV seems to be close to that of the Apollo LM. However, it is important to note that the terrain conditions and missions for RLRV mission differs from the Apollo LM. Hence, this only provide a validity guideline for the values calculated for the initial mass estimation.

Table 7-1 Mass percentage comparison of RLRV landing system and Apollo LM landing system

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>RLRV</th>
<th>Apollo LM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parameters</td>
<td>Unit</td>
<td>Honeycomb</td>
<td>Metal bellow</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>------</td>
<td>-----------</td>
<td>--------------</td>
</tr>
<tr>
<td>Primary Struts</td>
<td>[kg]</td>
<td>517.8</td>
<td>476.7</td>
</tr>
<tr>
<td>Secondary Struts</td>
<td>[kg]</td>
<td>34.9</td>
<td>34.3</td>
</tr>
<tr>
<td>Footpads</td>
<td>[kg]</td>
<td>76.9</td>
<td>77.0</td>
</tr>
<tr>
<td>Deployment Mechanism</td>
<td>[kg]</td>
<td>49.8</td>
<td>48.9</td>
</tr>
<tr>
<td>Thermal Insulation</td>
<td>[kg]</td>
<td>34.9</td>
<td>39.3</td>
</tr>
<tr>
<td>Absorber Element</td>
<td>[kg]</td>
<td>12.4</td>
<td>71.2</td>
</tr>
<tr>
<td><strong>Landing System Mass</strong></td>
<td>[kg]</td>
<td>726.7</td>
<td>747.3</td>
</tr>
</tbody>
</table>

Another contributing factor to the landing system mass to note for the metal bellows required. The metal bellows are made of 304/347 stainless steel [23]. The sizing of the metal bellows depends on the stroke required and the outer diameter of the metal bellows allowed in the design. The longer the stroke required, the larger the mass of the metal bellows required element.

### 7.2.4 Material of Landing System

AL7075 and CFRP are materials considered in the struts of the landing system. AL7178 is traditionally used in the struts of the Apollo LM while CFRP is a proposed material as an alternative to reduce the mass of the landing system. AL7075 is chosen, as explained in Table 7-3 shows the comparison between AL7075 and CFRP.
<table>
<thead>
<tr>
<th>Landing System</th>
<th>Unit</th>
<th>AL7075</th>
<th>CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landing System with Honeycomb Absorber</td>
<td>[kg]</td>
<td>726.7</td>
<td>446.9</td>
</tr>
<tr>
<td>Landing System with Metal Bellow Absorber</td>
<td>[kg]</td>
<td>747.3</td>
<td>501.1</td>
</tr>
</tbody>
</table>

The use of CFRP on the landing system with honeycomb absorber reduces the mass by 38.5% and for the landing system with metal bellow absorber by 32.9%. This shows that the using CFRP as struts material could greatly lessen the mass of the landing system. With the increasing technology in using composites in space applications, it is a feasible option consider CFRP for the RLRV.
Chapter 8
Conclusion and Future Work

8.1 Conclusion

This thesis work begins with an objective to develop a preliminary design of the landing systems for a reusable lunar resupply vehicle to transport payloads between the Moon’s surface and Moon’s rendezvous orbit. During the period of the thesis, the landing system configurations, design parameters, types of material, shock absorber types and landing dynamic are studied to provide a preliminary design for the landing system.

Design parameters are identified to set the design requirements and defines the overall design of the landing system. Design drivers are used to measure the landing performance of the study. Touchdown conditions are set according to the required missions of the RLRV.

Case simulations show how certain design parameter could influence the outcome of the design drivers. Landing away from slopped terrain has lower stability than landing towards slopped terrain. Higher ground friction leads to lower stability for toppling over. Increasing the footprint radius contributes to stability. Primary angles and secondary angles were chosen at 25° and 80° respectively. Footprint radius for landing system with honeycomb absorber is 6.0 m and for landing system with metal bellow absorbers is 6.5 m.

Honeycomb absorber provides an effective and simple energy absorption by crushing which is an irreversible process. Lower crush force for honeycomb absorbers provides more effective energy absorption hence, increases stability but decreases the ground clearance due to larger stroke. For the purpose of landing different payloads, two–staged honeycomb absorber can be implemented to account for this difference. Honeycomb absorbers are relatively light weight options for energy absorption elements.

Metal bellow shock absorbers are shown to be possible reusable shock absorbers to be used in future lunar mission. Landing performance of lander model with metal bellow shock absorbers, however, exhibits a more elastic and less damping landing performance as compared to honeycomb absorbers. Parameters in the metal bellow absorbers are required
to be optimised to obtain the damping coefficient required for the system. The mass increase in using the metal bellow shock absorber can be compensated by the lower forces induced by the metal bellow shock absorbers.

Aluminum alloy material provides a stable material of choice for the primary struts, secondary struts and other sub components of the landing system. On the other hand, CFRP can be the possible material choice which can reduce the mass of an aluminum alloy landing system by approximately 35%, which is a considerable amount of mass saving for space applications.

Finally, it can be concluded that the objective of the thesis work to provide an initial mass estimation of the preliminary design landing system is met. This thesis presented two options of shock absorbers to be considered to meet the higher intent using reusable components in the landing system. Two important materials considerations are also implemented in this preliminary phase to obtain an understanding of the material influence on the mass of the landing system.

### 8.2 Future Work

This preliminary study provides an initial baseline for the design of the landing system for RLRV. Future work can be follow up to improve on the design and eventually leading it to the actual design of the landing system.

Different landing configurations such as the inverted tripod landing gear design could be looked into as a comparison with the cantilever landing gear design. It is possible that other landing gear design type could provide a better mass and landing performance of the lander.

Three dimensional landing model can be developed to simulate the landing dynamics of the case simulations. High fidelity models will provide a more accurate results of the landing. Uncertainties effect such as variation of ground frictions or ground obstacles could be factored into the analysis for a more realistic landing.

More possibilities of other shock absorbers for space applications such as the electromagnetic shock absorbers or electromechanical shock absorbers can be studied and implemented into the landing model for landing performance comparison with the honeycomb absorbers.
Optimisation of the design parameters will improve on the overall landing system design. Lighter structure of the landing systems are always sought after for space applications to reduce the amount of fuel required for the mission.

Finally, the cost modelling of the landing system components and materials would be necessary in the further design stages to keep the cost of manufacturing of the landing system to an effective and minimum value.
References


[12] W. S. Gullotta, Coleton G. Kirchner, Aaron P. Yuengert, Peter A. Zink, Resettable Landing Gear for Mars Hopper, 11th International Planetary Probe Workshop, June 2014.


Appendix A

This appendix shows the simulation results for the landing system with honeycomb shock absorber for load case 1.
Appendix B

This appendix shows the simulation results for the landing system with honeycomb shock absorber for load case 2
Appendix C

This appendix shows the simulation results for the landing system with metal bellow shock absorber for load case 1.
Appendix D

This appendix shows the simulation results for the landing system with metal bellow shock absorber for load case 2
Appendix E

The following MATLAB code and Simulink model are used to simulate the landing dynamics of the lander model as discussed in the work of this thesis. This appendix only present an example of the code and model used for the landing system with honeycomb absorber to give the reader an idea of the implementation.

MATLAB Code:

```matlab
close all
clear all
clc

%% Input Parameters
orientation = '1-2-1';
config = 'config07';
absorber = 'honeycomb';
lunarmodel = 'lunarlander04_model01';
output = 'true';
test = 'Test01';

% Mass Estimation Parameters
materialprimary = 'CFRPSTD'; % [-] Material of Primary Strut
diameterprimary = 0.3; % [-] Diameter of Primary Strut
materialsecondary = 'CFRPSTD'; % [-] Material of Secondary Strut
diametersecondary = 0.15; % [-] Diameter of Secondary Strut
materialfoot = 'AL7075'; % [-] Material of Footpad

% Body Parameters
[m,I,Lb] = lunarlanderconfig(config);
L1 = 2.25; % [m] Width Body Left
cdist = 4.0; % [m] Initial Clearance Distance

% Approach Velocity
Vhor = 1.0; % [m/s] Horizontal Touchdown Velocity
Vver = -1.5; % [m/s] Vertical Touchdown Velocity
Vapproach = 'drop'; % [-] touch or drop

% Landing Gear Parameters
Footprint = 6.0; % [m] Footprint Radius
Pangle = 25/180*pi; % [rad] Primary Angle
Sangle = 80/180*pi; % [rad] Secondary Angle

% Absorber Parameters
LLp1 = 20000; % [N] Primary Strut Stage 1 Load Level
LLp2 = 80000; % [N] Primary Strut Stage 2 Load Level
SLp1 = 0.5; % [m] Primary Strut Stage 1 Stroke Limit
SLp2 = 0.3; % [m] Primary Strut Stage 2 Stroke Limit
LLs1 = 20000; % [N] Secondary Strut Stage 1 Load Level
LLs2 = 40000; % [N] Secondary Strut Stage 2 Load Level
SLs1 = 0.2; % [m] Secondary Strut Stage 1 Stroke Limit
SLs2 = 0.4; % [m] Secondary Strut Stage 2 Stroke Limit

% Solve Parameters
```
dt = 0.00001; % [s] integration/simulation time step
tdur = 15; % [s] simulation duration
dslimit = -1.0; % [s] limit of instability

% Simulation Parameters
di = 5000; % [-] simulation step

%% Environment Parameters
g = 1.62; % [m/s^2] Gravity
c = 5.0e5; % [Ns/m] Ground Damping Coefficient
k = 5.0e8; % [N/m] Ground Stiffness Coefficient
mui = 0.3; % [-] Friction Coefficient
theta = -2/180*pi; % [rad] Terrain Slope

%% PARAMETERS
% Body Structure Parameter
Fp = Footprint; % [m] Footprint
L3 = L1; % [m] Width Body Right
tau0 = Pangle; % [rad] Angle of primary strut with vertical
taus0 = Sangle; % [rad] Angle of secondary strut with vertical
phi0 = 0/180*pi; % [rad] Initial elevation of lander
phidot0 = 0; % [rad] Initial elevation rate of lander

% Landing System Parameter
Lh = Fp-L1; % [m] Horizontal Length of Landing System
Lv = Lh/tan(tau0); % [m] Vertical Height of Landing System
Ld = Lv - cdist; % [m] Length of Upper to Lower Attachment
L2 = Lb - Ld; % [m] Vertical Distance from CG to the Top Attachment
psi = atan(L1/L2); % [rad] Angle of Primary Strut attached point to CG

Ls0 = Ld*tan(tau0)/(sin(taus0)-cos(taus0)*tan(tau0)); % [m] Length of Secondary Strut
Lsv = Ls0*cos(taus0); % [m] Vertical Length of Secondary Strut
Lsh = Ls0*sin(taus0); % [m] Horizontal Length of Secondary Strut
Lpv = Lsv + Ld; % [m] Vertical Length of Primary Upper Section
Lph = Lsh; % [m] Vertical Length of Primary Upper Section

L10 = (cdist-Lsv)/cos(tau0); % [m] Length of Leg1
L20 = L10; % [m] Length of Leg2
Lm = sqrt(Lv^2+Lh^2); % [m] Length of Primary Strut
Lr = L10/Lm; % [-] Ratio attached at Leg1
Lp = sqrt(Lpv^2+Lph^2); % [m] Length of Primary Upper Section
Np = 2; % [] Number of Primary Struts to each leg assembly
Ns = 2; % [] Number of Secondary Struts to each leg assembly

%% Mass Structure
lengthprimary = L10+Lp;
lengthsecondary = Ls0;
psisecondary = taus0-tau0;
ratioprimary = Lr;
mass = lunarlanderconfig('config07');

%% Landing Orientation
if strcmp(orientation,'2-2')
m = 0.5*m;
I = 0.5*I;
Fp = Fp*cos(pi/4); % [m] Footprint Radius
L1 = L1*cos(pi/4); % [m]
L3 = L1; % [m]
Lh = Fp-L1; % [m] Horizontal Length of Landing System
tau0 = atan(Lh/Lv); % [rad] angle of primary strut
taus0 = atan(Lsh*cos(pi/4)/Lsv); % [rad] angle of secondary strut
Lv = Lh/tan(tau0); % [m] Vertical Height of Landing System
Ld = Lv - cdist; % [m] Length of Upper to Lower Attachment
L2 = Lb - Ld;

Attachment:
psi = atan(L1/L2); % [rad] Angle of Primary Strut attached point to CG

Ls0 = Ld*tan(tau0)/(sin(taus0)-cos(taus0)*tan(tau0));
Lsv = Ls0*cos(taus0); % [m] Vertical Length of Secondary Strut
Lsh = Ls0*sin(taus0); % [m] Horizontal Length of Secondary Strut
Lpv = Lsv + Ld; % [m] Vertical Length of Primary Upper Section
Lph = Lsh; % [m] Vertical Length of Primary Upper Section

L10 = (cdist-Lsv)/cos(tau0); % [m] Length of Leg1
L20 = L10; % [m] Length of Leg2
Lm = sqrt(Lv^2+Lh^2); % [m] Length of Primary Strut
Lr = L10/Lm; % [-] Ratio attached at Leg1
Lp = sqrt(Lpv^2+Lph^2); % [m] Length of Primary Upper Section

end

if strcmp(orientation,'1-2-1')
m = 0.5*m;
I = 0.5*I;
end

%%
% Mass of Footpad
m1 = 50; % [kg] Mass of Footpad 1
m2 = 50; % [kg] Mass of Footpad 2

% Main Strut
c1 = 2.0e5; % [Ns/m] Damping Coefficient of Main Leg1
k1 = 1.0e8; % [N/m] Stiffness Coefficient of Main Leg1

c2 = 2.0e5; % [Ns/m] Damping Coefficient of Main Leg2
k2 = 1.0e8; % [N/m] Stiffness Coefficient of Main Leg2

% Secondary Strut
c3 = 2.0e5; % [Ns/m] Damping Coefficient of Main Leg1
k3 = 1.0e8; % [N/m] Stiffness Coefficient of Main Leg1

c4 = 2.0e5; % [Ns/m] Damping Coefficient of Main Leg2
k4 = 1.0e8; % [N/m] Stiffness Coefficient of Main Leg2

% Load Factor
LF = 4.0;
LFS = 4.0;
N = 2;

switch orientation
  case '2D'
    hcF = LF*m*g/N; % [N] Force of Primary Absorber Stage 1
    hcF2 = 1.5*hcF; % [N] Force of Primary Absorber Stage 2
    dmax = 1.0; % [m] Maximum crush length
    hcFs = LFs*m*g/N; % [N] Force of Secondary Absorber Stage 1
    hcFs2 = 1.5*hcFs; % [N] Force of Secondary Absorber Stage 2
  end
dmaxs = 1.0; % [m] Maximum crush length

case '2-2' % 2-2 landing
hcF = sqrt((LLp1*cos(Pangle))^2+(LLp1*sin(Pangle)*cos(pi/4))^2); % [N] Force of Primary Absorber Stage 1
hcF2 = sqrt((LLp2*cos(Pangle))^2+(LLp2*sin(Pangle)*cos(pi/4))^2); % [N] Force of Primary Absorber Stage 2
dmax = SLp1; % [m] Maximum crush length
hcFs = LLs1*cos(pi/4); % [N] Force of Secondary Absorber Stage 1
hcFs2 = LLs2*cos(pi/4); % [N] Force of Secondary Absorber Stage 2
dmaxs = SLs1; % [m] Maximum crush length

case '1-2-1' % 1-2-1 landing
hcF = LLp1; % [N] Force of Primary Absorber Stage 1
hcF2 = LLp2; % [N] Force of Primary Absorber Stage 2
dmax = SLp1; % [m] Maximum crush length
hcFs = LLs1; % [N] Force of Secondary Absorber Stage 1
hcFs2 = LLs2; % [N] Force of Secondary Absorber Stage 2
dmaxs = SLs1; % [m] Maximum crush length
otherwise
end

%% Initial Condition
if theta == 0 && phi0<0
    stat = 1;
else if theta == 0 && phi0>0
    stat = -1;
else
    stat = sign(theta);
end

% % SIMULINK SOLVER
sim(lunarmodel, tdur)

%% Simulation
xmin = -15; xmax = 15; ymin = -5; ymax = 20;
ground = [xmin xmax; 0 0];
ground = rot2D(theta)*ground;
body = rot2D(theta)*[x y]';
bodydot = rot2D(theta)*[xdot ydot]';
bodydotdot = rot2D(theta)*[xdotdot ydotdot]';
top1 = rot2D(theta)*[topx1 topy1]';
top2 = rot2D(theta)*[topx2 topy2]';
bottom1 = rot2D(theta)*[bottomx1 bottomy1]';
bottom2 = rot2D(theta)*[bottomx2 bottomy2]';
mid1 = rot2D(theta)*[midx1 midy1]';
mid2 = rot2D(theta)*[midx2 midy2]';
foot1 = rot2D(theta)*[footx1 footy1]';
foot2 = rot2D(theta)*[footx2 footy2]';
position = rot2D(theta)*[x y]';

Ds1 = body(1,:) - foot1(1,:);
Ds2 = foot2(1,:) - body(1,:);
Ds1min = min(Ds1);
Ds2min = min(Ds2);

%% Report
lunarlanderreport;

%% Mass Estimation
lunarlander04_mass;

%% OUTPUT REPORT
if strcmp(output, 'true')
    lunarlandersavefile
end

%% Plot
lunarlanderplot;

%% SIMULATION
dend = tout(end)/dt;  % [-] simulation step duration
lunarlandersimulation

%% Save data file
save(strcat(lunarmodel, '/test', config, test, '.mat'));
Simulink Model