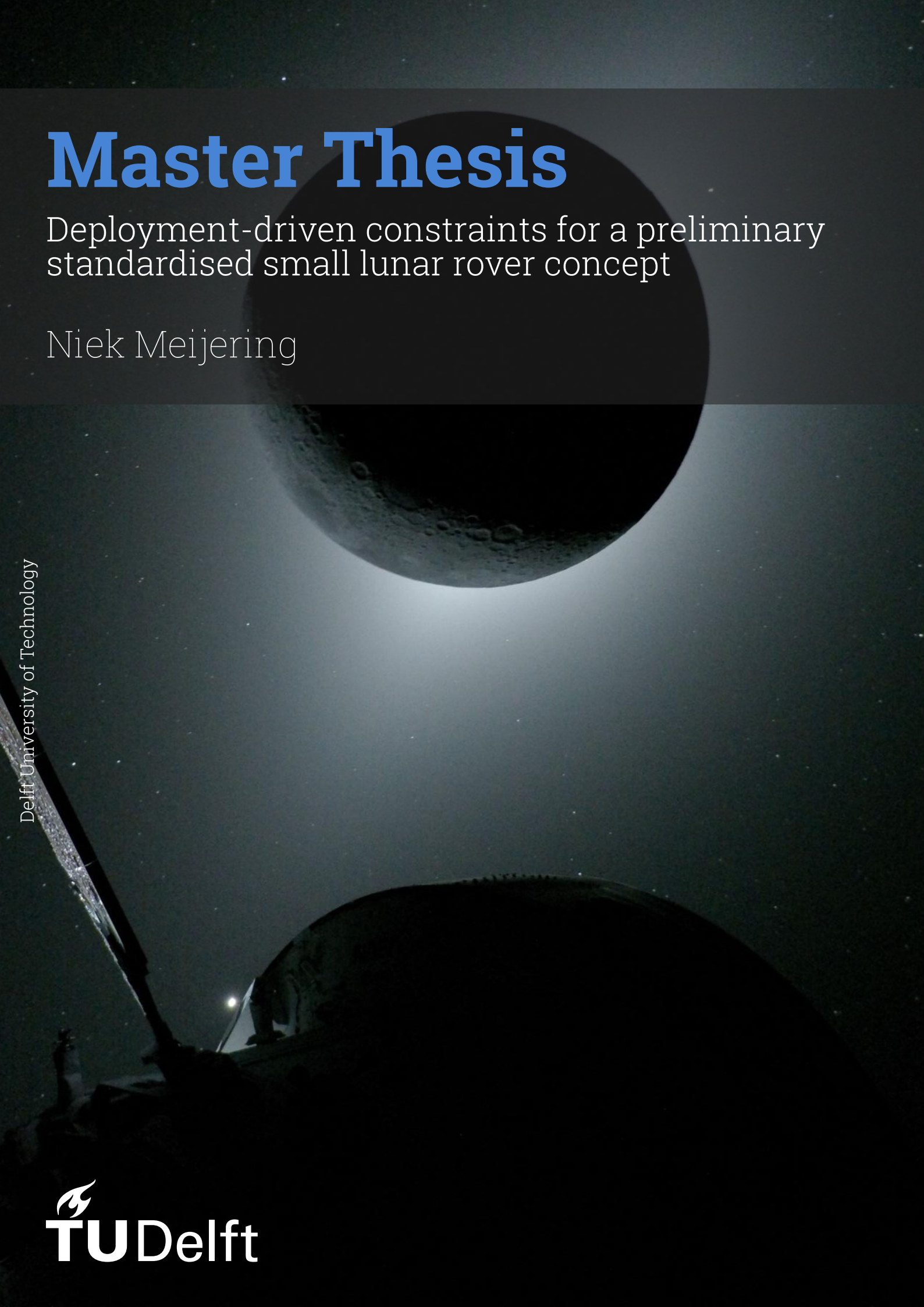
Master Thesis

Deployment-driven constraints for a preliminary standardised small lunar rover concept

Niek Meijering



Delft University of Technology

TU Delft

Master Thesis

Deployment-driven constraints for a preliminary standardised small lunar rover concept

by

Niek Meijering

Student Name	Student Number
Niek Meijering	5071585

Supervisor: M. Ş. Uludağ
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Faculty: Faculty of Aerospace Engineering, Delft

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TU Delft

Abstract

Small lunar rovers are becoming increasingly relevant as NASA's Artemis programme and the growing availability of commercial lunar landers drive renewed interest in returning to the Moon. However, the barrier to entry for developing such rovers remains substantial, and no common framework currently exists to guide their design. Similar to CubeSats, small lunar rovers could benefit from a shared size and interface framework. Such a framework could give designers a clearer set of constraints to work from, making small lunar rover missions more accessible for universities, research groups and small companies. This thesis investigates a deployment-driven standardised small lunar rover concept with a mass of 10 kg and below, and derives preliminary constraints and design guidelines.

Deployment is taken as the common starting point, since rover missions may differ strongly in payload, mobility system and subsystem design, but every rover carried by a lander must still be deployed onto the surface. The thesis first reviews current rover developments and commercial lander interfaces, followed by a trade-off of candidate deployment methods. The drop/push concept is selected as the most suitable baseline because of its low mechanical complexity, limited lander impact and scalability for multiple small rovers. A simplified two-dimensional model is then used to analyse free fall, release disturbances and initial touchdown stability.

The results show that, for the investigated case, initial tip-over stability at first contact is not the limiting constraint. However, this does not guarantee full post-touchdown stability, since effects such as bouncing, sliding, wheel deformation and terrain interaction are not included in the simplified model. Instead, the lateral clearance required during deployment becomes the dominant design driver, especially when multiple rovers are accommodated within a single lander. The case study translates these findings into preliminary rules for rover geometry, centre-of-gravity placement, drop height, surface clearance, release conditions and multi-rover spacing. The main contribution of this thesis is therefore the identification of deployment-driven constraints and their translation into first-order design rules for a preliminary standardised small lunar rover concept.

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Niek Meijering
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From the beginning, I wanted to connect with people working directly in rover development, since the industry perspective can differ from the university perspective. With Şevket's help, I got in contact with Ertan Umit from Ispace and Assoc. Prof. Dr. Halil Ersin Söken from METU. I would like to thank them both for their time, enthusiasm, and valuable insights, which helped me better understand how deployment affects rover design and operations in practice.

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Nomenclature

Abbreviations

Abbreviation	Definition
ASA	Australian Space Agency
CCSDS	Consultative Committee for Space Data Systems
CDS	CubeSat Design Specification
CG	Centre-of-Gravity
CLPS	Commercial Lunar Payload Services
CNSA	China National Space Administration
COTS	Commmercial Off The Shelf
CSA	Canadian Space Agency
DEF-STAN	Defence Standard
DFKI	German Research Center for Artificial Intelligence
DLR	German Aerospace Center
ECSS	European Cooperation for Space Standardization
EMI	Electromagnetic Interference
EMC	Electromagnetic Compatibility
ESA	European Space Agency
ISRO	Indian Space Research Organisation
JAXA	Japan Aerospace Exploration Agency
LEO	Low Earth Orbit
LSP	Launch Service Provider
MBRSC	Mohammed Bin Rashid Space Centre
METU	Middle East Technical University
MIL-STD	Military Standard
NASA	National Aeronautics and Space Administration
P-POD	Poly-Picosatellite Orbital Deployer
UNAM	National Autonomous University of Mexico

Symbols

Symbol	Definition	Unit
a	Acceleration	$\mathrm{m\,s^{-2}}$
V	Velocity	$\mathrm{m\,s^{-1}}$
t	Time	s
w	Width	m
h	Height	m
g_{moon}	Lunar gravity constant	$\mathrm{m\,s^{-2}}$

Symbol	Definition	Unit
α	Half-cone separation angle	$^\circ$
Θ	Angle	$^\circ$
ω	Angular velocity	$^\circ$/s
ϵ_{bis}	Bisection tolerance	–

1| Introduction

Rover missions are expanding rapidly as lunar and planetary exploration returns to the forefront of spaceflight and access to launch and landing services becomes increasingly commercial. NASA's Commercial Lunar Payload Services (CLPS) initiative, in particular, has accelerated the availability and cadence of commercial lunar landers, creating new rideshare and secondary-payload opportunities for rovers and other payloads. This opens the possibility for smaller rovers to conduct science, serve as technology demonstrators and investigate areas inaccessible to stationary lander payloads.

A way to make these missions more accessible is through standardisation. As seen with the CubeSat, over two decades, the standard can grow from a simple idea into a platform on which many users can develop and launch their own technology. With its common size, interface, and deployment method, the CubeSat has reduced the barrier to entry for space engineering for universities, research groups, and commercial companies. It has been shown that a fixed framework can reduce complexity, shorten development time and support innovation.

A standardised rover could follow a similar path to the CubeSat approach. Such a framework is especially relevant for small lunar rovers, since no common standard currently exists and access to the lunar surface remains costly and technically challenging. However, a rover standard can not simply be copied from the CubeSat approach. A satellite is deployed in orbit, while a rover must be released from a lander, survive touchdown, and come to rest in an orientation from which it can begin operations. The deployment therefore becomes more critical, as the rover needs to deal with gravity, impact loads, lunar dust, terrain uncertainty and land safely without tipping over.

The goal of this thesis is to derive preliminary constraints and design rules for a standardised small lunar rover concept based on deployment. Deployment is taken as the starting point because every lunar rover carried by a lander must be released onto the surface, while each mission may still use its own payload, mobility system and subsystem design. The thesis does not aim to define a complete standardised rover, but instead investigates what the deployment phase requires of such a standard. Moreover, it includes multi-rover accommodation and the implications for the standard, as it supports the concept's scalability and flexibility, allowing a single deployer to accommodate different rover sizes or several rovers without requiring a fundamentally new deployment system.

The rover mass is limited to 10 kg. This limit is used as an initial practical boundary rather than a definitive mass requirement for a standard. Below this mass, a rover can still include the main functions required for a small platform, while remaining small enough to be considered as a secondary payload on a lunar lander. In this context, the lander is not primarily designed around the rover, meaning that rover accommodation and deployment must remain relatively simple and low-impact. For larger rovers, different deployment concepts, larger lander accommodation volumes

and higher mission costs may become necessary. The 10 kg limit therefore, keeps the study focused on small, accessible rover concepts that could be relevant for universities, research groups and start-ups.

1.1. Research questions

This study investigates the feasibility of a standardised rover, using deployment as the starting point. The focus is on how the deployment concept constrains the rover geometry, the centre of gravity position and the scalability of the concept when multiple rovers are integrated in a single lander. The main research question guiding this thesis is therefore:

> What design requirements and constraints does the selected deployment concept impose on a standardised small lunar rover (mass ≤ 10 kg) deployed as a secondary payload from a lunar lander?

To answer this question, the main research question is divided into the following sub-questions:

- *Which deployment concept is most suitable as a baseline for a standardised lunar rover with a mass of up to* 10 kg*, deployed as a secondary payload from a lunar lander, when assessed against defined criteria such as mass, stowed volume, mechanical complexity, reliability, scalability, and deployment risk?*
- *For the selected deployment concept, how do drop height, centre-of-gravity location, release attitude, release velocity, and first-contact conditions affect touchdown stability of a standardised lunar rover with a mass of up to* 10 kg*?*
- *What stowed-volume, clearance, spacing and deployment-path requirements are imposed when multiple standardised lunar rovers, each with a mass of up to* 10 kg*, are accommodated within a single lunar lander?*

1.2. Thesis outline

The thesis is structured as follows. First, the state of the art is reviewed in chapter 2, focusing on standardisation, small lunar rovers, lander interfaces and deployment methods. Next, the standardisation approach is defined in chapter 3 and a trade-off is performed to select a baseline deployment concept in chapter 4. The selected concept is then analysed using a simplified numerical model, in which the influence of drop height, release conditions, centre-of-gravity position, and rover geometry is investigated in chapter 5. In chapter 6, a representative case study is used to translate these results into preliminary deployment-driven constraints. These constraints are then generalised into derived preliminary standardisation requirements and design rules in chapter 7. To conclude, the results are summarised in the conclusion in chapter 8.

2 | State of the art

In this chapter, the state of the art will be described. Starting with standardisation in general, the thinking behind the CubeSat platform and its impact. Then, the challenges of a rover will be explained, where the environment has a huge impact. And lastly, a survey will be made of past, present, future and failed projects. Displaying some trends and common issues.

2.1. Standardisation

Standardisation is the process of defining important parameters for a larger audience to conform to. To set a record of what works for certain problems and to make engineering, for example, simpler for the next iteration. It is a common language for a specific goal, in which requirements, rules, and guidelines are set for processes and systems. With the intention to ensure safety, reliability and consistency[1].

In aerospace, standards began with the military standards of countries where it was important to repair equipment and maintain performance at an acceptable level. Most countries have their own set of standards, while the United States has its MIL-STD and Britain uses DEF-STAN. These military standards were carried over into the standards required for rocket launches post-Second World War. The NASA STD and ECSS, which are still in use, were developed for performance, reliability, and regulatory purposes [2]. Later, the CCSDS standards for communications and data handling were established to promote commonalities among countries using space [3]. And just before the 2000s, the CubeSat standard was developed to establish a framework for small satellites.

2.1.1. CubeSat standard

Space engineering has always been costly and has a steep learning curve. A large amount of knowledge is required before a working spacecraft can be developed, which makes it difficult for universities and smaller institutions to start from scratch. Since learning by doing is one of the most effective ways to gain this knowledge, easier access to space can improve the industry as a whole. The idea of a standardised satellite came from this need. The CubeSat concept started at California Polytechnic State University and Stanford University in 1999, with the goal of giving universities and educational institutions more affordable access to space [4].

The CubeSat provides a platform on which missions can be built, without having to define the complete spacecraft framework from the start. This reduces development time and costs and allows for greater focus on experimentation and payload development. The basic CubeSat unit is a satellite of 10 by 10 by 10 cm, equal to 1U. Larger satellites can then be made by scaling this unit, as shown in Figure 2.1.

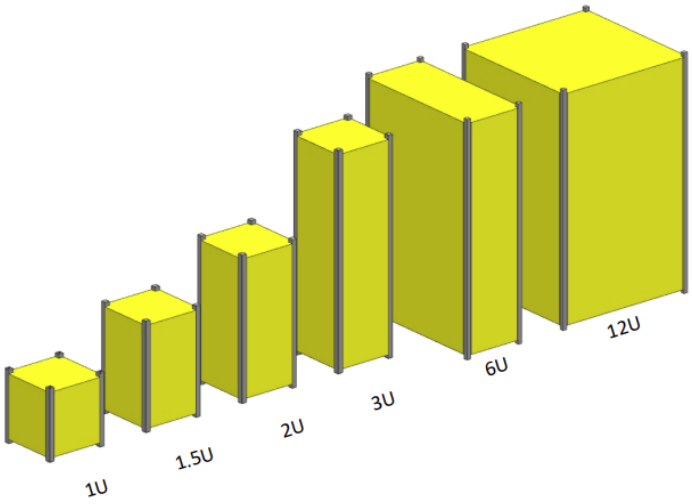

Figure 2.1: Varying sizes of the CubeSat as per the CubeSat Design Specification [5].

The standard is presented in the CubeSat Design Specification Document (CDS) [5]. The CDS gives guidelines for specifications required for CubeSats, from mechanical design, to electricity, operations testing, and all interfaces with the dispenser. All launcher requirements should be taken into account first, as these are regarded as driving requirements. The CDS provides just the framework, and the launcher, as well as the dispenser provider, sets the final requirements. It is to ensure the safety and success of the mission for both the satellite itself and the other payloads. These standards have been used for over two decades, with ongoing updates to provide greater clarity. It also includes maximum weights, specific tolerances, and recommended materials.

The satellite dispenser is just as important as the satellite for the standard. These various standardised sizes need to be deployed reliably and should be easy to scale up. To accommodate this, the dispensers have been created to carry multiple CubeSats in different sizes. The CubeSat can be ejected in a timely manner so that the satellites do not interfere with each other. It started with the P-POD (Poly-Picosatellite Orbital Deployer), which is a structure with an interface that is able to launch up to three 1U CubeSats. It is enclosed so that it would not interact with the primary payload of the launcher [6]. There are many companies supplying these dispensers like the Dutch company ISISPACE. There are also larger sizes available as of now, up to 27U.

The CubeSat dispenser uses standardised compartments in which CubeSats are placed according to their unit size. Depending on the dispenser configuration, these compartments can accommodate different CubeSat formats. There is a latch, and once opened, the CubeSat is ejected by a spring, guided by rails on the corners of the dispenser. Deployment switches are used to keep the CubeSat idle until pushed out, after which the CubeSat can start itself up. It is a rather simple mechanism to ensure that the payload is put in the correct orbit safely [7].

Thousands of CubeSats have been launched since 1999, with the most being launched in the last couple of years [8]. Over 2500 CubeSats are up and running as of 2025. The growth of the satellites is shown below in Figure 2.2.

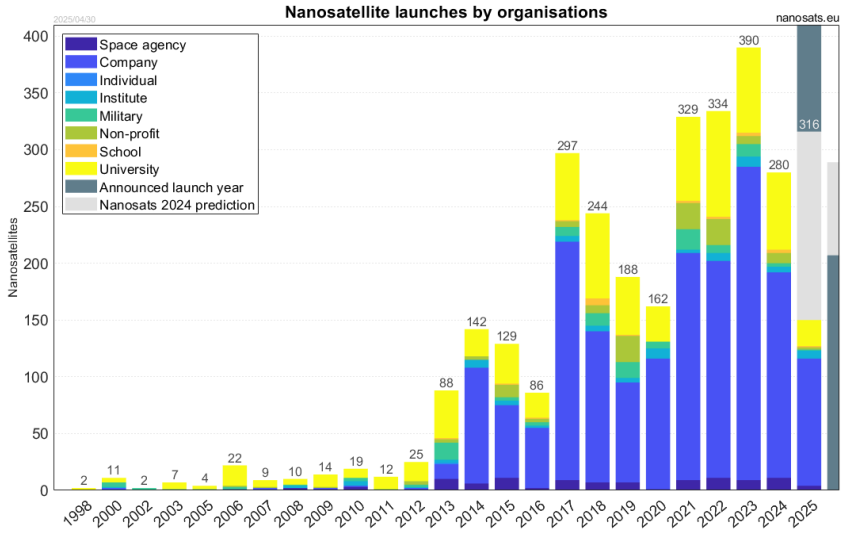

Figure 2.2: Nanosatellite launches over the years, where the majority are CubeSats[9].

The effects are immense, as can be seen in Figure 2.2 above. Initially launched in very small numbers, as of 2014, 100+ CubeSats are launched every year. Moreover there has been a shift from mostly universities to companies also taking part in the trend.

CubeSats were not initially designed for optimal performance but, as previously noted, for ease of access and reduced costs. Where CubeSats would be a secondary payload to the launcher's main payload. Due to this increase in the number of satellites, the market has shifted toward a more commercial outlook. This led to a rise in companies' engineering and selling subparts of the whole system. Currently, there are many choices for subsystems, sensors, and instruments. Some companies now offer complete satellite platforms, where most subsystems are developed in-house, and the customer only needs to provide the payload. An example of this is the Danish company Space Inventor [10]. The countless Commercial-Off-The-Shelf (COTS) items make it more reliable, and as investments have grown, performance has also increased.

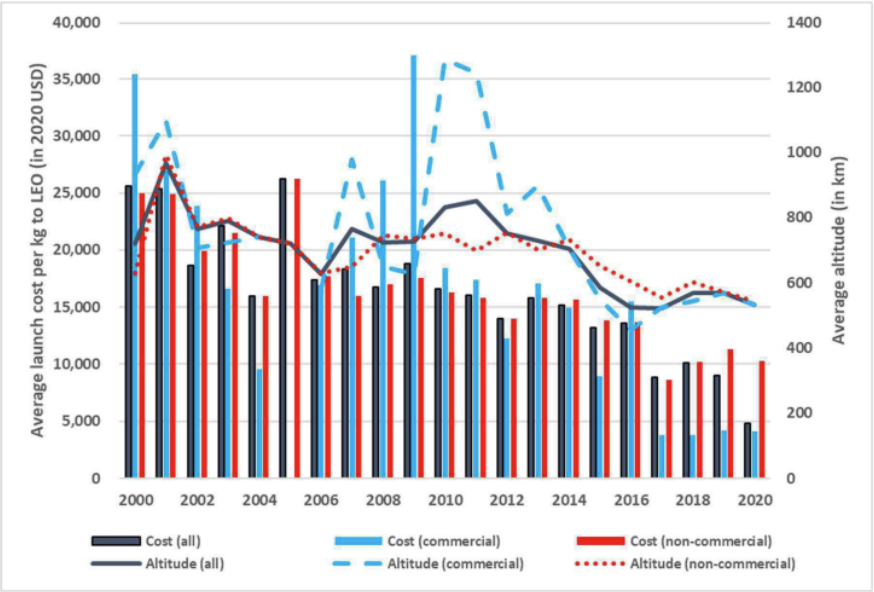

Figure 2.3: Launch costs per kilogram into LEO over the years[11].

As shown in Figure 2.3, launch costs have nearly halved over the last 20 years. This is because launchers are more cost-effective due to their reusability and the ability to fly more often [12]. This makes it easier to access space, since launch costs can be a substantial share of the total cost.

There are also limitations to the CubeSat approach. The fixed unit size makes the system scalable, but it also constrains the available volume and external surface area. Some payloads may not fit efficiently within the standard envelope, especially when they require a specific geometry or a longer focal length. This also limits the available area for power generation. These limitations show that a standard must balance simplicity and flexibility, which is also important when considering a standardised rover concept.

2.1.2. PocketQube standard

Next to the CubeSat standard there is one more satellite standard, the PocketQube. It is an eighth of the size of a CubeSat, being 5 x 5 x 5 cm. The intent of the PocketQube is the same: to reduce costs even more and therefore make space even easier to access. It was introduced by Professor Twiggs in 2009, and Alba Orbital, TU Delft and Gauss Srl. continued on with making the standard [13, 14]. Various sizes are viable once again, being sized with the unit 'P', in 1, 2 and 3P.

The PocketQube standard gives the general and mechanical requirements. Where it refers to the Launch Service Provider (LSP) for the electrical, operational and testing requirements. This standard's mechanical requirements mention the maximum allowable mass per 'P', the envelope of the PocketQube and technical drawings [15].

The ejection method is very much like the CubeSat, with the opening of a latching door and being pushed out by a spring. It has tabs to hold down the satellite on two sides, similar to the rail system in the CDS. Moreover, a minimum of two kill switches for redundancy reasons so that the satellite remains dormant during flight and turns

on when released from the dispenser [16].

2.1.3. Lessons for rover standardisation

The CubeSat and PocketQube standards show that standardisation can be very useful when it provides a fixed framework without fully defining the mission. One of the main lessons is the effectiveness of a small and fixed envelope. This bounds the geometry of the spacecraft and therefore gives the designers a certain volume to develop their own mission instead of engineering a completely new configuration. This restricts the design problem and shifts the focus more towards the payload, instrumentation, operations and mission objectives.

The fixed envelope also supports scalability in both size and number. CubeSats can vary from 1U to larger configurations, while still using the same design logic with trusted components and compatible deployers. This gives the design freedom without losing the benefits of the framework. Over time, this also created commercial interest, from which structures, subsystems and complete platforms became available as commercial-off-the-shelf. These components can greatly reduce the development time, especially for universities.

A second lesson is that the deployer is part of the standard. It is therefore a key component and should be taken into account from the start, because it shapes the design and decides where the mission begins. Any faults during the deployment can mean the end of the mission. It needs to be reliable, repeatable and easy to operate. Additionally, for a rover it is required to be deployed onto the surface.

A third lesson is the importance of a standardised interface. This interface makes integration easier for both sides, the payload developer and the dispenser provider. Providing a starting point and reducing the specific needs for certain missions. Applied to small lunar rovers, this means that the rover should not only be designed as a vehicle, but also as a payload with a transferable interface. The interface should be simple to use and compatible with different landers where possible.

Fourth is the verification simplicity. As standardised satellites are often used, the required test and verification steps are well-known and better understood. Where the limits for repeated use are well known and test procedures can be adapted. This reduces uncertainty and development effort, as not every designer needs to redesign the tests and validate them. The same could hold for a standardised rover concept, using simple and repeatable criteria which can be checked, like the centre of gravity placement, mass and geometry.

Lastly, protection from other payloads as a secondary payload is of significant value. This means that the other payloads are not affected, as well as the launch provider itself. For that reason, the deployer must avoid other systems. The rover deployment mechanisms should therefore reduce risks. The CubeSat uses a kill switch to not have power on during the launch, and is housed inside a dispenser to withstand the loads during flight and if there were a fault, it would be a barrier to the other payloads. This should be kept in mind for a rover as well.

Together, these lessons show that a rover standard would need to take into account multiple criteria for it to be successful. From reliability, ease of use and being scalable

with the view of both the deployment and the rover.

2.2. Rover challenges

A rover is a spacecraft that is able to move and is designed to operate on the surface of a non-terrestrial body. Here, it can support the exploration of the solar system and investigate the Moon in this case. The rover can be remotely controlled, autonomous, or human-operated, although current developments increasingly move towards autonomous operations [17]. The main advantage of a rover is that it allows a planetary surface to be explored without requiring humans to be present. Its mobility makes it possible to investigate multiple locations, compare different sites, and collect measurements over a large area.

Rovers are complex systems, comparable to satellites in the sense that they require many of the same subsystems, such as power, communication, thermal control, structure, onboard computing and payload support. However, they also face additional specific challenges. They must survive launch and landing, be deployed safely from a lander, operate in rough terrain, and function in harsh environmental conditions such as radiation, dust and large temperature variations [18].

There is no single rover design that suits all missions. Past and planned rovers vary strongly in size, mass, mobility system, mission duration and science objective. Some missions are designed to operate only during the lunar day, avoiding the difficulty of surviving the cold lunar night, which lasts approximately two weeks [19]. Others are larger and more capable systems intended to operate for months or years. Mobility concepts also differ, ranging from wheels and tracks to legs, hopping mechanisms and rotor-based systems. This diversity shows that rover design is mission dependent, which makes standardisation more challenging than for simpler spacecraft platforms.

2.2.1. Environmental and operational challenges

As mentioned, rovers and satellites share many subsystems; their operational challenges are however, very different. A satellite is usually deployed into a stable orbit, where its first task is to reorient, to establish a communication link and generate power. A lunar rover would first need to reach the surface safely. Its operation therefore, does not start in a stable position after release. This makes the transition from the lander to the surface one of the most critical phases.

A lunar rover is normally transported to the Moon by a lander and therefore dependent on the lander for delivery, accommodation and deployment. The rover does not need its own propulsion system to land, but it is constrained by the available volume, mass, attachment points, electrical interface and thermal environment. Small rovers are often secondary payloads, so these constraints can dominate the design. A failure of the lander usually results in a direct loss of the mission. This is not uncommon, where the Resilience mission by Ispace crashed, which led to the Tenacious rover not being able to operate [20]. The rover's success begins before it touches the ground. Where launchers for satellites almost never fail, the lunar landers are in their early days and are expected to crash more often.

The deployment itself is already different from satellites. In orbit, the spacecraft that is

released is able to change its attitude in microgravity conditions. A rover is normally released onto a surface where reorientation is not an option to be performed by itself. As gravity does not allow for large corrections in very little time, unless the attitude control systems are extremely large. If the rover lands in the wrong orientation, the mission could be compromised already, the solar panels might not be able to generate sufficient power, antennas may not point in a useful direction, instruments could have the wrong view and the mobility system is not able to work properly. So, most small rovers are dependent on their deployment system from the lander to function correctly.

Upon reaching the surface safely, the rover has to deal with the terrain. It must move over regolith, slopes, rocks, craters and other uneven types of terrain, while maintaining stability. This affects the design of the wheel system, suspension, ground clearance and centre of gravity[21, 22]. The possible wheels should not only be designed for movement but also stability, as they need traction to drive over hills, and the rover mustn't tip over once it encounters an unforeseen small crater.

The lunar environment further increases the difficulty of rover design. The Moon has a long day-night cycle, with approximately 14 Earth days of continuous illumination followed by approximately 14 Earth days of darkness. Surviving the lunar night is especially challenging, since the rover must maintain critical subsystems, such as batteries and electronics, within their allowable survival temperature ranges. Surface temperatures can fall below 100 K, which means that small rovers may require heater power, insulation and thermal control to remain functional [19]. For very small rovers, providing sufficient energy and thermal protection for the full lunar night can be impractical. As a result, many small rover missions are designed to operate only during the lunar day. The approximate temperature ranges that a rover may encounter in different lunar surface regions are shown in Table 2.1.

Table 2.1: Approximate lunar surface temperature ranges for different surface regions [23].

Lunar atmosphere	**Minimum**	**Maximum**
Equatorial	95 K	287 - 397 K
Polar	50 K	202 K
Crater	18 - 20 K	

The rover must also endure the harsher radiation environment. The Moon has no atmosphere to protect against high-energy radiation. Electronics, sensors, and onboard computers must tolerate deep-space conditions, from transfer to lunar orbit to surface operations. The trajectory to the Moon could play an important role, as some trajectories could take much longer and lead to repeated exposure to trapped particles [24]. Once on the surface, deep-space radiation, the solar wind, and galactic cosmic rays can affect electronics and contribute to surface charging [25].

Lunar dust and regolith also create challenges for the systems. It can adhere to surfaces, enter mechanisms, reduce optical performance and interfere with joints. For a rover, that means that mechanical interfaces must be designed to mitigate the effects of build-up or require sealing [26]. Lunar dust can reduce the available power, as dust can gather on the solar panels or lenses. This must be taken into account to survive the environment for the duration of the mission [17].

All of these factors play a major role in the design of a rover, where subsystems are very similar, and the environment could be the same. But the missions could differ widely: one might need to survive just a few days, and the other maybe weeks. This makes standardisation more difficult, as the requirements might restrict mission operations.

2.3. Survey of missions

This section surveys the rover missions and concepts that have been developed for surface exploration. The purpose is not to provide a complete overview of every mission, but to identify the trends that are relevant for the rover standardisation. Particular attention is given to the mass of the rover, the commercial involvement over the past decade, the trend of miniturisation and modular rover platforms. Additionally the possible solutions to common problems are investigated.

The survey includes past, current, planned and potential prospects for rover missions. The lunar surface is included, along with other destinations, to provide a broader view of the design choices made for various environments. The focus is on lunar surface missions, as this is the scope of the standardisation concept for this thesis. The missions are compared mostly by their rover mass, because this is one of the consistently given parameters and a direct driver to the lander and the standardisation through accommodation, deployment method and cost.

2.3.1. Method and scope of the survey

The catalogue lists rover missions for which mass and dimensional data are publicly available. In some cases, the available information is incomplete or could change over time, especially for missions that are still planned or under development. For this reason, the catalogue should be used to identify general trends rather than as a precise database. The catalogue is ordered by rover mass, including the payload mass where this information is available.

The selection criterion for the survey is that the rover should be intended to perform science or technology demonstrations and be able to traverse the surface of a non-terrestrial body. Human-driven vehicles are therefore not included. Some Earth-based platforms are included, but only when they are directly relevant to planetary rover development. These cases are explicitly mentioned in the catalogue.

The dimensions shown for the rovers should be treated as estimates. In many cases, detailed stowed dimensions are difficult to find. Some sources give the fully deployed state of the rover, where wheels, antennas, solar panels or extendable arms may be included in the total size. This deployed state is less useful for the standard itself, since the most important configuration for lander accommodation is the folded or stowed state inside the lander. Moreover, for some rover concepts, such as the CubeRover, only the payload size is known; the rover size has been estimated based on visual inspection, using the number of solar arrays and the known payload size.

Lastly, the launch date is not always known, and some concepts may never reach the lunar surface. This is especially the case for start-ups or early-stage rover concepts, where the design may still change or may not become a final product. However, these concepts are still included when they provide useful information on rover size, mass,

mobility method or commercial direction. In this way, the survey gives a broader view of the current small rover development and the different approaches being considered for similar mission goals.

Things that the survey lacks are the costs and the power budget. Most of the companies do not provide that data. There are some that do, Astrobotic mentions that the costs lie around 4.5 million dollars per kg of payload, so not a rover [27]. Whereas the price per kilogram to reach the surface would be around 1.2 million dollars per kg [28].

2.3.2. Mission catalogue and mass classes

Below in Table 2.2 is shown the catalogue of the rovers launched and set to launch, including some prospects.

Table 2.2: Catalogue of rover missions launched and set to launch.

Rover name	Company	Weight (kg)	Dimensions	Destination	Year	Ref(s)
A-Puffer	NASA	0.15	10×7.5×7.5 cm expanded; 14.5×7.5×4.5 cm folded	Moon	2020	[29]
LEV-2	JAXA	0.229	∅80 mm	Moon	2024	[30]
Yaoki	Dymon	0.489	15×15×10 cm	Moon	2025	[31, 32]
Colmena-1	UNAM	0.608	∅12 cm; external envelope 12×12×4 cm	Moon	2024	[33]
Minerva-II	JAXA	1.1	∅18 cm × 7 cm	Ryugu Asteroid	2019	[34]
Asagumo	Spacebit	1.5	0.10×0.10×0.15 m	Moon	2024	[35]
IRIS	Carnegie Mellon University	2	Shoe-box size	Moon	2024	[36]
LEV-1	JAXA	2.1	–	Moon	2024	[37, 38]
Lunar Zebro	TU Delft	2.5	21×29.7×10 cm	Moon	–	[39]
Nanokhod	Von Hoerner & Sulger GmbH	2.55	250×160×65 mm	Mars	2007	[40, 41]
MoonRanger	Carnegie Mellon University	3.2	Small suitcase	Moon	2029	[42]
Sorato	Ispace	3.8	57.5×52.1×31.7 cm	Moon	–	[43, 44, 45]
Prop M rover	Soviet	4.5	0.215×0.160×0.060 m	Mars	1971	[46]
Jinchan	CNSA	5	–	Moon	2024	[47]
Tenacious	Ispace	5	26×31.5×54 cm	Moon	2027	[48]
Cheri Rover	METU	5	0.30×0.30×0.35 m	Moon	2029	[49, 50]
MoVe [2]	DFKI	5.9	0.47×0.45×0.65 m	–	–	[51]
CubeRover 2U	Astrobotic	7	0.20×0.30×0.25 m [1]	Moon	2025	[52]
CADRE	NASA	8.6	0.546×0.385×0.235 m	Moon	2026	[53]

Continued on next page

Rover name	Company	Weight (kg)	Dimensions	Destination	Year	Ref(s)
Neurospace	Hiver	–	0.45×0.35×0.30 m	Moon	–	[54]
Hopter Galago	Astronika	9	∅50 cm	Moon	–	[55]
RASHID	MBRSC	10	70×50×50 cm	Moon	2026	[22, 56]
Sojourner	NASA	10.5	62×47×32 cm	Mars	1997	[17]
CubeRover 4U	Astrobotic	12	0.30×0.25×0.30 m[1]	Moon	–	[52]
CubeRover 6U	Astrobotic	16	0.30×0.30×0.45 m [1]	Moon	2026	[52]
Roo-ver	ASA	20	Suitcase size approx.	Moon	–	[57, 58]
R1	Mawson Rover	20	0.50×0.50×0.30 m	–	–	[59]
IDEFIX	DLR	23.12	557×512×314 mm	Phobos	2026	[60, 61]
MAPP	Lunar Outpost	25	45×38×30 cm	Moon	–	[62]
Pragyan	ISRO	27	0.90×0.75×0.85 m	Moon	2023	[63]
MPR-1	Stells	30	–	Moon	–	[64]
Amalia [2]	Team Italia	30.9	–	Moon	–	[65]
Unnamed rover	SUPARCO	35	–	–	2029	[66]
LUVMI-M	Space Applications Services	50	0.60×0.60×0.50 m	Moon	2028	[67]
MAPP-Ultra	Lunar Outpost	60	1×2×1 m	Moon	–	[62]
Small Planetary Rover Platform [2]	CSA	95	1.2×1.2×0.7 m	Earth	–	[68]
YUTU-2	CNSA	135	1.5×1×1 m	Moon	2019	[69]
Polaris	Astrobotic	136	1.7×2.2×2.4 m	Moon	–	[70, 71]
YUTU	CNSA	140	1.5×1×1 m	Moon	2013	[72]
Opportunity / Spirit	NASA	185	1.6×2.3×1.5 m	Mars	2003	[73]
Zhurong	CNSA	240	2.6×3.0×1.85 m	Mars	2021	[74]

Continued on next page

Rover name	Company	Weight (kg)	Dimensions	Destination	Year	Ref(s)
LUPEX	JAXA	350	2.0×1.8×3.3 m	Moon	2028	[75]
VIPER	Blue Origin	450	1.5×1.5×2.5 m	Moon	2027	[76]
HL-MAPP	Lunar Outpost	450	1×2×2 m	Moon	–	[62]
Flip	Astrolab	500	–	Moon	2026	[77]
Lunokhod 1	Soviet	756	1.7×1.6×1.35 m	Moon	1970	[78]
Lunokhod 2	Soviet	840	1.7×1.6×1.35 m	Moon	1973	[78]
Curiosity	NASA	899	3.0×2.7×2.1 m	Mars	2011	[79]
Perseverance	NASA	1025	3.0×2.7×2.0 m	Mars	2020	[80]

[1]The size is approximated through visual inspection and in reality might differ.
[2]This rover is a testbed not meant for lunar exploration, but made to simulate the rover on Earth.

Table 2.2 displays up to 50 rovers that have launched, are about to be launched or prospects that have failed. The mass ranges from below 1 kg to greater than 1000 kg. From small hopping rovers or with only two wheels to the upper end Mars rovers like the Perseverance with many instruments and very big. Between these extremes, there are also ones that fall right in the middle, with various mobility systems and sizes of payloads used as tech demonstrators.

Just as with satellites, there is also a suggested class system for rovers by Ellery, which is not commonly used yet [17]. Table 2.3 displays this suggested class system, and next to it are the commonly used satellite classes. For this thesis, the most important class would be the Nano size and possibly down to pico. To be accessible to universities and start-ups, it should not be too large as the cost might quickly rise, and the starting point for CubeSats also starts at this size.

Table 2.3: Comparison between rover and satellite mass classes [57][17].

Name	Rover class	Satellite class
Large	Na	1000+ kg
Medium	100+ kg	500 - 1000 kg
Mini	10 - 50 kg	100 - 500 kg
Micro	10 - 50 kg	10 - 100 kg
Nano	5 - 10 kg	1 - 10 kg
Pico	Na	0.1 - 1 kg
Femto	Na	$\leq$ 0.1 kg

The catalogue shows that the selected rover concepts vary strongly in both mass and size. To visualise this spread, Figure 2.4 plots the rover mass against the external volume for small rover concepts where dimensional data are available.

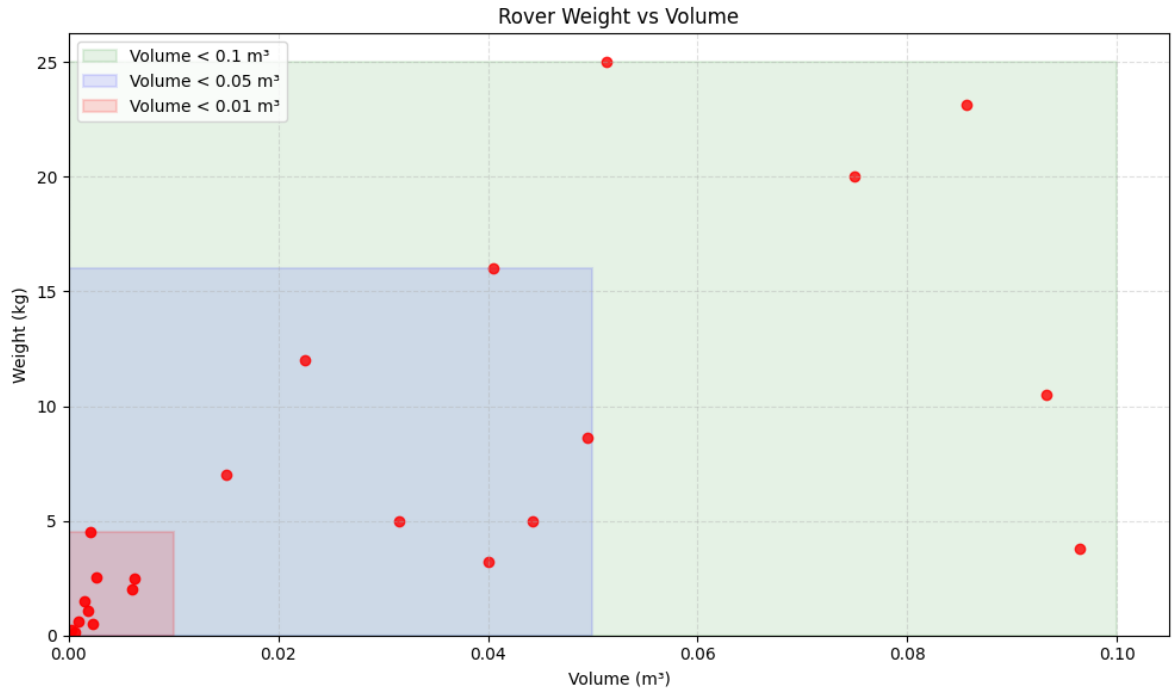

Figure 2.4: Mass-volume distribution of selected small rover concepts from the mission catalogue. The volume is estimated from publicly available external dimensions and should therefore be treated as approximate.

Figure 2.4 shows that most of the smallest rover concepts are clustered at a mass below 5 kg. These are mainly technology demonstrators or highly compact rover concepts. As the volume increases, it starts to spread, as the external volume is included. An extendable arm would have a large impact, and ground clearance plays a large role in the volume of the rover.

2.4. Trends in current small rover development

The recent rover developments clearly show that there is an increase in small lunar systems. The smaller rovers are more frequent and can also operate on the lunar surface as a technology demonstrator, trying out new mobility systems. For example with the LEV-1 and LEV-2 by JAXA. The LEV-1 moves by releasing a spring and hopping over the surface, and the LEV-2 is a ball-shaped rover, acting as wheels when extended [37][30].

Another development is that multiple rovers could operate together through autonomous communication. NASA's CADRE mission will launch three rovers that can explore the lunar surface, coordinating their activities [53]. This way, it can cover more ground, and it shows that the scalability of multiple rovers can be put to good use. Where tasks can be taken over by multiple smaller rovers rather than a single big one.

There are also platforms that are being developed to support payloads intended for lunar exploration. This way, the rover does not need to be designed; the payload would just have to fit the payload bay. These range from small to large, where Astrobotic provides 2u, 4U and 6U of payload and lunar outpost far larger up to 30 kg with the

MAPP Ultra rover [27] [62]. These platforms show that it can become a service to get a payload to the moon.

2.4.1. Trends and gaps

There are various trends that can be observed from the mission catalogue. The first few rovers were deployed just after 1970, still in the middle of the space race. After this, there was a large gap to the early 2000s, where Mars became the target for missions with the Sojourner and Spirit & Opportunity. From 2019 onwards lunar exploration missions started to become far more frequent and still more to come in the future with missions planned.

These early missions were mainly dedicated to launches to the surface with very large rovers on them. Many of the recent rovers are below 10 kg and even lower. This is enabled by the smaller electronics, compact sensors, improved batteries, lightweight structures and the small spacecraft development through the CubeSat. It does not replace the large rovers, but makes technology demonstration easier for shorter missions.

The market is also currently dominated by commercial rovers, where the first few were launched by the national agencies. The development of these commercial rovers is strongly linked to the Commercial Lunar Payload Services program by NASA[81]. NASA enabled commercial companies to provide a delivery service through multiple companies like Astrobotic, Ispace and Firefly [28][82][83]. They all have their own lander in development and in the next couple years should be able to bring more payloads to the lunar surface. Allow for more rovers and investigate the moon and get humans back to the Moon.

The lunar night survival remains a major challenge for many of the rovers. The smaller rovers below approximately 20 kg are not meant for night survival. As it would require large batteries to power the heaters to keep within surviving temperatures, together with insulation. For this reason, the small rovers limit their mission duration to just the lunar day of 14 days. It simplifies the design and keeps the costs low.

Lastly, the type of mobility is different from mission to mission. Technology demonstrators make it easy to test it out, for example the Asagumo by Spacebit tried a rover with legs to walk through lunar lava tubes [35]. But others have tracks, will hop and the most common is still the wheel to move. For the possible standard, the mobility type should not be determined beforehand, leaving specific solutions open for design.

2.4.2. Implication for rover standardisation

The mission survey supports the choice of a small rover standard focused on masses below 10 kg. This class is large enough to carry a useful payload, but small enough to be compatible with secondary-payload accommodation on commercial lunar landers. It is also the class in which miniaturisation, swarm concepts, and commercial platform development are most visible.

At the same time, the survey shows that there is no single rover design that can do all. Rovers differ in mobility system, payload, mission duration and science objective. Therefore, a useful standard should not define the full architecture. Instead, it should

define the common constraints that every rover in this class must satisfy.

2.5. Current practice for commercial landers

The Commercial Lunar Payload Services (CLPS) programme has led to several commercial lunar landers being developed by Ispace, Astrobotic and Firefly to deliver payloads to the lunar surface. For a rover as a secondary payload, the lander is not only a transport system, but also the system that defines the external constraints from integration until deployment. The lander determines where the rover can be mounted, which environments it must survive, which services may be available during the mission, and under what conditions the rover can be released onto the lunar surface.

Commercial lander providers typically describe these constraints in payload user guides. These documents are not detailed enough to be an interface control document, but they do give an indication of the accommodation. They describe mechanical mounting options, environmental loads, power availability, thermal assumptions, data interfaces, communication possibilities, integration timelines and testing expectations.

This section reviews the current state-of-practice of commercial lunar lander interfaces and discusses their implications for small rover design. The focus is on the common interface categories and the differences in how lander providers approach payload accommodation. The interfaces are divided into mechanical, electrical power, data and communication, thermal, and operations and testing aspects.

2.5.1. Mechanical accommodation

The mechanical interface starts with the integration and placement of the payload onto the lander. Commercial landers can provide multiple options for payload accommodation, such as placement on an aft deck, mounting to a side wall, hanging from a structure, or placement on an upper deck. Which option is used depends on the lander design and on the specific needs of the payload. For a rover, this is especially important, because the mounting location also influences how the rover can later be deployed onto the lunar surface. Figure 2.5 displays some of the possible locations for placement onto a lander.

The payload location is therefore not always the same between commercial landers or even between different missions using the same lander. It can change depending on the size and mass of the payload, its mission needs, and the presence of other payloads. The lander provider may also define keep-out zones, specific mounting regions, or required attachment points. This means that the rover cannot assume one universal lander geometry, but must be able to adapt to the available accommodation.



Figure 2.5: Payload accommodation locations on the Blue Ghost lunar lander, showing the different regions where payloads can be mounted [83].

After integration, the rover must survive the transport to the Moon. This means that it has to endure the loads and shocks from both launch and landing. The payload user guides therefore provide the expected mechanical environments, including sine and random vibration, acoustic loads, maximum predicted shock and pressure profiles. These environments are mostly dominated by the launch phase, since launch is usually one of the harshest parts of the mission. However, the exact conditions can still change depending on the payload location and the specific lander configuration [28].

For rover standardisation, this means that the mechanical interface should not only be seen as a common bolt pattern. It should also include the rover envelope, load path, release direction, mounting region and keep-out zones. These parameters determine whether the rover can be integrated safely and whether it can later be deployed without interfering with the lander or other payloads.

2.5.2. Power and data services

The user guides of the commercial landers describe whether payload power and data services are provided throughout the different mission phases. The exact implementation differs per lander, but in practice they describe similar things. They mention when payloads can be powered, what nominal or peak power could be available, and through which connectors this is provided. The guides also describe the data interfaces and communication options. In this way, the lunar lander can also act as a communication link between the rover and the ground station, where data from the rover can be sent to Earth through the lander [28].

For a rover, access to power might be required before deployment. It could be used to charge the batteries, support thermal control during transit, or monitor the health of the rover. Data services can allow the rover to send telemetry and receive commands while it is still attached to the lander. This service is however not always available. During certain phases, such as launch or landing, payload power and data services may be limited or shut off.

A standardised rover would therefore benefit from a simple electrical and data interface. This would make it possible to monitor its health, receive basic commands, and support the rover before release. For every lander this interface is currently different, but a common rover-side interface would make the rover more easily transferable between landers. A lander-specific adapter could then be used for the final connector and

communication protocol.

2.5.3. Thermal and environmental interfaces

The lander, and therefore the rover, experiences harsh conditions and environments during the mission. During transit, the spacecraft can experience extreme cold when it is in shadow and high temperatures when it is exposed to direct sunlight. In addition, the payload has to survive the radiation environment, including galactic cosmic rays, solar particles and possible exposure when travelling through the radiation belts [28].

The rover is mostly shielded from the direct space environment while it is inside or attached to the lander, but it still needs to survive the thermal and radiation conditions imposed by the mission. The exact environment depends on the trajectory, the payload location on the lander and the level of shielding provided by surrounding structures. For this reason, the lander user guides provide the expected environmental conditions, while the payload provider remains responsible for showing that the rover can survive them.

Thermally, the rover may receive some protection from the lander during transit, but this does not mean that the thermal problem is removed. Critical components, such as batteries and electronics, still need to remain within their allowable survival temperature range. During extreme cold phases, the lander might provide heater power or other thermal support, but this is a service that depends on the lander and mission. In other cases, the rover must provide its own thermal control through insulation, heaters or other design choices.

2.5.4. Operations, testing and deployment

The user guides provide an outline of the process from testing, integration and eventual operation. This includes payload delivery dates, required documentation and the tests that need to be passed before the payload can be accepted. The APEX lander user guide, for example, lists mechanical testing such as vibration tests and strength verification, shock testing, thermal testing with thermal bakeout and thermal vacuum cycling, EMI/EMC testing, and functional testing [82]. Some of these tests are only required when the payload is sensitive to that specific environment.

These requirements are not uncommon and look similar to CubeSat testing and other testing required for space applications. The goal is to assess whether the payload can survive the mission and operate safely while ensuring it does not put the lander or other payloads in harm's way.

The deployment itself is not fixed in the user guides and is therefore still very mission dependent. Astrobotic mentions that deployment systems need to be non-pyrotechnic, create minimal debris and should not impart shocks greater than 300 g on the lander [28]. Payload adapter plates could also be provided, but the final solution remains open to differentiation based on the rover and lander configuration.

2.5.5. Implications for rover standard

The user guides of commercial landers generally describe the same main topics. They provide a service where the lander is responsible for safely transporting the payload

to the lunar surface, while also acting as the system through which the payload can receive power, transfer data and communicate with the ground. They also define the testing, documentation and safety requirements that the payload has to satisfy, so that it does not endanger the lander or the other payloads.

At the same time, the exact interface is still different for every lander. The payload can be placed in different locations, such as on a deck or side wall. The final placement depends on the payload's size, mass, and mission needs. The same holds for power, data and thermal support. These services may be available, but the exact implementation is lander-dependent. This means that the current commercial lander practice does not yet provide one common interface that can directly be used for a standardised rover.

This means that the standard should define a rover-side framework. This framework should include the mass class, stowed volume, mounting approach, basic power and data needs, thermal assumptions and safety requirements.

The largest missing part in the current lander user guides is the deployment of payloads. This deployment step can strongly shape the rover design, because it affects the attachment points, centre of gravity, geometry, clearances and operational sequence. For that reason, the deployment method is taken as the starting point for the standardisation approach in the following chapter.

3 | Standardisation approach

The goal of this standard is derived from the initial goal of the CubeSat standard. Namely, to make access to space feasible for universities and smaller institutions. Easier access means that these organisations can build, test and innovate without having to start from a highly complex system. Traditionally, space projects have been large, costly, and tailored to a single mission, making the barrier to entry for small teams too high.

The idea of a small, cost-effective satellite changed that. Low complexity, clear interfaces and a form factor that could have different uses created a common basis to build on. Once that basis was available, engineering effort could be focused more on the mission and specific systems rather than reinventing an entire platform.

For this preliminary rover standard, the goals are very similar. Lunar exploration remains inaccessible to many educational institutions and commercial companies, and even when launch or landing opportunities are available, the required knowledge is not readily available. A standard could solve some of these initial barriers and provide common solutions to problems that rovers would have. In that sense, the standard is not meant to define one complete rover design, including battery sizing, power generation or other subsystem choices. Instead, it should define the main framework of the rover, where the key engineering challenges are already taken into account and the main design parameters are given.

Another important reason for the CubeSat's success is the system's modularity. The possibility of scaling up and down, while all using the same design principles that made the standard useful for a wide range of missions. This rover standard should promote the same idea, since no two lunar missions will be exactly the same. A useful standard should therefore provide a common basis while still allowing flexibility for different mission needs.

The following sections, therefore, define the scope, design philosophy, and starting point of this standardisation approach.

3.1. Scope

The standard is initially aimed at a small lunar rover with a mass of up to 10 kg, carried as a secondary payload on a larger lunar lander mission. As a result, the rover is not required to land independently, but is expected to be accommodated by the lander and deployed onto the lunar surface after landing.

The 10 kg mass limit is used as a practical upper boundary for this preliminary standardisation approach. Below this mass, the rover can remain small enough to be considered a secondary payload, while still being capable of carrying the main subsystems required for a basic lunar surface mission. Larger rovers may require different deployment concepts, larger accommodation volumes and greater lander resources, which are outside the scope of this thesis.

The scope of this thesis is limited to lunar surface missions only. Other planetary bodies, such as Mars or other moons, are not considered in order to keep the standardisation approach focused and manageable. This does not mean that some of the conclusions could not later be transferred to other missions. The lunar case is considered the main focus due to the growing interest in lunar exploration, as shown by NASA and ESA goals to return to the Moon through the Artemis programme, and by the rise of upcoming rover missions identified in the mission survey.

Within this scope, the thesis focuses on the framework of a rover standard. The emphasis lies on the deployment mechanism, rover geometry, operational constraints and the interface elements that shape the standardised platform. It does not provide an industry standard or detailed subsystem design, such as power generation, communications, or thermal survival, which are left outside its scope.

3.2. Design philosophy

The design philosophy of this preliminary rover standard is to make lunar rover development accessible for a wide range of missions. The intent is to reduce the amount of custom engineering required, especially in the early stages of design, therefore lowering the barrier to entry for smaller organisations. Low complexity is therefore an important principle, since simpler systems are generally easier to integrate, operate and verify, while also helping to reduce cost and engineering effort.

A second principle is that the standard should start its design process from the interfaces throughout the mission. Individual missions may take different approaches in optimising their rover, but a standard should begin with the commonalities between them. For that reason, deployment is taken as the starting point, as it is the common factor within the standard's framework. This will be further explained in section 3.3.

The standard should be modular in its sizing for volume and mass, to extend the capabilities for the future rover. It should serve more missions, where scaling up the rover should be promoted while keeping the same design logic and practices. Moreover, a concept where multiple rovers could deploy from the same lander would allow for scalability of the concept. As can be seen from the CubeSat dispenser, where many fit into one compact system, this allows for efficient use of space, thereby reducing costs and complexity.

Lastly, the proposed standard should enable a multitude of mission objectives rather than being mission-optimised. Its purpose is to make lunar rover development repeatable on a larger scale, rather than have a single rover be optimised for its mission.

3.3. Deployment as the starting point

From the scope, a commonality in the rover design is that it must be deployed from a lander. This is a typical practice for most small rovers. Where the lander provides the final release onto the surface. Subsystems, instruments and mission architectures could all vary on a mission basis. Deployment, however, remains a common engineering problem that carries its operational difficulties and shapes the mission and rover from the start.

The deployment method restricts the rover through the volume available and therefore

its geometry is set by the lander or through the standard. For that reason, it introduces constraints on its geometry, mass, centre of gravity, integration attachment points and operations during release. These guide the placement of subsystems before any detailed subsystem choices can be made. Therefore it would be a good starting point for the framework of a standardised rover.

Moreover, it also impacts the lander through its required interface and operations. The lander must provide structural support, a power supply for the rovers, and the capability to lower the rovers onto the surface. The deployment affects not only the rover itself, but also other stakeholders who impose restrictions on the design.

For these reasons, this thesis takes the deployment method as a starting point for the standardisation approach. By establishing the possibilities for suitable deployment strategies and methods, and their design constraints and stakeholder impacts, a first framework can be created from which the rest of the rover standard can be developed.

4 | Deployment concept trade-off

The standardisation of a rover should start with constraints common across many missions, from which a platform can be created that serves a wide range of mission types. The deployment mechanism, as mentioned in chapter 3, is a commonality between lunar rover exploration missions and therefore chosen to be a starting point. While every mission may differ, they all share the need to land on the surface and survive the landing. This makes the deployment a problem that shapes the entire platform of a rover standardisation.

The deployment methods determine how the rover is brought to the lunar surface as a payload of the lander, how it is released and under which initial conditions. It affects the rover's design through its geometry, centre of gravity, the forces encountered during release and landing, and the structural strengthening required to withstand potential loads. Moreover, it impacts the lander itself, which needs to accommodate the rover's volume and mass, as well as the release operations and supporting interfaces that need to be provided. These constraints shape the rover before a detailed rover design can be performed.

The purpose of this chapter is to identify possible deployment strategies and assess their suitability. For each method, it is investigated whether it has been used previously for a different mission, what its main advantages and disadvantages are, and how well it fits within the thesis's design philosophy. Particular attention is given to the complexity of deployment operations and mechanisms, reliability, and scalability of the concept for the small rover. The investigated options are then weighted against each other in a trade-off to determine which concept is most suitable for this case. The selected concept is then further explored in the following chapter, in which design implications are investigated through simulation.

4.1. Candidate deployment methods

The survey shows that rovers have been deployed in different ways in the past, depending on their size, mobility system, mission needs, and the lander's constraints. Since this thesis examines a small rover carried as a secondary payload, it is assumed that the rover does not land on its own but must be deployed from the lander once it reaches the lunar surface.

This section provides an overview of the candidate deployment methods relevant to this case. Both previously used methods and concepts that could be used in future missions are discussed. For each option, how it would work, its main advantages and disadvantages, and its suitability for a standardised rover concept are described. This then forms the basis for the trade-off in the following section.

4.1.1. Ramp

Early rover missions often used a ramp to deploy the rover from the lander onto the surface. A panel would be extended downward, with a ramp reaching the ground.

This would provide a track for the rover to drive out of the lander. Inside the lander, the rover could be attached either to the upper deck or to the sidewall, as shown in Figure 4.1 and 4.2. This method is mostly used for larger rovers, since it provides a highly controlled deployment by allowing the rover to drive down gradually. In this way, no large landing forces need to be absorbed by the rover itself, which can simplify the suspension, especially if the rover weighs hundreds of kilograms.

There can be a single point of failure when only one ramp is available. However, as shown in Figure 4.2, there are also cases where the design includes two ramps for redundancy. The Sojourner rover also used two ramps in its design to drive onto the Martian surface [84]. To date, this method has not failed and is being used for upcoming missions, such as the Polaris Astrobotic rover [71]. It remains rather complex due to the many moving parts required to work properly.

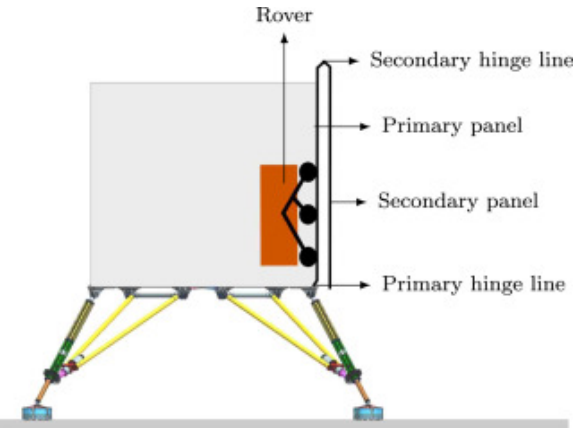

Figure 4.1: Ramp deployment method Chandryaan rover by ISRO[85].

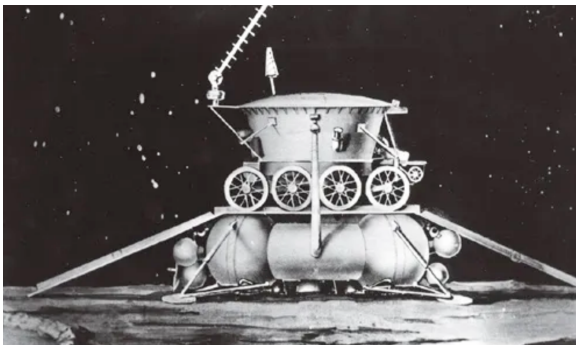

Figure 4.2: Artist impression of the first lunar rover landing and deployment of the Lunokhod 1[86]

4.1.2. Drop/push deployment

Dropping would mean a free-fall from the lander to the lunar surface. The rover could be dropped from underneath or from the side of the lander. It is a very simple method to operate: the connection points are released, and free fall begins. There is also the possibility of the rover being pushed out or away, to increase its initial velocity or to move it clear of landing legs or other instrumentation that might be in the way. Compared to the ramp, the rover would need to withstand landing loads. This might not be a major problem for smaller rovers, since lunar gravity is relatively low and they would reach the ground slowly. This deployment method is less controlled, where the release conditions determine its fall. If any disturbances, such as rotation or lateral movement, occur, they will affect the landing and may cause tipping over without recovery.

The planned CHERI rover by METU will be dropped from the side of the Chang'e 8 lander[87]. It will be attached from the belly of the rover to the lander, and will need to rotate to land on its wheels. This makes it extra complex, but it is due to the landing legs being underneath the dropzone otherwise. This was confirmed by Assoc. Prof. Ersin Soken, Chief Design Engineer at METU (personal communication, February 2026).

4.1.3. Skycrane

A previously used deployment is the Skycrane by NASA, used with the Perseverance and Curiosity rovers. It has its own descent stage, in which it initially lowers its velocity by breaking in the Martian atmosphere. In the end, a hovering platform with thrusters breaks away, from which the rover, attached to tethers, is craned down. Upon landing, the hovering stage above the rover flies away to avoid any collision with the rover itself. Therefore, there is no lander required besides the rover and no need for a very large ramp[88].

This method is very complex, also being at the Martian surface, everything needs to be done autonomously due to the time delay. It requires a hovering platform, controlled lowering and release, and a fly-away manoeuvre. There are many critical points for operations that could go wrong. This will not be considered for a baseline for a small, scalable rover, as it would not be suitable for a secondary payload, with major complexities.

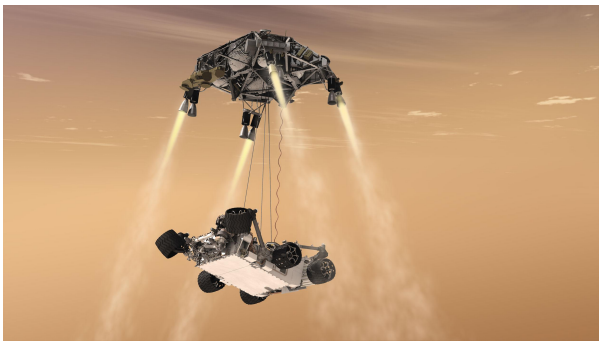

Figure 4.3: Artist impression of the Curiosity rover landing on the Martian surface[89].

4.1.4. Tethered lowering

The skycrane is a rather complex mechanism for a small rover, but the crane or tethered-lowering idea could still be used for smaller missions and is planned for rovers such as CADRE and the Tenacious rover[53][48]. In this method, the lander carefully lowers the rover onto the lunar surface using tethers. The rover would need to be attached in such a way that the drop zone underneath remains clear, and could therefore be placed underneath or to the side of the lander, where the latter is shown in Figure 4.4. This method is more complex because there are many moving parts, and probably multiple attachment points are required to control the rover during lowering. However, the rover can be carefully planted on the surface without risk of tipping over, as it is never in free fall.

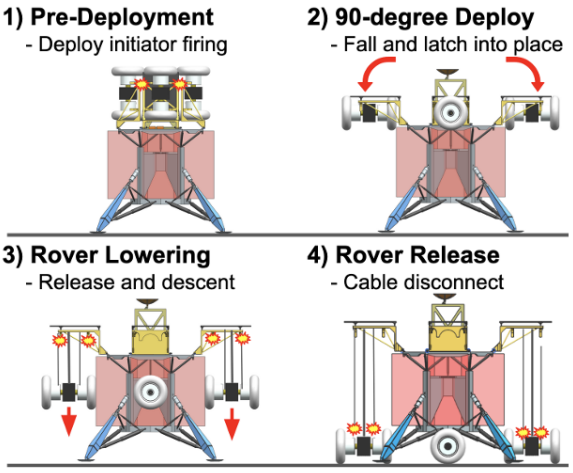

Figure 4.4: Sketch of procedure of tethered lowering of a rover from a lander[90].

4.1.5. Early release

Then there is the possibility of releasing the rover before the lander has reached the surface. The rover would detach from the lander, and gravity would bring it down to the ground. This could reduce the risk of interference with other rovers, the lander's landing legs, or other structures. The MASCOT rover was released in this way at a height of 50 m above the surface, mainly due to the very low gravity of the asteroid environment[91]. Such a low gravity leads to a much softer landing than would be the case on the Moon.

In this thesis, however, only the lunar surface is considered. A release from such a significant height would result in high-impact forces upon impact with the ground. A controlled landing would then almost be out of the question, and a wheeled rover would have difficulty reaching the surface in the correct attitude. An additional mechanism would likely be required to reorient or tip the rover onto its wheels, adding further complexity to the rover design.

4.1.6. Robotic arm

Another deployment method, which has not been used before for a rover, would be a robotic arm placing the rover onto the surface. Similar uses have been seen with the Canadarm on the International Space Station, where a long, controlled arm can perform maintenance and repairs, and assist with assembly and operations. This could also be done for a lander, in which the rover would be retrieved from the payload bay and placed on the surface. It would be able to position the rover in a more suitable spot, with greater freedom of movement, without rocks, holes, or other obstacles. It is also a versatile concept, since if other payloads or equipment need handling, a single arm can serve multiple purposes.

This method would, however, become very complex, especially if it has to operate autonomously. Constant communication might not be possible, which means that the many moving parts need very precise handling. From attachment with the rover and controlled release to the surface. Such a system would ultimately be rather large and heavy, which is not ideal.

4.1.7. Pod deployment

Very similar to the dropping deployment would be the use of a pod in which the rover is situated. This pod could be dropped onto the surface and, once landed, open up so the rover could drive out. The difference is that the rover does not directly handle the first landing loads and is protected from the initial lunar environment, including dust particles and regolith. The pod could also use techniques to soften the blow on the surface. For example, following the idea of the Pathfinder mission with Sojourner, where a cushion of airbags was inflated to take up the fall and then slowly deflated to lower the rover [92].

There would be additional complexity compared to the standard drop method, since the pod would need to open via some form of actuation after landing. If the mechanism fails, the rover might not be able to deploy. Moreover, the same conditions for the pod's free fall still hold, and the attitude upon landing is essential for the rover to exit properly.

4.1.8. Human-assisted detachment

Lastly, there is the possibility of human assistance in rover deployment. This is foreseeable, with new human lunar missions on the way. However, a standardised rover deployment that solely relies on humans is not preferable. It might still take years for humans to reach the Moon again. It is not scalable, since it is far more complicated for humans to land than for a mission that does not rely on them.

4.1.9. Deployment methods to be traded-off

The egress types to be included in the trade-off are shown below in the summation. The skycrane, early release, and human-assisted detachment are not considered further, as they are either too complex from the start or not easily scalable for a standardised rover concept.

- Ramp
- Drop/ Push down
- Robotic arm
- Craned/ Tethered
- Pod

4.2. Trade-off method

Based on the criteria with given weighting, the trade-off will be performed. The criteria and their weights will be explained, and afterwards, the weights will be varied to study the sensitivity of the results of the trade-off.

4.2.1. Trade-off scoring

The following scoring convention is used for the trade-offs performed in this chapter:

- 5: Excellent, exceeds expectation
- 4: Good, just reached expectation

- 3: Some correctable deficiencies
- 2: Many correctable deficiencies
- 1: Unacceptable

Each criterion is assigned a weight on a scale from 0 to 1. This scaling is relative to the other criteria for each trade-off and therefore, no general scoring categories are identified. The trade-off criteria weights always add up to 1. The width of the columns of the trade-off table is scaled according to this weight, with more relevant criteria having wider columns.

Swing weighting will be used to define the weights for the criteria. This is a widely used method in Multi-Criteria Decision Analysis (MCDA), since it is a structured and transparent method [93]. The criteria used in this study are mostly qualitative, where mapping of the criteria can not be done with exact numbers. Therefore, the criteria will be mapped from 0 to 100 qualitatively and then normalised to 0 to 1, as mentioned before. At the start, the baseline is that the criteria are at their worst, then the criteria can be ranked according to what would give the biggest improvement to the mission value. Afterwards, the criteria can be put side by side to obtain the relative weighting.

The criteria will first be discussed with their given weights. Following this, the trade-off table will be filled in and discussed afterwards.

4.2.2. Trade-off criteria

This trade-off will be based on five criteria that need to evaluate the egression types on different aspects. The main aspects are the lander's impact, the rover's impact, the deployment system complexity, the terrain robustness and lastly the standardisation capabilities. The criteria are first explained, and the extent to which they will rank the deployment types. Then the scoring from 1 to 5 will be clarified, so as to keep it repeatable and non-opinion-based.

- **Mechanism and operational complexity**
  This criterion weighs in on the impact of the dispenser's complexity and its usability. Whether the five given options of egression types are mechanically viable, it is possible to autonomously operate and handle the loads of flight. It takes into account whether the technology has been used in a similar case before. And if single points of failure can be foreseen. In the end, simplicity of design leads to reliability in use. A higher score on this criterion indicates a less complex method, making it more favourable for a standardised rover concept.
  - **5:** Mostly passive, simple operation, does not rely on active feedback, tolerant to sequencing or timing variation, fail-safe behaviour, no obvious critical single point of failure.
  - **4:** Limited active parts, forgiving sequencing, basic sensing only for confirmation, and failures are unlikely to cause total loss.
  - **3:** Requires coordination, with some single points of failure that can be mitigated.
  - **2:** High complexity, sensitive sequencing or alignment, requires active control during deployment, and contains major single points of failure.

  - **1:** Very complex, tightly coupled actions require continuous control or monitoring, low tolerance to deviations, and several foreseeable single points of failure.

- **Standardisation potential**
  This criterion ensures the scalability and adaptability of the deployment type. The mechanical interface should be easy to use. Moreover, just like the CubeSat, this standardised rover would get better traction in industry when it is scalable in size. This leaves more room for innovation and tailoring the needs of a specific mission to an existing standard. Therefore, the egression type should accommodate changeability in the design of the rover. Finally, it should be easily interchangeable over different lander configurations. A higher score on this criterion indicates that the method is better suited for standardisation.
  - **5:** Clear, stable interface concept, compatible with many landers using adapters without changing the core concept, scalable rover sizes without changing the deployment principle
  - **4:** Interface concept mostly stable, minor mission-specific adaptations (brackets, clearances, harnessing) are expected, scaling feasible within a broad range with limited redesign
  - **3:** Partially reusable interfaces, moderate redesign often needed (geometry, mounting, harness routing), scaling possible but regularly forces concept adjustments
  - **2:** Lander- or mission-specific geometry drives the solution, reuse is limited, scaling frequently requires substantial rework of interfaces and surrounding structure
  - **1:** Bespoke per mission/lander, no stable interface definition, poor scalability, "standard" would not meaningfully reduce redesign effort

- **Lander mass / volume impact**
  This criterion establishes the importance of the integration and ease of use for the lander. As this standard should provide a secondary payload dispenser, it should be efficient with mass and volume. This is always of great importance within the space industry; any extra performance to be gained should be taken advantage of. Moreover, it includes whether various egress types require extra power and controls required from the lander during the flight, so not during the deployment itself. Furthermore, a bigger dispenser would lead to added structural complexity for the lander. Lastly, mass and volume always affect costs; they will not be taken into account since they are impossible to quantify, but they should be noted. A higher score on this criterion indicates that the method has a lower impact on the mass and volume of the lander and is advantageous.
  - **5:** Minimal additional structure/envelope, little effect on lander packaging; minimal additional power/controls, integration is straightforward with low structural impact
  - **4:** Small packaging/structural penalty, limited additional power/controls, minor integration complexity, but no major lander redesign drivers
  - **3:** Moderate structural/envelope penalty, requires dedicated integration effort and some additional controls/harnessing; noticeable impact on lander

layout

- **2:** Significant added structure/envelope and integration complexity, requires additional subsystems (controls/sensing/power) that meaningfully affect lander design
- **1:** Major driver of lander redesign (structure, layout, controls/power), large volume/mass penalty, high integration and verification burden

- **Rover design impact**
  This criterion assesses how strongly the deployment system constrains the rover design. It considers whether the rover requires specific attachment points, release interfaces, keep-out zones or structural reinforcements to be compatible with the deployment method. It also includes the effect on the centre-of-gravity location, mass distribution and available internal volume. These aspects are important because they can limit the placement of subsystems. A deployment method with a high impact on rover design may force the rover architecture to be designed around the deployment system rather than the mission needs. A higher score, therefore, indicates that the deployment method leaves more freedom for the rover layout, mobility concept and payload accommodation.
  - **5:** The deployment method requires only simple and accessible attachment points on the rover. The rover can keep its preferred body shape, mobility system, payload location and centre-of-gravity placement.
  - **4:** The deployment method introduces minor interface or keep-out requirements, such as mounting brackets or local reinforcement. These changes do not strongly affect the rover layout, payload volume or mobility system.
  - **3:** The deployment method requires clear design adaptations to the rover, such as specific attachment locations, stronger structure, limited centre-of-gravity placement or restricted packaging. These changes are feasible, but must be considered early in the rover design.
  - **2:** The deployment method strongly constrains the rover layout. It may require impact protection, strict centre-of-gravity placement, or changes to the wheelbase, suspension, body shape or payload location.
  - **1:** The rover must be designed mainly around the deployment method. The deployment system dictates the rover shape, structure, attachment points, centre-of-gravity location or mobility concept, leaving little freedom for mission-specific rover design.
- **Terrain robustness**
  This criterion assesses how well the deployment method can deal with the uncertainty of the lunar terrain and the lander's attitude. It considers whether the rover can be deployed with a slightly tilted lander when there are rocks at the landing zone or craters. This is important since conditions are unknown before the landing, and the thrusters of the lander can change the surface terrain. A deployment method that is more robust to various terrains and initial conditions is less dependent on an ideal environment and would be better suited for deployment. A higher score indicates that the method can place or release the rover safely under a wider range of realistic lunar surface conditions.
  - **5:** High tolerance to realistic variability(lander tilt, small rocks, regolith unevenness, success not dependent on precise contact conditions, low

sensitivity to local terrain features

- **4:** Tolerant to moderate variability, only extreme tilt/ obstacles are problematic
- **3:** Works under nominal conditions and moderate unevenness/ tilt, sensitive to more challenging terrain but still plausible with reasonable site conditions
- **2:** Requires relatively favorable terrain, sensitive to tilt/rocks/regolith
- **1:** Highly sensitive to terrain and lander pose, success strongly depends on near-ideal conditions, high chance of failed egress with realistic surface variability

Weighting of criteria

To reiterate the goal of this trade-off, it is to identify the preferred deployment type that enables small rovers to be launched on a larger scale. The weights reflect the importance of the objective of the lunar standardised small rover. The system should be reliable and repeatable, and easy to use from integration through egress operations to safe landing. The primary stakeholders, in this case mainly the lander provider and rover manufacturer, should not be affected too much by their design, as it is still seen as a secondary payload to the lander. It should be transferable over various lander providers, and a multitude of landing sites should be viable through its robustness. The weights reflect the importance of this standardised rover's objective.

Landing safely on the lunar surface is priority number one for the rover mission to succeed. The criterion that drives it most strongly is the mechanical and operational complexity. Moving parts, tight sequencing and intricacy increase the chance of failure through multiple failure modes. The simplest design is most often the most promising. For this reason, this criterion will be awarded 100 points, and the remaining criteria will be weighted relative to this.

Secondly, for the concept of rover standardisation to work, it should provide an accessible platform for educational institutions and commercial companies. It should be easy to use, flexible for modification, and scalable to different rover sizes. Moreover, it should allow multiple rovers to be deployed within a single mission and be transferable between different landers rather than being dedicated to a specific provider. Therefore, the standardisation potential criterion is awarded 80 points, as it is essential to the thesis's purpose.

Third is the impact on the lander, because the concept needs a lander willing and able to provide the deployment. When the choice of deployment gets too demanding and causes large penalties in lander volume, mass, integration effort and or operations. This all reduces the likelihood of the concept of a rover working. It will be awarded 70 points.

The impact on the rover design is weighted lower because rover manufacturers can design around interface constraints and other restrictions. However, it remains important, since the manufacturers should be given freedom, where the workarounds should not be too demanding. This will be awarded 50 points.

Lastly, terrain robustness is weighted the lowest. This is partly because it can be seen

as a subset of the operational complexity, although it is treated separately here. It is also strongly mission-dependent, and additional measures can be taken when the landing site is expected to be more challenging. However, if a deployment method is too sensitive to terrain conditions, this should still become visible through the trade-off. The criticality of terrain is difficult to quantify and justify directly, and from discussions with companies, it appears to be largely a matter of risk assessment and available budget for a more complex but forgiving deployment mechanism. For this reason, terrain robustness is awarded 35 points.

These criteria exclude the monetary costs of this trade-off because they are difficult to quantify. No number can be put to the specific options shown. However, all of these criteria encompass cost in the end. The complexity of a system requires higher engineering costs and testing time. Lander impact, either mass or volume, drives the cost since less effective use of space will leave less room for other payloads. Standardisation potential in the end works the same. When a dispenser could be used often and reliably, it would lead to more customers and could drive up competition for dispensers. This might then reduce costs for a spot to the lunar surface.

Shown in Table 4.1 below are the normalised weights for the trade-off.

Table 4.1: The weighting of the criteria based on swing weighting, with normalised values

Criteria	Complexity	Standardisation	Lander	Rover	Terrain
Weight	100	80	70	50	35
Normalised weight	0.30	0.24	0.21	0.15	0.1

4.3. Trade-off results

Table 4.2 shows the results of the trade-off for the five selected deployment concepts. The drop/push method achieves the highest total score, followed by the pod and tethered-lowering concepts. The ramp and robotic arm methods score lower, mainly due to their higher complexity and less favourable fit with the objective of a standardised small rover platform.

Table 4.2: Trade-off table for the standardised rover with 5 criteria and 5 options, including the normalised weights and results.

Criteria / Options	*Complexity*	*Standard potential*	*Lander impact*	*Rover impact*	*Terrain*	*Total score*
Weights	0.3	0.24	0.21	0.15	0.10	1
Drop / Push	5	4	5	3	3	4.25
Ramp	3	3	3	4	4	3.25
Pod	4	5	4	3	3	3.99
Robotic arm	2	3	2	4	5	2.85
Tethered	3	4	3	4	5	3.60

Table 4.3 explains the reasoning for the given scores of the trade-off in simple terms and is extended in the following text.

Table 4.3: Justification of the trade-off scores for the deployment concepts.

Concept	Complexity	Standardisation	Lander impact	Rover impact	Terrain robustness
Drop/push	**5:** Mostly passive release, few moving parts and limited sequencing.	**4:** Fixed release interface can be reused and scaled, requires specific placement and spacing inside the lander so lander configuration could be impacted.	**5:** No additional controls required, simple release	**3:** Rover must tolerate impact, rotation and possible tip-over this could constrain placement of CG.	**3:** Success depends on clear drop zone and release conditions.
Ramp	**3:** Proven concept, but requires a deployment mechanism and drive-off operation.	**3:** Ramp geometry depends on rover size, mobility system, difficult to scale for multiple rovers, would require reuse of ramp or to be single-use.	**3:** Adds stowed volume, structure and mechanism to the lander.	**4:** Controlled egress reduces impact loads on the rover, constrained by choice of mobility choice.	**4:** Controlled path, but still affected by lander tilt and ramp-ground contact.
Pod	**4:** Release is simple, but pod opening adds an extra mechanism.	**5:** Pod size can be scaled, similar to a containerised payload.	**4:** simple release mechanism, no controls, additional pod mass and volume are required with possibly additional structural complexity.	**3:** Rover is protected during first impact, but depends on pod attitude and opening, restrictions on CG placement.	**3:** Pod still lands uncontrolled and must open correctly, could tip over.
Robotic arm	**2:** Many moving parts, sensing, control and autonomous placement are required.	**3:** Versatile, but strongly lander-specific, failure of arm leads to multiple rover failures.	**2:** Arm mass, volume, power and control are major lander penalties.	**4:** Rover can be placed gently with fewer rover-side constraints.	**5:** Can avoid local obstacles if sensing and control work correctly.
Tethered lowering	**3:** Controlled lowering, but needs motors, tethers, release control and sequencing.	**4:** Rover interface can be repeated, would require own mechanism for every rover.	**3:** Requires lowering hardware and integration effort on the lander.	**4:** Soft touchdown reduces rover impact and tip-over risk, requires multiple connections to be lowered.	**5:** Tolerant of rough terrain.

Drop/push method
The drop / push method was deemed the preferred option for the given weighting, as it provides the best balance between simplicity, low impact on the lander, and good standardisation potential. Its main strength is that it is mechanically straightforward. The rover only needs to be attached to the lander and then released, with the possibility of a small push force to move it clear of the lander. Compared to the other options, this means fewer moving parts, fewer active operations, and fewer possible failure modes. Since the complexity criterion was weighted the highest, this gives the drop/push method a strong advantage. In addition, the impact on the lander remains limited, as no large ramp, robotic arm, or full lowering mechanism is required. The concept is also regarded as having good standardisation potential, since the same basic release principle could be used for different rover sizes with fixed interface locations and known release conditions. Its main disadvantage is that the rover has no control during the free fall and must be able to withstand the landing loads, while disturbances during release may lead to rotation or tip-over. However, for a small rover in low lunar gravity, these disadvantages are considered more acceptable than the added complexity of the other methods. For that reason, the drop/push method achieved the highest total score and is selected as the baseline concept for further analysis.

Pod deployment
Then there is the pod deployment, which scored relatively high. As it is in essence very close to the drop deployment, with the benefit that the rover does not need to absorb the initial landing loads. The pod provides some extra protection from dust and regolith. So, from that view, it is more forgiving. The concept is also easy to scale, both in the rover sizing, where a similar pod structure can be made with a larger size, and in that multiple rovers can be integrated in a single lander. However, the pod also holds the same downsides of rotation and tip over and additional complexity in the form of actuation, electronics and mechanisms. As the door for the pod needs to open up, it leads to an extra failure mode and the rover might not be able to drive out. Moreover, the pod itself adds structural mass and packaging volume. So these all reduce the simplicity advantage. For that reason, it is still attractive, but not regarded as a baseline for the extra mechanism and structure.

Tethered lowering
The tethered lowering method is in third, with relatively high scores as well. This is mainly because it provides a more controlled landing compared to the drop method. The rover can be placed more gently on the surface and is less dependent on perfect conditions, reducing the risk of tipping over. For that reason, it scores more favourably in terms of terrain robustness. However, this method loses points on complexity and lander impact. The lander must provide the full lowering mechanism, including motors and control. This leads to additional mass, volume, and operational difficulty. Moreover, every rover would require its own lowering mechanism, which makes it more difficult to scale up the number of rovers within a single mission. If the lowering does not function properly, it effectively becomes the dropping method, which would include extra redundancy; however, it is not meant for what it is supposed to do. For this reason, it remains a viable option. As discussed before, some companies may prefer such a method, since it offers more certainty and lowers the risk once properly

tested. However, due to the added complexity, it is not preferred over the drop method for a cost-effective and low-complexity standardised rover concept.

Ramp deployment
The ramp deployment will not be further explored as an option for the small standardised rover, even though it provides a controlled deployment, has been used previously and performs well in various terrain conditions. Its main disadvantage is that the lander must provide the ramp and its required mechanism, which all adds mass, volume and complexity. In addition, the ramp would need to be suitable for different rover sizes and mobility methods, so there might not be a single solution to the ramp. Furthermore, a shared ramp could create operational problems as one rover would fail, the ramp would be blocked and the other payloads would have problems. But a separate ramp for every single rover would be too heavy. For these reasons, the ramp is not considered viable for the standard.

Robotic arm deployment
Lastly, the robotic arm concept is seen as an even less suitable deployment method. Its main advantage is that it provides the best placement of the rover onto the surface, since rocks, holes, and other obstacles can be avoided. However, the system is too complicated for this use case and brings many operational complexities. A robotic arm would require many moving parts, precise autonomous control, reliable attachment to the payload, and a controlled release onto the surface, and would most likely also become rather large and heavy. Furthermore, it introduces a clear single point of failure, since if the arm does not function properly, the payloads cannot be deployed. In the end, although the rover itself would be less constrained, the complications introduced by the system outweigh the added design freedom. For that reason, this concept is not considered further.

4.4. Sensitivity analysis

The sensitivity analysis will verify the credibility of the trade-off performed. As said before, it is a qualitative trade-off where the criteria are difficult or impossible to quantify. Therefore, swing weighting is again used in this analysis to assess sensitivity to stakeholder priorities. Various cases and stakeholders will be broken down to see whether a change of weighting for the criteria has a large impact on the resulting trade-off solution. The performance scores of the trade-off will remain unchanged. The swing weighting reflects the preference for the criteria's weighting under plausible stakeholder priorities.

Four alternative cases are considered: the rover manufacturer for themselves, the lander's view, increased terrain robustness and lastly, where everything would get equal weighting. For each case, the criteria of highest importance will be given 100 points, and the other criteria will be scored respectively to that. After which, the points will be normalised and used as trade-off weights and the trade-off could be performed.

Lander view
Starting with the situation where the lander provider is allowed to adjust the weighting of the criteria in their favour. First and foremost, the impact on the lander should be

very minimal. The deployment method should be low in mass and volume, leave room for other payloads and use simple integration methods and interfaces. Related to this, the mechanical and operational complexity should not be a burden to the lander provider, which is responsible for safe delivery to the surface. A method with additional steps would require extra testing and create operational risks. For these reasons, lander impact and complexity are given the highest weights.

The standardisation potential is less important, since scalability and adaptability primarily benefit the rover client; a successful standard could attract more future customers. The impact on the rover is also weighted lower, as the rover is expected to adapt to the constraints imposed by the lander. These should be reasonable and allow sufficient design freedom to remain attractive to customers. Terrain robustness remains relevant, but is not the primary driver as long as the deployment risks can be managed within the selected landing site.

Rover view

From the rover manufacturer's perspective, the deployer should make it easy to achieve performance by imposing few constraints while maximising the probability of success. The rover must be able to achieve its objectives while remaining cost-effective. For this reason, the impact on the rover is given the highest importance.

The complexity is less critical from this perspective if it reduces deployment risk. A more complex system may be acceptable if it enables a more controlled deployment. However, it should not add too many risky failure modes.

The lander mass and volume impact are less direct concerns for the rover manufacturer, although they may influence cost through payload constraints. Standardisation potential is important, as it enables easier integration across different landers and may reduce development effort. Terrain robustness is also relevant, as surface conditions can directly affect deployment success.

Increased terrain robustness

An additional case is considered in which terrain robustness is given increased weight. This weighs in on missions where the landing site is more uncertain or where surface hazards are expected to play a significant role. The impact of terrain on deployment is difficult to quantify, as local conditions such as rocks, slopes, and regolith properties can strongly influence the outcome.

In such scenarios, the deployment method should be more tolerant of uneven terrain and uncertainties in the lander position. A single obstacle in the deployment area could lead to mission failure, particularly for a small rover. Therefore, in this case, terrain robustness is weighted equally with mechanical and operational complexity, while the remaining criteria are kept consistent with the nominal trade-off.

The weights given are shown below in Table 4.4. Also, for the equal weighting scenario. Various stakeholders are considered, with their specific reasoning for the changes. This shows whether the concept is sensitive to changes in priorities and whether it remains preferred.

Table 4.4: Swing weighting results for the various stakeholder views used for the sensitivity analysis.

Criteria / Stakeholder	*Complexity*	*Standard potential*	*Lander impact*	*Rover impact*	*Terrain*
Normal	100	80	70	50	35
Lander view	80	40	100	20	60
Rover view	50	70	30	100	50
Terrain	100	80	70	50	100
Equal	100	100	100	100	100

Table 4.5 shows the weighted trade-off for the various stakeholders described above.

Table 4.5: Weighted trade-off results for the alternative stakeholder weightings.

	Stakeholders				
Option	*Normal*	*Lander view*	*Rover view*	*Terrain*	*Equal*
Drop / Push	4.25	4.33	3.77	4.05	4.00
Ramp	3.25	3.27	3.50	3.38	3.40
Pod	3.99	3.87	3.73	3.83	3.80
Robotic arm	2.85	2.87	3.40	3.20	3.20
Tethered-lowering	3.60	3.60	3.90	3.83	3.80

4.4.1. Discussion and selected baseline for further analysis

The results show that the drop / push method is preferred in almost every way, except from the view of the rover manufacturer. This indicates that the method closely aligns with the nominal trade-off with the main goal of a low complexity, scalable, standardised rover. The ramp and robotic are still not receiving high scores, primarily because they are too complex for the goal.

The drop deployment and the pod concept show similar results in the trade-off, since both rely on basically the same releasing method. The difference is an additional container around the rover. This would provide the rover with extra protection at the cost of added structure and an opening mechanism upon landing. These reduce the simplicity and is therefore not selected as a baseline even though it remains a viable option.

Similarly, the winch or tethered-lowering method also scores high, and in the case of the rover view, would be preferred. This method is already in use for various rover missions. The connections to the rover would be very similar to the drop method and should provide a smooth landing. However, it requires a more complex deployment system from the lander's view, with additional mechanisms and controls. For the rover concept that is mostly focused on simplicity and scalability, this makes it less suitable. It should not be fully disregarded for future cases where risk reduction is prioritised more.

To conclude, the drop/push mechanism is selected as the baseline for further analysis. It is not selected because it provides the most controlled touchdown, but because it best fits the aim of a preliminary standardised rover concept. The method is simple, has a low impact on the lander, can be integrated through a common release interface, and is suitable for scaling to multiple small rovers. This makes it accessible and repeatable compared to more controlled but more complex deployment concepts.

The sensitivity analysis also shows that drop/push is not universally the best deployment method. In cases where rover-side risk reduction is prioritised, a more controlled method such as tethered lowering can become preferable. However, drop/push is the best baseline for this thesis because its main risks can be translated into clear design parameters, such as drop height, release velocity, separation angle, centre-of-gravity location and rover spacing. These parameters can then be investigated directly in the following chapter using a simplified deployment simulation.

5 | Deployment simulation model and results

The trade-off in the previous chapter presented that the drop/push deployment would be preferred for the standardisation of a rover. The fall offers clear benefits with its simplicity and scalability as main strengths, however the release mechanism still introduces uncertainties for the stability of landing onto the surface. To investigate the effects of possible tip-over, a simplified two-dimensional model has been developed. The goal is not to fully simulate the drop method's reality, given its many unknowns and intricacies, but to identify the key parameters that influence touchdown stability. This way, the rover geometry, centre of gravity and initial conditions could be assessed for a preliminary standard.

5.1. Objective of the simulation

The objective of the simulation is to determine how the initial conditions of free fall after release from the lander affect the landing behaviour on the lunar surface. In particular, the simulation analyses the effect of initial angular velocity, drop height, rover geometry and centre of gravity position. These all affect the tip-over dynamics directly and the corresponding critical angle for a safe landing. When these parameters are varied, their dependence to the changes could be measured. This can then inform the requirements to be set for the rover standardisation and deployment interfaces.

Moreover, this simplified simulation is used as a first-order design tool to estimate geometric and mass-distribution boundaries. Such boundaries could include an allowable centre-of-gravity offset within the available volume, or desirable proportions between rover height and base of support. The model can therefore help define preliminary limits on the rover geometry and assess the design's sensitivity to disturbances induced by the deployer. In this way, it demonstrates the rover's robustness during deployment.

As previously mentioned, scalability is also an important aspect of standardisation. Multiple rovers side by side might be necessary to achieve this scalability in practice. This also brings its extra challenges, for example, the spacing required between rovers inside the lander. Collisions during the free fall to the other payloads should be avoided, as they could damage fragile structures. By modelling the descent and the effects of rotation, it can estimate the clearance required between rovers and other payloads and highlight potential issues when the configuration is packed very compactly.

5.2. Deployment concept and relevance

The deployment concept selected in chapter 4 is the drop/push method. In this concept, the rover is released from the lander and reaches the lunar surface through a short free-fall phase in the lunar environment. The main advantage of this method is its simplicity, as it does not require an actively controlled lowering or placement

mechanism. However, this limited control also introduces uncertainty after release. Any disturbance in attitude, angular velocity, or lateral motion can therefore directly affect where the rover touches down and the orientation it reaches the surface in.

For the simulation, the drop/push method is implemented as a rail-guided push-out system based on a CubeSat dispenser, as shown in Figure 5.1. The CubeSat dispenser is not assumed to be directly applicable as a rover deployer, but is used as a reference because it provides a simple and established release principle. In such a system, the payload is guided by rails and pushed out by a spring force after the dispenser door is opened. This makes it useful for the present study, since dispenser characteristics can be used to define representative release disturbances, such as exit velocity, angular velocity and lateral deviation.

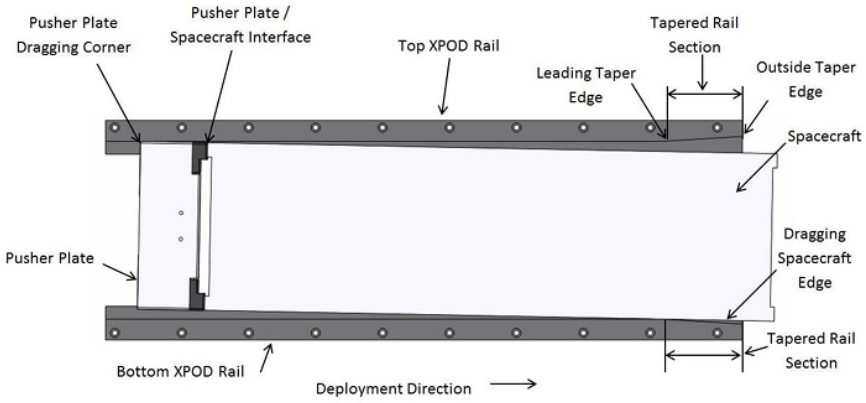

Figure 5.1: Schematics of the XPOD CubeSat dispenser [94].

During the guided phase, the rover is constrained by the rails and remains aligned with the desired release direction. For CubeSats, the spring force is required to separate the spacecraft from the launcher or deployment platform in microgravity. For a rover on a lunar lander, this push may not be required, since lunar gravity already accelerates the rover towards the surface. However, a push force may still be useful to ensure separation from the deployer or to move the rover away from the lander structure. The resulting exit velocity can also introduce disturbances similar to those observed in common spacecraft dispensers.

The same free-fall behaviour can also occur for other release mechanisms. For example, the rover could be attached to the lander by several hold-down release mechanisms. If these attachment points do not release at exactly the same time, a rotation can be introduced at the start of the free fall. Although the mechanism is different from a rail-guided dispenser, the resulting free-fall condition can still be represented by similar model inputs, such as an initial angular velocity. This is difficult to characterise in general, since it depends strongly on the specific release system. The MoonRanger rover, shown in Figure 5.2, is an example of a rover attached through multiple hold-down points.

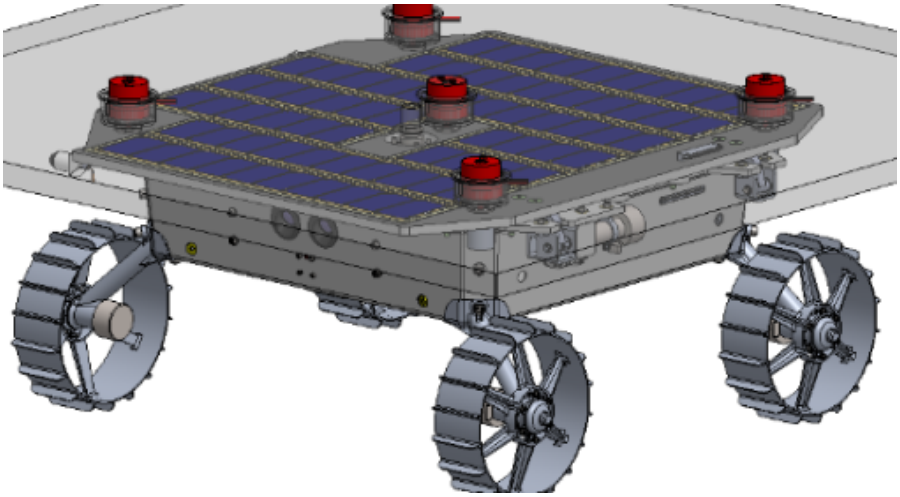

Figure 5.2: Top-mounted attachment points of the MoonRanger rover by Carnegie Mellon University [95].

The model is also relevant for tethered-lowering concepts when the rover is released slightly above the surface. In that case, the rover is controlled during most of the deployment, but the final part may still include a short free-fall phase. The same basic mechanics of rotation and lateral displacement can therefore apply, although the drop height would be much smaller than for a direct drop/push deployment. This type of approach is currently used by ispace with the Tenacious rover, where the rover is lowered and then released from a limited height above the surface. This was confirmed by E. Umit, Payload Systems Engineer at Ispace (personal communication, November 2025).

This section therefore defines how the selected drop/push concept is represented in the simulation. CubeSat dispenser characteristics are used as a reference for the release conditions, while other release mechanisms are represented through the same simplified inputs. This links the selected deployment concept to the simplified model introduced in the next section.

5.3. Model description

In essence, what is being modelled is a free-falling rigid body released from the lander two-dimensionally. The rover is represented by a square with four corners and a centre of gravity, initially rotated at an initial rotational velocity, falling under the moon's gravity, and could be pushed out by a spring force. This centre of gravity is shifted relatively to the geometric centre of the body. This is done to study the effects and boundaries of the rover's landing stability.

The motion is described through a translational displacement and a rotation through its centre of gravity (CG). Before the release of the rover, an initial height, initial velocity, and angular velocity are assigned, representing conditions that might occur during free fall. The free fall is forced by the gravitational force and the possibility of a spring force pushing the rover out of its deployment mechanism. Moreover, the rover is initially guided by rails just like a CubeSat would. This implies that as long as the rover has not fully released from the dispenser, no rotation and lateral movement can

take place.

During the free fall, the position of the centre of gravity and the four corners are tracked at every time step. Using the body-fixed corner coordinates and the rotation angle, the global coordinates can be determined. Through the position tracking, the moment of touchdown of the rover onto the surface can be taken, at which the simulation stops. At this moment, the orientation can be compared to the critical tip-over angle to assess whether the landing is stable upon touchdown. This does not imply that the rover is stable once settled, as interaction with the ground could induce other dynamics not included in this thesis.

Besides rotation by a small disturbing force through the spring or gravity, there could also be lateral movement out of the dispenser. This will affect the time till impact and position. Therefore additionally to its stability, the model also provides an estimate of the clearance envelope of the rover during descent. This is relevant when considering multiple rovers or other payloads that could be in the way and could cause collisions during the free fall. This simulation would therefore serve as both an analysis of the initial stability during landing and a first-order design tool for geometric constraints of both the deployment mechanism and the rover.

5.3.1. Assumptions and simplifications

To obtain a first-order understanding of the fall mechanics of the rovers during deployment, a number of assumptions and simplifications are made. These will reduce the complexity of the simulation and allow one to study the release conditions, rover geometry and centre of gravity.

The rover is modelled as a rigid body that translates only vertically and laterally and rotates only out of the plane. So, a full three-dimensional attitude motion is neglected. The main concern is tipping over in the most critical plane, which would be where the base of support is the smallest. This is therefore justified as simulating the worst-case scenario. As it is a rigid body, the suspension or non-rigid wheels are not taken into account in the tipping over tendency.

Moreover, the lunar surface is assumed to be flat and rigid. There are no rocks or craters which could affect the motion, and no interaction of slipping is included. This is to isolate the release conditions, but it will definitely impact the tipping analysis.

The initial angular velocity used simplifies the deployer's mechanics. As there can be many ways the deployer could affect the rotation through the pusher plate mechanics, the small gap between the rails and the rover body and the centre of gravity. These mechanics are not taken into account because there are too many unknowns that could have a major impact, and there is no good enough model to justify the assumptions. The angular velocity induced upon release by CubeSat dispenser is studied, where the EXOpod dispenser mentions that angular velocities up to $10\,^{\circ}/s$ could be expected at maximum [96]. As this is quantifiable, various angular velocities around this number will be modelled to show the impact of rotation and will therefore be a parameter.

The forces acting during the free fall are only the gravity and no aerodynamic drag. As the moon has no substantial atmosphere, it would therefore not affect the free fall. Moreover, the gravity is assumed to be constant, there are noticeable variances

depending on the landing location of the lander. Inside the deployer, the assumption is that there is a lack of friction, so the rover has no friction with the guide rails.

The spring force pushing the CubeSat dispenser will serve as the initial velocity. This is because the forces can vary per weight class and size. However, the exit velocities stay more or less constant over various sizes. Where the velocities range between 1 and $2\,\mathrm{m\,s^{-1}}$ for the EXOpod [96]. The minimum taken for this simulation will be slightly lower, as there is also an effect of gravity that accelerates the fall and therefore increases the speed at impact.

Lastly, sideways movement could be induced by inconsistencies in the dispenser and is also observed with CubeSat dispensers. Most dispenser suppliers do not provide numbers, as it is not a real problem to get a CubeSat close to the correct orbit, since these inconsistencies are only small in the vastness of space. It could, however, affect the rover's landing site and be detrimental to operations. Any collisions with other hardware must be avoided, such as the landing legs or other rovers. This sideways movement will be represented by a half-cone separation angle as EXOpod mentions it [96]. Where up to $7.5\,^\circ$ could be endured. This will also be taken into account for the simulation.

5.3.2. Numerical implementation

The free-fall motion is solved numerically by updating the translational, lateral and rotational states at discrete time steps. The state variables are the centre-of-gravity release conditions; these variables are updated iteratively until the rover reaches the lunar surface.

The model separates the deployment into two phases. In the first phase, the rover is still guided by the rails of the dispenser. During this guided phase, the rover is constrained by the deployer and is not allowed to rotate or move sideways. Only the motion along the deployment direction is updated. The rover is considered to have left the dispenser once it has travelled the full rail length L_{rail}.

The translational motion is integrated with a semi-implicit Euler scheme. With this approach, the velocity is updated first, followed by the position. This method is selected for its simplicity and sufficient accuracy, since the acceleration during free fall is constant and caused by lunar gravity. If a push from the deployment mechanism is included, it is represented by an initial velocity in the deployment direction.

The simulation updates with a constant time step:

$$t_{n+1} = t_n + \Delta t \tag{5.1}$$

The translational acceleration is caused by lunar gravity and is written as:

$$\mathbf{a} = \begin{bmatrix} 0 & -g_{moon} \end{bmatrix} \tag{5.2}$$

During the guided phase, the velocity and position are updated as:

$$\mathbf{v}_{n+1} = \mathbf{v}_n + \mathbf{a}\Delta t \tag{5.3}$$

$$\begin{bmatrix} x_{n+1} & y_{n+1} \end{bmatrix} = \begin{bmatrix} x_n & y_n \end{bmatrix} + \mathbf{v}_{n+1}\Delta t \tag{5.4}$$

As long as the rover is inside the guide rails, the lateral velocity is set to zero. The rover therefore only moves along the deployment direction during this phase.

Once the rover has passed the guide rails, it enters free-fall. From this point, the rover is no longer constrained by the dispenser and can both rotate and move laterally. The angular velocity is then applied and is assumed to remain constant, since no external moment is included after release.

Lateral motion is introduced through the half-cone separation angle α. This angle acts as the possible deviation caused by inconsistencies in the spring or deployer mechanism. The half-cone separation angle is applied to the exit velocity rather than to the initial velocity. The exit velocity is the velocity of the rover at the moment it clears the guide rails:

$$v_{exit} = \left| v_y(t_{exit}) \right| \tag{5.5}$$

where t_{exit} is the time at which the rover leaves the guide rails. After rail exit, the velocity components are defined as:

$$\mathbf{v}_{exit} = \begin{bmatrix} v_{exit}\sin(\alpha) & -v_{exit}\cos(\alpha) \end{bmatrix} \tag{5.6}$$

The sign of the lateral component depends on the direction of the sideways deviation. After rail exit, the same translational update equations are used, but now with both a vertical and lateral velocity component.

The angular position is updated as:

$$\theta_{n+1} = \theta_n + \omega \Delta t \tag{5.7}$$

This update is only active after rail exit. Before this point, the rover is constrained by the guide rails and the rotation angle remains constant.

The rotation matrix used to transform the rover geometry is:

$$R = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \tag{5.8}$$

The local coordinates of the four corners are defined relative to the centre of gravity. The centre-of-gravity offset (x_{cg}, y_{cg}) is measured from the geometric centre of the rover body:

$$L = \begin{bmatrix} +w/2 & +h/2 \\ +w/2 & -h/2 \\ -w/2 & -h/2 \\ -w/2 & +h/2 \end{bmatrix} - \begin{bmatrix} x_{cg} & y_{cg} \end{bmatrix} \tag{5.9}$$

Here, L contains the local coordinates of the four corners around the centre of gravity, while w and h are the rover's width and height.

The world coordinates of the four corners at time step n are then obtained by rotating the local coordinates and translating them to the global centre of gravity position:

$$W_n = \left(RL^T\right)^T + \begin{bmatrix} x_n & y_n \end{bmatrix} \tag{5.10}$$

At each time step, the four world coordinates are checked. The simulation stops once one of the corners reaches or passes the lunar surface. Due to the discrete time step, the final vertical coordinate of the first contact point may be slightly below zero.

5.3.3. Stability criterion

This runs until one of the corner points is below the ground level, and therefore it has hit the surface. It will iterate over the points and find which corner has hit the ground.

The rover will tip over when the centre of gravity is outside the base of support. With the base of support being the two outer bottom corners/wheels of the rover

The critical tip-over angle would be :

$$\Theta = \arctan\left(\frac{w/2 - |x_{cg}|}{h/2 + y_{cg}}\right) \tag{5.11}$$

where w is the width and h is the height of the rover. These are the outer dimensions of the rover, including wheels and other attachments. The CG is expected to start at the geometric centre of the box, so a positive shift in x or y would move it to the right and/or up.

There would be two critical angles when the centre of gravity is not perfectly in the middle of the x-axis. The set angular velocity could rotate positively or negatively. This would mean one of the corners having a smaller tip-over angle, and this would be the worst case.

5.3.4. Bisection to find critical rotational velocity

To find the critical point at which it tips over, the geometrically calculated stability criterion will be compared to the last recorded angle. This angle should be larger than the stability criterion. As computing a large range of parameters is numerically intensive, the critical rotational velocity is found via bisection, a root-finding method. A range is split in half, and it will be checked whether it meets the criterion. If it has not tipped in the second half, it is split once again and tested. Till a tolerance is met, where the numbers are very small. At this point, the largest of the two is taken to ensure tip over, the middle point would statistically be the closer point to the actual critical number. However, this should not matter, as the margins are so small for this simplified simulation.

5.4. Parametric study of deployment parameters

A parametric study is performed to analyse how design and deployment parameters influence touchdown stability and lateral displacement. The purpose is not to verify full deployment behaviour but to identify the sensitivity to certain parameters and show what effects it would have to the drop deployment for a standardised rover concept.

The parameters considered are:

- Drop height
- Initial angular velocity
- Centre of gravity position
- Rover geometry
- Initial velocity
- Half-cone separation angle

These are chosen because they directly affect either the fall time to impact, the critical tipping criterion or the lateral displacement.

The outputs of the analysis are the impact time, the maximum rotation angle at impact, the critical angular velocity, whether it tips over, and the maximum horizontal displacement. These will later be used to derive preliminary constraints for the rover standard, providing a centre-of-gravity envelope and a required clearance around the rover.

The drop height affects the time from release to impact on the surface. More time till impact means that it could rotate for longer and displace more sideways. Therefore, with a given initial angular velocity, a greater drop is more likely to reach the critical tipping angle and widen the required clearance.

The initial angular velocity represents the inconsistencies in the deployment mechanism. These arise from the contact with the pusher plate, rail clearances, and asymmetric release forces[94]. Since the exact value of the initial angular velocity is difficult to determine from these parameters, specifically for a rover, it will be based on previously and currently used CubeSat dispensers [97].

The centre of gravity position determines the critical tipping angle. A low and central position increases stability, whereas an upward or lateral shift increases the tip-over likelihood. By varying the centre of gravity within the rover body, the model can identify when it would remain stable under certain conditions.

The rover geometry affects the base of support and, therefore, when it will tip over. A wider base increases stability while keeping the centre of gravity in the same position relative to the geometric centre. This parameter is included to assess how the geometry influences stability during deployment and when the configuration becomes unsuitable.

The initial velocity represents the push induced by the possible spring force. Various sizes and masses for rovers would require a different force, this is simplified to an initial velocity, which results in an exit velocity after release from the rails. A larger downward velocity reduces the time till impact, but increases the lateral velocity component. The initial velocity impacts, therefore, both stability and clearance.

The half-cone separation angle stands for the lateral movement that might occur after release from the deployer. This is used to estimate the horizontal motion and the accompanying clearance required when the trajectory is modelled.

5.5. Verification

To verify that the simulation is doing what it is supposed to do, several checks are performed. These checks should provide confidence that the numerical model behaves as in the above-mentioned case study to determine what could happen to a falling or pushed-out rover. The verification is performed across three aspects: the fall time, the critical tipping criterion, and the rover's collision point. Lastly, the influence of the numerical time step and the bisection tolerance is discussed.

Unless stated otherwise, the verification in this section is performed using the reference case given in Table 5.1. This reference case is chosen as a representative configuration for the simplified rover model and is used consistently throughout the verification checks.

Table 5.1: Reference case used for the verification of the simulation.

Parameter	Value
Geometry ($W \times H$)	0.15×0.20 m
Centre of gravity position	$(-0.04,\ 0.05)$ m
Drop height	1.5 m
Rail length	0.2 m
Initial rotational velocity	0 °/s unless varied
Initial vertical velocity	0 m s^{-1} unless varied
Half-cone separation angle	0 ° unless varied
Lunar gravity const.	1.62 m s^{-2}

5.5.1. Free-fall time

The first verification step is the time required to reach the surface of the moon. In the simplest case, without spring force or rotation, the rover experiences only the gravitational force. The vertical translation should therefore follow the free-fall relation.

$$t = \sqrt{\frac{2s}{g_{moon}}} \tag{5.12}$$

Where s is the drop height and g_{moon} is the acceleration. In this case, g_{moon} is equal to the lunar gravitational acceleration of 1.62 m s^{-2}. When considering a deployment height of 1.5 m, this results in a free-fall time of $t = 1.3608s$.

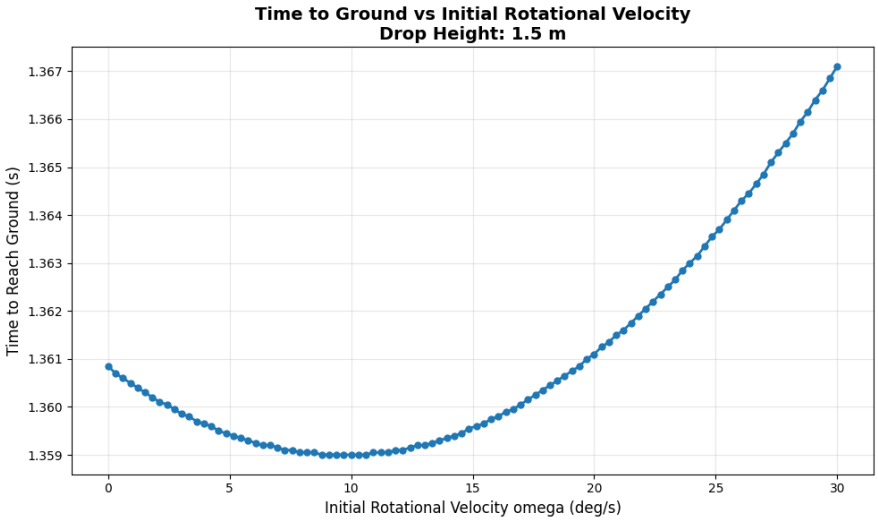

Figure 5.3: First-contact time as a function of initial rotational velocity for a 1.5 m free fall without initial vertical velocity or lateral motion. Rotation changes which rover corner reaches the surface first, resulting in a small variation in impact time.

Figure 5.3 shows the time to the lunar surface as a function of the initial rotational velocity. For the case where the initial translational velocity is equal to zero and no lateral movement is present. The value at zero rotational velocity corresponds to the analytical free-fall time; this therefore demonstrates that the simulation stops at the correct time for the simplest case.

Effect of rotation on impact time

The next step is to verify whether the timing remains physically accurate when the rover rotates during its fall. As the rover rotates due to an initial rotational velocity, the collision time should initially decrease as one of the corners would move downwards relative to the CG. This reduces the relative distance to the surface. At larger rotations, the collision time should increase again once that same corner has passed underneath the CG and starts moving upward relative to it.

This can be checked geometrically, through the rotation matrix shown in Equation 5.8. For the left corner,

$(x_3, y_3) = (-0.075, -0.1)m$

This is the third corner in the array of the local coordinates around the geometric centre. If the CG were placed at (-0.04, 0.05) relative to the geometric centre, then the local coordinates of this corner with respect to the CG become

$(x_{3,0}, y_{3,0}) = (-0.035, -0.15)m$

If the body rotates by 10° in the positive direction, the new vertical coordinate becomes

$y_{3,1} = x_{3,0}sin(10°) + y_{3,0}cos(10°)$

which results in

$y_{3,1} = -0.15379m$

This is slightly lower than the initial value of -0.15, so the corner has moved downward. The effective drop height therefore becomes

$s_1 = s_0 + (y_1 - y_0)$

Using 1.5 m as reference height gives $s_1 = 1.496201$. Substituting this into Equation 5.12 results in a fall time of $t = 1.3591s$, which is slightly smaller than the non-rotating case.

Under the assumption of constant angular velocity, the corresponding initial angular velocity can be calculated. With the addition of a rail, the rover is not able to turn as long as it has not passed the rail height. For an initial rail length of 0.2 m and using Equation 5.12, this leads to $t_{exit} = 0.4969\,^\circ/\text{s}$. Subtracting the time inside the deployer, and considering the rover has turned 10 ° this leads to an initial rotation of 11.598 °s once the rover has left the deployer. This agrees with Figure 5.3 and confirms that the model captures the change in collision timing correctly for a given height and geometry. Moreover, the figure shows that after approximately 10 °/s, the collision time starts increasing again because the collision point has passed beneath the centre of gravity and is moving upward relative to it.

Collision point verification

The same case can be used to verify the collision point. After a rotation of 10 °, the horizontal position of the corner that collides becomes

$x_{3,1} = x_{3,0}\cos(\Theta) - y_{3,0}\sin(\Theta) = -0.008421$

This shows that the point has moved closer to the centre of gravity, but has not yet passed it.

The model confirms the position after a rotation of 10 °, giving a first contact point of $(-0.008420, -0.000004)m$. Since the y-coordinate is slightly below zero, the simulation correctly stops at impact.

Effect of initial velocity on impact time

An initial velocity can be induced by the spring force. This should reduce the collision time. Using the quadratic formula, the new time to reach the ground is given by Equation 5.13.

$$t = \frac{v_{y0} + \sqrt{v_{y0}^2 + 2g_{moon}y_0}}{g_{moon}} \tag{5.13}$$

A negative initial velocity corresponds to a downward push. For a case with $v_0 = -0.5\,\text{m}\,\text{s}^{-1}$ and no rotation, this gives $t = 1.08675s$.

The model returns a first-contact time of 1.087 674 s, using a tolerance of 10^{-5} for both the time step and the bisection tolerance. This comes close to the analytically calculated value.

Effect of half-cone separation

Due to the half-cone separation angle, the velocity is divided into horizontal and vertical components. This first affects the collision time, because the velocity component in the vertical direction is slightly smaller. Taking a separation angle of 7.5 ° in the positive direction and still using a downward velocity of $-0.5\,\text{m}\,\text{s}^{-1}$,

$v_y = -0.4957m/s$

This gives an impact time of 1.0888 s, which is marginally larger than in the previous case.

The lateral component becomes

$v_x = -0.065\,26\,^\circ/\mathrm{s}$

It starts laterally moving after it has passed the rails; this exact time can be calculated with Equation 5.13 and results in $t_{exit} = 0.2776s$. Subtracting that from the time to the ground and the velocity laterally results in

$\Delta x = v_x t = -0.05294m$

To compare the shift due to the lateral motion, first, the case should be known where no shift has occurred. If the rover falls straight down, its landing point should be $(0.115, 0.0)$. This is the first of the bottom corners in its matrix, and once that has passed the surface, the simulation should stop.

This would then be shifted by Δx, and results in a collision point of $(0.062056, 0)m$. The model presents a collision point at $(0.062053, -0.000057)m$, which is horizontally almost exactly the position and additionally a slight numerical tolerance vertically.

5.5.2. Critical tipping angle

The next verification step is the critical tipping angle and whether the simulation is able to recover it correctly. The critical tipping angle depends on the location of the centre of gravity and the geometry of the rover body. The stability criterion can be determined geometrically, and the numerical approximation should be equal to or slightly larger than the geometric value to ensure that tipping indeed occurs.

The reference case shown previously is used for this analysis. Geometrically, this gives a critical tipping angle of 13.134 02 ° as per Equation 5.11.

The numerical value depends on both the time step and the bisection tolerance, as will be further discussed in subsection 5.5.3. The last recorded angle is compared to a geometric value. The bisection method searches for the rotational velocity at which the rover just tips over. Since the upper bound of the final interval is taken to ensure tipping, the resulting maximum angle is expected to lie above the geometric value.

An additional check, the tipping condition can also be verified by confirming that the centre of gravity lies outside of the base of support at impact. This can be done by comparing the horizontal position of the collision point with that of the centre of gravity.

Shown in Table 5.2 is the case where both the time step and bisection are of the size 10^{-3}. As can be seen, both the maximum angle reached numerically and the horizontal position are positive, indicating that it should tip over in this simplified case.

Table 5.2: Verification of the numerical tipping criterion for the reference case with $\Delta t = 10^{-3}$ s and a bisection tolerance of 10^{-3}.

Geometric critical tipping angle	13.134 022 3 °
Max angle sim.	13.134 624 023 4 °
Margin angle to geometric	0.000 601 7 °
Margin position to geometric	0.000 001 6 m

5.5.3. Time-step and bisection convergence

Lastly, the time-step and bisection are discussed, since they indicate whether the model approaches a stable result when a higher numerical precision is used. Moreover, this can show at what point the precision is sufficiently high for this simplified model.

The time-step size and the bisection tolerance work hand in hand to determine the level of precision. One may be chosen very small while the other remains relatively large, but in that case, the overall result is still limited by the less precise of the two. In particular, the bisection method may converge to a very precise critical rotational velocity, while the time step is not close to the actual result. This is also shown by the results, which indicate a large angle difference between the geometric and numerical critical angles.

Therefore, it is important to keep both the step-size and the bisection tolerance close to each other. Table 5.3 displays the differences between the geometrically calculated and numerical tipping angle for varying time steps and bisection tolerances. Table 5.4 shows the results of lowering them together with their effect on approaching the stability criterion.

Table 5.3: Difference between the geometric and numerical critical tipping angle for varying time steps and bisection tolerances. Positive values indicate that the numerical result exceeds the geometric tipping criterion.

Δt \ ϵ_{bis}	10^{-2}	10^{-3}	10^{-4}	10^{-5}
10^{-2}	5.18×10^{-3}	4.07×10^{-4}	9.40×10^{-6}	3.0×10^{-6}
10^{-3}	6.01×10^{-4}	6.01×10^{-4}	9.1×10^{-6}	3.7×10^{-6}
10^{-4}	1.05×10^{-3}	2.66×10^{-4}	1.98×10^{-5}	1.3×10^{-6}
10^{-5}	5.99×10^{-3}	4.74×10^{-4}	3.00×10^{-5}	5.4×10^{-6}

Table 5.4: Convergence of the critical angular velocity with time-step and bisection tolerance.

$\Delta t = \epsilon_{\text{bis}}$	ω_{crit} [°/s]	t_{impact} [s]	$\Delta\theta$ [°]	Δx [m]
10^{-2}	15.1025	1.360	5.19×10^{-3}	1.39×10^{-5}
10^{-3}	15.2197	1.359	6.02×10^{-4}	1.62×10^{-6}
10^{-4}	15.2332	1.359	1.98×10^{-5}	5.32×10^{-7}
10^{-5}	15.2347	1.359	5.40×10^{-6}	1.44×10^{-8}

As can be seen from Table 5.4, the results approach a stable value as the time-step is reduced and a higher precision is taken into account for the critical rotational velocity through bisection. The numerically calculated angles remain slightly larger than the geometric tipping angle. In addition, the difference between the horizontal collision

position and the centre of gravity becomes very small while remaining positive, which confirms that the centre of gravity lies just outside of the base of support.

Lastly, an example of performing bisectioning is shown in Figure 5.4.

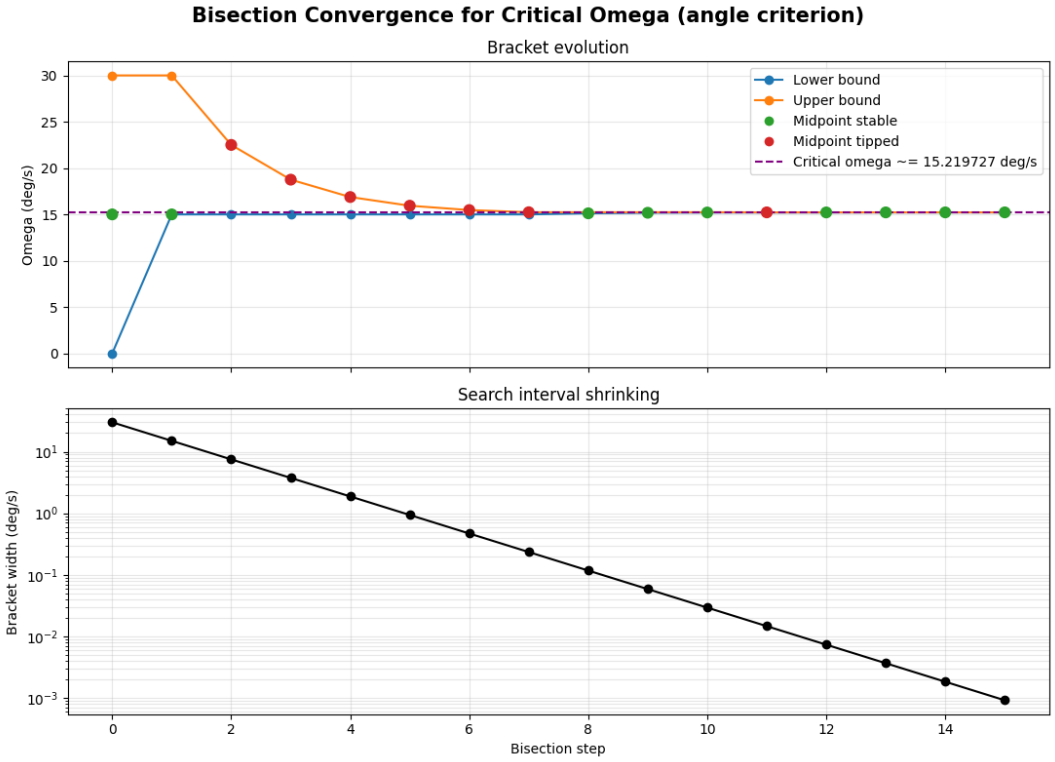

Figure 5.4: Bisection convergence used to determine the critical initial angular velocity. The upper plot shows the stable and unstable midpoint evaluations, while the lower plot shows the shrinking search interval down to 10^{-3}.

A takeaway is that the bisection tolerance and the time step should match. For this simplified model, a precision of 10^{-3} already significantly reduces the difference while keeping the computation time limited. Therefore, this value is used for the remainder of the simulation.

5.5.4. Conclusion verification

The verification of the model shows that the simulation behaves as expected according to the way the simplified model is set up. The free-fall time, the effect of rotation on both the impact time, the collision point and critical tipping angle all agree with the analytical or geometric expectations. Moreover, the convergence study displays that the time-step and bisection tolerance both influence the numerical result and should therefore be chosen sufficiently small. For this simplified model, a value of 10^{-3} for both is considered sufficient, as it reduces running time while still giving only deviations of similar size as the tolerance. This gives confidence that the simulation can be used to study the influence of the main design and deployment parameters.

5.6. Model results

This section shows the main results of the simplified deployment model. Starting from a reference case, to show the influence of the most important parameters, which would translate into design restrictions for a standardised rover concept. It is a competition of time to impact, initial angular rate and the critical tipping angle. The time to impact is primarily determined by the rover's drop height and the initial downward velocity, which could be enhanced by a spring force. The initial angular velocity is seen as the result of inconsistencies in the deployment system and will be an input that could vary. The critical tipping angle is dependent on the geometry of the rover and the placement of the centre of gravity within this envelope. Lastly, the drop zone envelope can be simulated through the lateral displacement in case the rover is pushed to the side.

5.6.1. Reference case

This reference case is taken to initially show the results of the simplified model, to be later implemented in a real case, from which design restrictions can be shown.

Table 5.5: Reference case inputs and resulting impact metrics

Reference case

Geometry (W×H)	15×20 cm
CG position	(-0.04, 0.05)
Drop height	1.5 m
Rail length	0.2 m
Init. rotational velocity	8 °/s
Init. velocity	0.0 m s^{-1}
Half-cone sep. angle	0.0 °

Results

Time collision	1.359 s
Contact corner	(-0.0167, -0.00019)
Contact corner idx	3
Maximum angle	6.904 °
Tip result	False

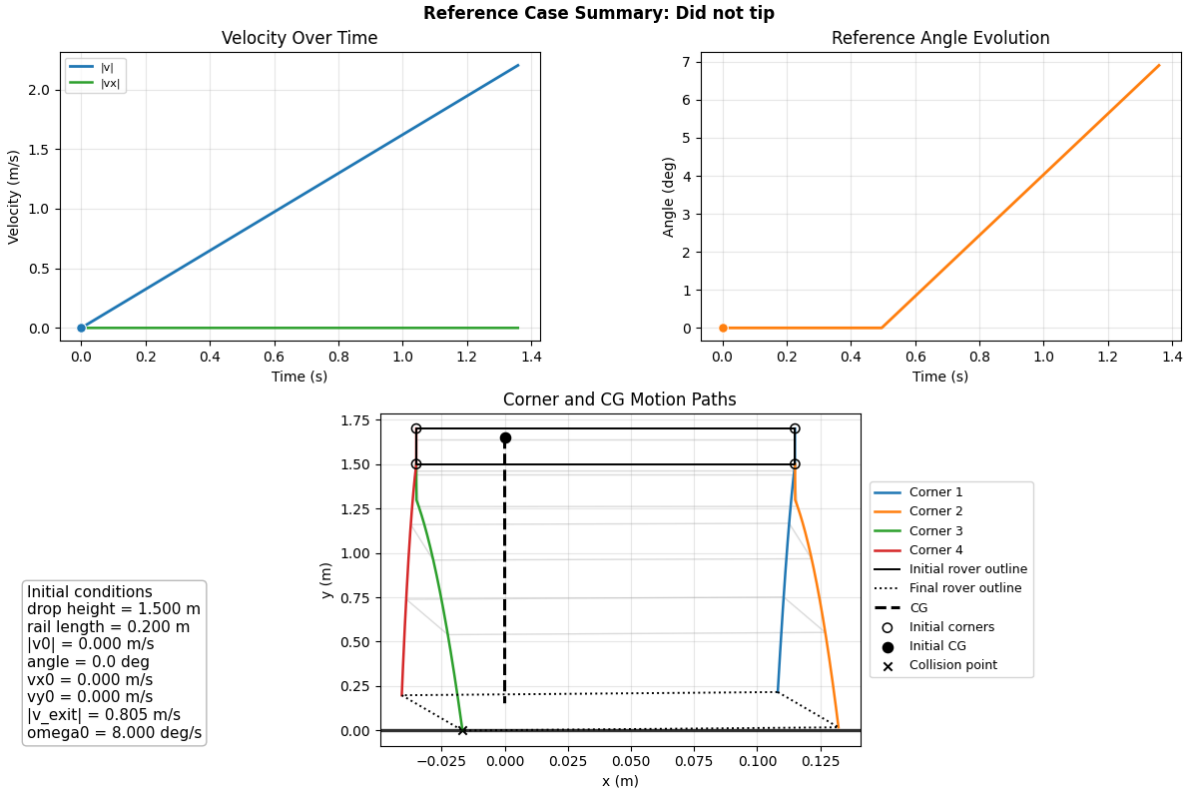

Figure 5.5: Reference-case free-fall response of the simplified deployment model. The rover is initially constrained by the guide rails and starts rotating only after leaving the deployer. The plots show the velocity evolution, rotation angle and corner trajectories up to first surface contact. For this case, the centre of gravity remains within the base of support at touchdown, so no initial tip-over occurs.

As can be seen in Table 5.5, the rover does not tip over in this case. Figure 5.5 shows the trajectory of the deployment. Initially, it moves straight down, guided by the rails, and therefore is not able to rotate, but it does accelerate. Once it is out of the deployer, it starts rotating around the centre of gravity, which is why the CG is moving in a direct line to the ground. Upon collision, the simulation stops, where the CG is inside the base of support and will therefore not tip over.

5.6.2. Initial angular velocity

The initial angular velocity is one of the main disturbances induced by the deployment in the model. For the reference case, the initial angular velocity is varied while keeping the same centre of gravity and geometry and this led to Equation 5.7. The critical angular velocity is found through bisectioning. As expected, the maximum rotation angle at impact increases linearly with the initial angular velocity. As the time until impact only changes very slightly when the angular velocity is increased, seen in Figure 5.3.

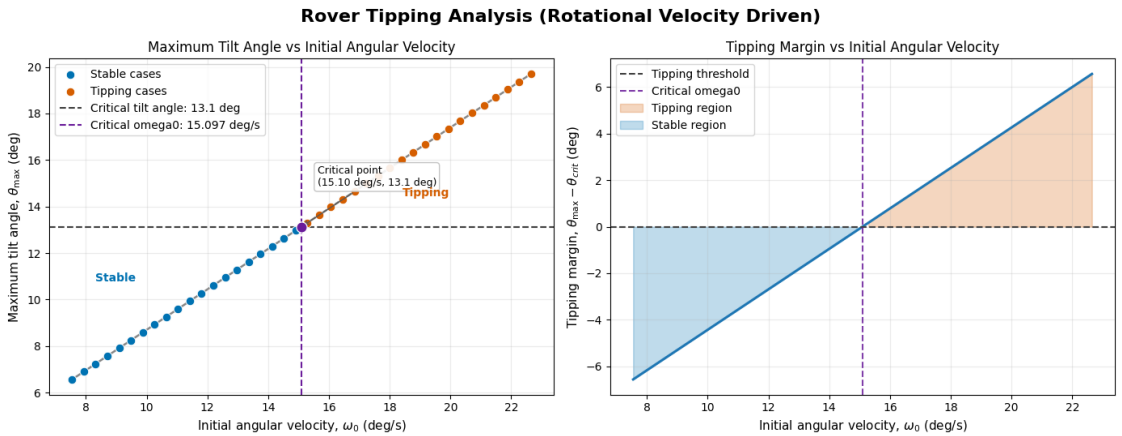

Figure 5.6: Critical initial angular velocity for the reference case. The maximum tilt angle increases with initial angular velocity until it reaches the geometric tipping limit. Values below the critical angular velocity remain initially stable at touchdown, while values above it exceed the tipping criterion.

Figure 5.6 displays the critical angular velocity for the given reference case, where the critical tipping angle is geometrically measured. The time to impact determines the critical angle, and it furthermore shows the margin to tipping over.

As the figure shows, the initial angular velocity functions as a stability driver for the drop deployment concept. Since this parameter is determined by the deployer mechanics, such as pusher contact, rail clearance, and release symmetry, it should be minimised. A lower, more consistent tip-off rate increases the stability margin and allows a wider centre-of-gravity envelope for the rover design.

5.6.3. Centre of gravity shift and base of support

The centre of gravity position and the base of support together determine the critical tipping angle of the rover. Both will be varied to assess their influence and reveal the sensitivities. From this, a minimum size of geometry might be concluded.

Figure 5.7, 5.8, and 5.9 show the geometrically calculated critical angle for the specific geometries. The base of support is gradually increased over these figures. It is observed that the area of stability increases as the base of support expands. A higher critical angle means the rover is less likely to tip over at a given angular velocity. Moreover, as expected, the rover is most stable when the centre of gravity is at the centre line and low, where the largest critical angles are at the bottom of the rover envelope. It is therefore highly sensitive to both a vertical and lateral shift of the centre of gravity.

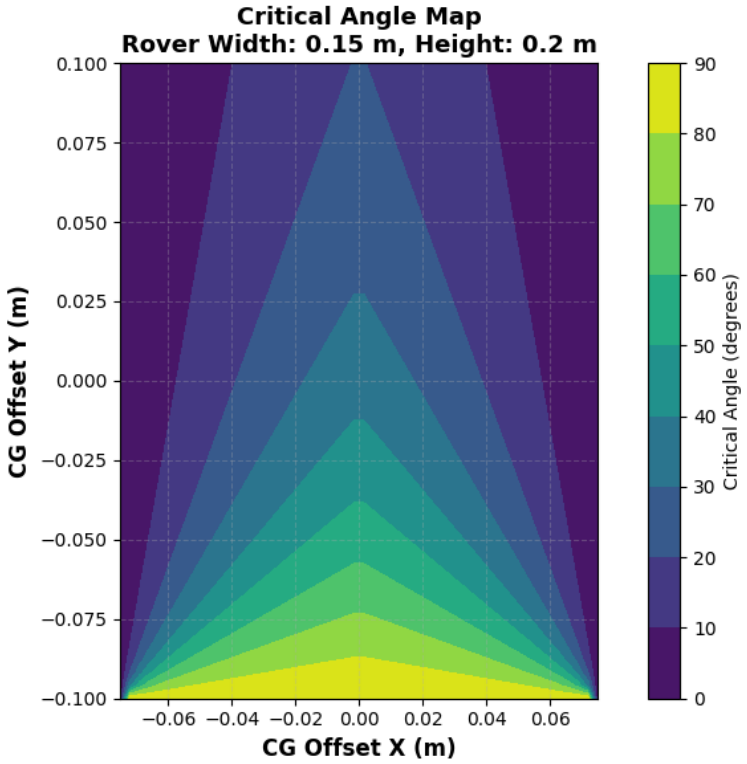

Figure 5.7: Critical tipping angle as a function of centre-of-gravity position for a rover width of 15 cm and rover height of 20 cm.

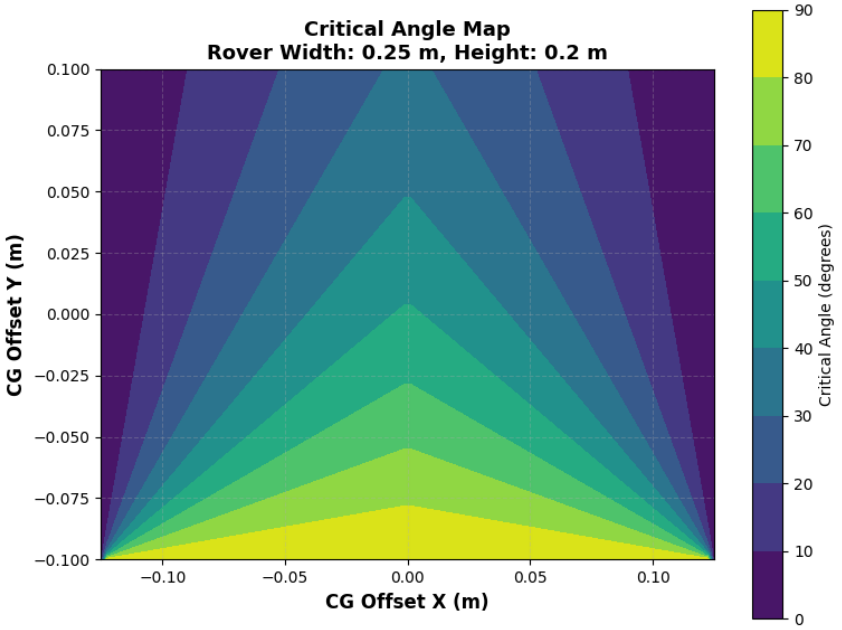

Figure 5.8: Critical tipping angle as a function of centre-of-gravity position for a rover width of 25 cm and height of 20 cm.

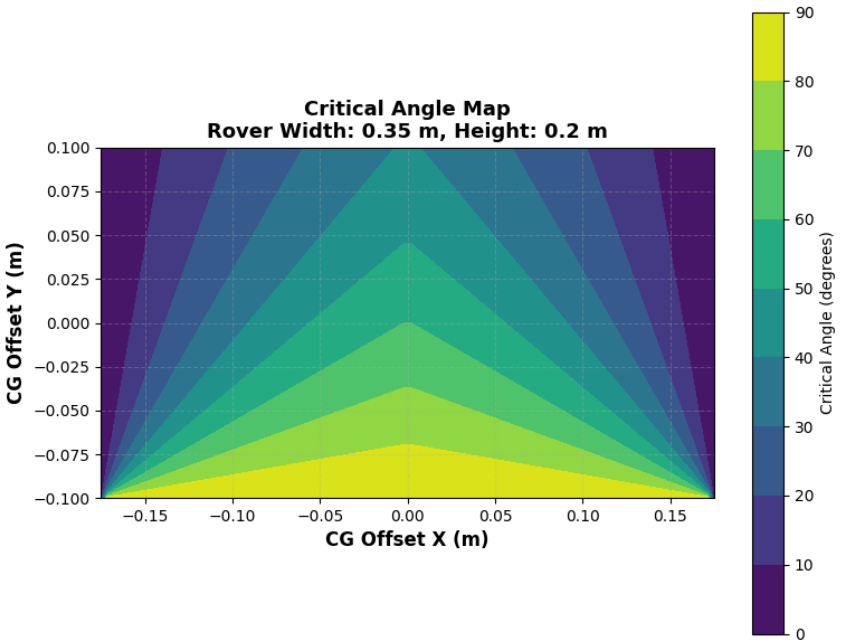

Figure 5.9: Critical tipping angle as a function of centre-of-gravity position for a rover width of 35 cm and height of 20 cm.

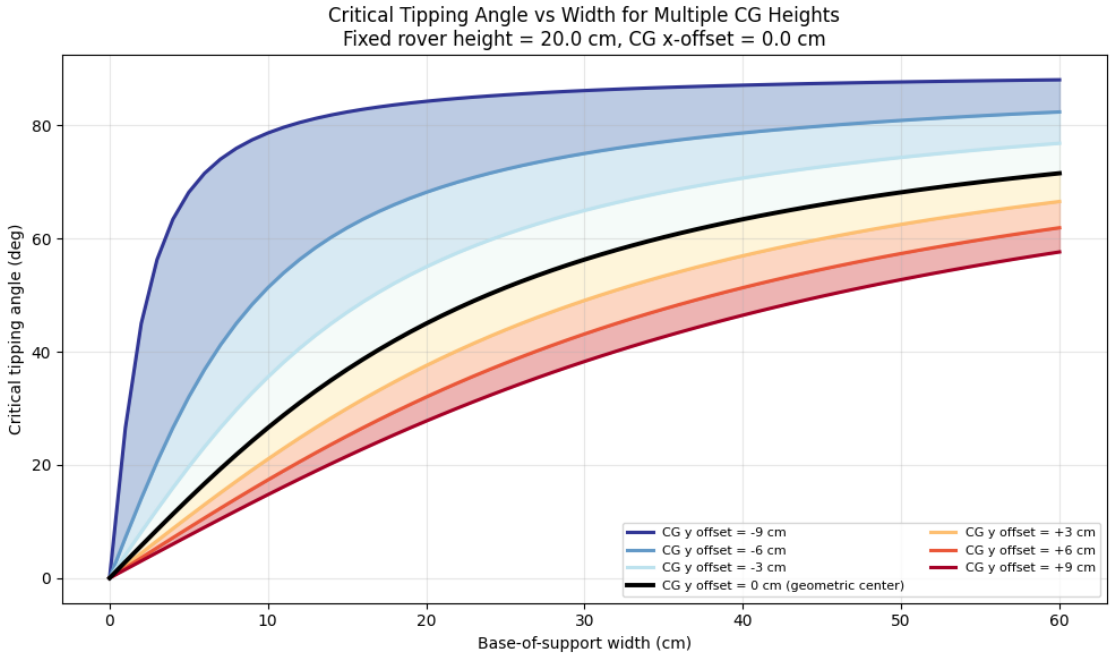

Figure 5.10: Critical tipping angle as a function of base-of-support width for different centre-of-gravity heights. Increasing the support width increases the tipping limit for all cases, while a higher centre of gravity reduces the critical tipping angle and therefore decreases stability.

Figure 5.10 shows the same results as the previous figures, but more quantitatively. Here, the base of support is varied when the centre of gravity is placed at the height, keeping the height stable. The lines show the y-position. The higher it goes, the more

the centre of gravity is shifted upwards from the geometric centre. Where a low centre of gravity is likely to be stable for any width, as can be seen when the CG is shifted to 9 cm downwards. Here, the critical angle quickly approaches 80 ° and above. As the base of support further increases, the differences get smaller between the placements of the y position. It matters less where it is placed at this point. But below a 10 cm the centre of gravity should be carefully placed. This is all dependent on the time to impact and the rotation induced by the deployer.

From a design perspective, the base of support should be as wide as is allowed to increase stability. When this is not possible, the centre of gravity should be placed low, as this increases the critical tipping point and improves stability.

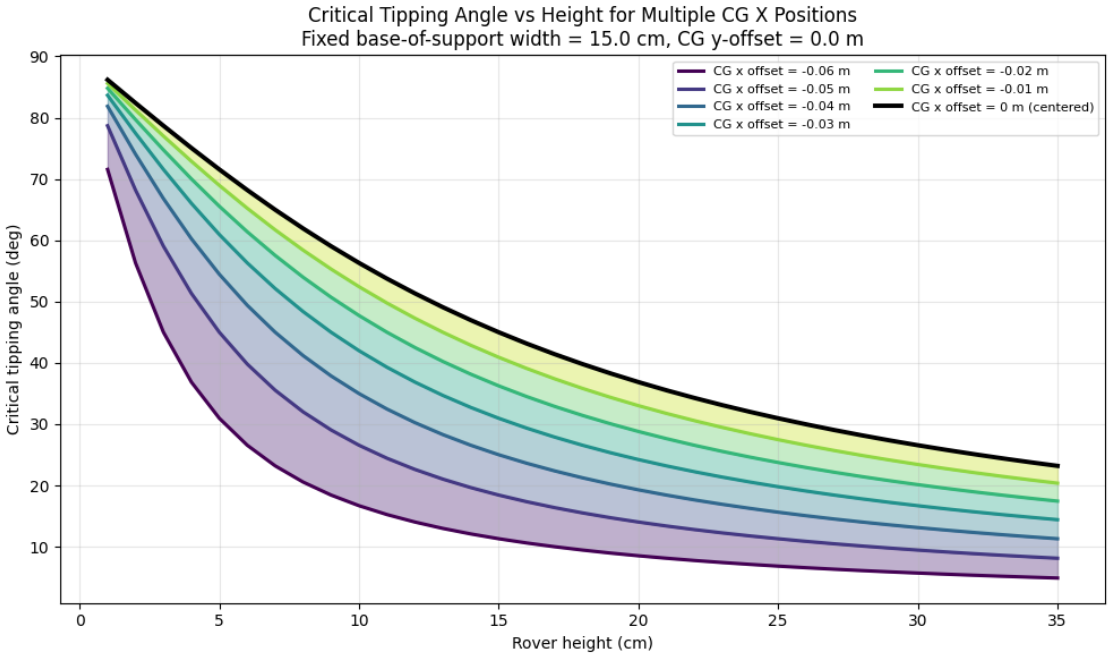

Figure 5.11: Critical tipping angle as a function of rover height for varying centre-of-gravity (CG) offsets along the lateral axis, with a fixed base-of-support width of 15 cm. Increasing rover height reduces the critical tipping angle, indicating decreased stability, while shifting the CG further from the centre significantly lowers the tipping threshold. Central and lower CG configurations provide the highest stability margins.

Figure 5.11 displays the sensitivity to the height of the rover for the same base of support but for varying shifts laterally for the centre of gravity. As the height increases, the geometric centre also shifts upwards, so that should be taken into account when looking at the figure. However, the result is that a taller rover is less stable with the same base of support. As it gets bigger, the mass generally shifts upwards, leading to a less stable configuration.

The ratio between the height of the centre of gravity and the base of support should stay low for a more robust design. Depending on the time until impact and the deployer conditions, there is considerable design variability.

5.6.4. Drop height and initial velocity

The drop height and the initial velocity both impact the time to impact, which determines how long the rover will rotate before touchdown. Together they could be varied and shifted, as one worsens, the other could be adjusted.

The drop height will naturally be an input from the lander and is therefore more difficult to adjust. As the drop height increases, the time to impact also increases. For a given initial angular velocity, this gives the rover more time to rotate before touchdown, increasing the likelihood that the rotation angle at first contact exceeds the critical tipping angle. Therefore, the drop height should preferably remain low.

The velocity represents the initial push that could be given by a spring force, but simplified to a velocity. Where an increase in downward velocity reduces impact time. An upward velocity is not possible, as it is restricted by the deployer. An initial velocity of $0\,\mathrm{m\,s^{-1}}$ would demonstrate the case without a spring force.

The impact on the time for both parameters is shown in Figure 5.12. This shows that both have drastic impacts on time.

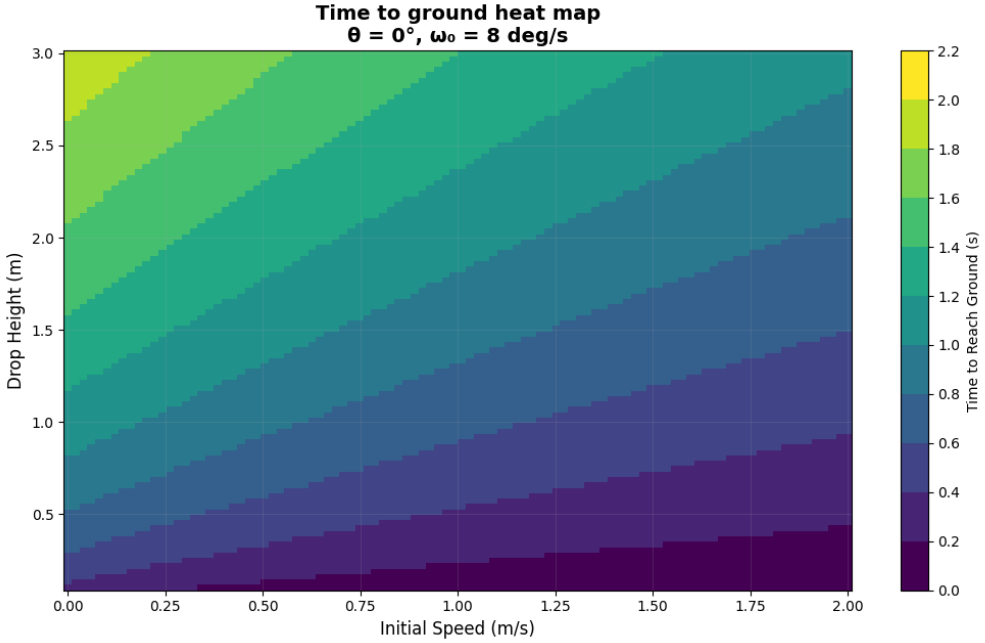

Figure 5.12: Impact time as a function of drop height and initial vertical velocity. A higher drop height increases the time to impact, while a larger downward initial velocity reduces the time available before touchdown.

Figure 5.13 displays the influence of height and velocity on the critical angular velocity for the reference case. This is dependent on the centre of gravity position and should therefore be reviewed on a case-by-case basis. But it shows that the critical angular velocity changes by adjusting one or both. Given a drop height and a desired critical angular velocity, the initial velocity can be determined. The rover would reach the ground early enough to tip over. The other way around is also possible, but the drop height is not as easily changed.

For example, if the height is set at 1.5 m and the critical angular velocity it needs to

endure is 20 °/s, the initial velocity would need to be close to $-1.3\,\mathrm{m\,s^{-1}}$. This can then be translated into an exit velocity and be further deduced to a spring force.

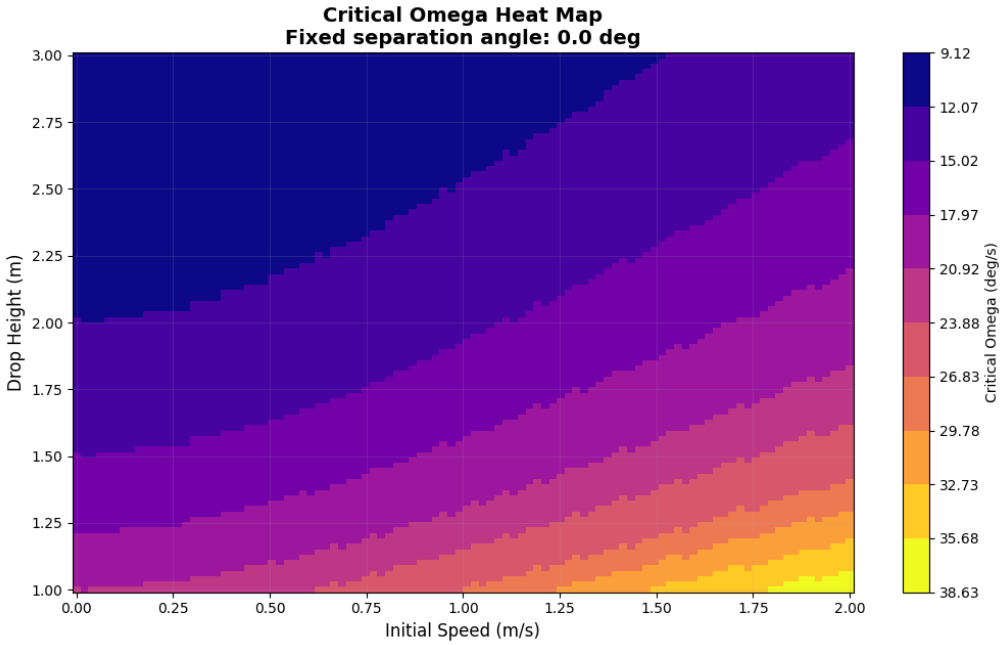

Figure 5.13: Critical angular velocity as a function of drop height and initial deployment speed for the reference case. The initial speed is directed downwards to the surface, so an increased speed translates to a shorter time to impact.

Figure 5.13 is restricted to a minimum height of 1 m as the critical angular velocity quickly increases and blurs the rest of the figure, which does not show representative results. Below a drop height of 1 m, the rover is generally stable for most configurations of geometry.

5.6.5. Effect of separation angle and lateral displacement

The separation angle, or the half-cone separation angle, is the deviation of the translational motion to the sides. This is also caused by the inconsistencies in the deployment mechanism.

The reference case is once again displayed, showing the effect of horizontal movement on the trajectory in Figure 5.14. The figure has an additional initial velocity, which both increases the exit velocity and reduces the time to impact. What can be seen is that the rover moves substantially laterally; this can be deduced from the centre of gravity position, as it would normally move straight down since the rover rotates around the centre of gravity.

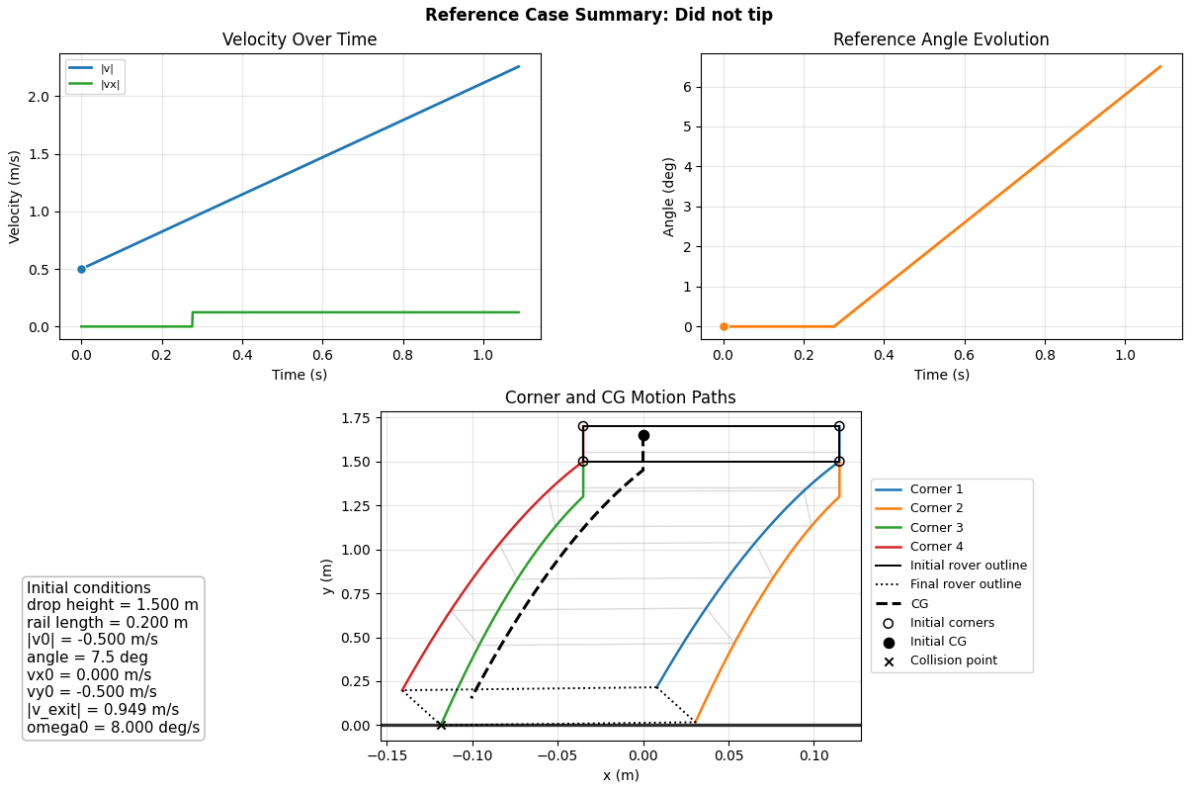

Figure 5.14: Reference-case trajectory with an initial downward velocity of $-0.5\,\mathrm{m\,s^{-1}}$ and a half-cone separation angle of 7.5°, showing the combined effect of lateral displacement and rotation during free fall.

Figure 5.15 displays the effect of increasing the half-cone separation angle and its given critical angular velocity. As can be seen, the higher the separation angle, the lower the critical angular velocity becomes. As more speed is transferred into sideways motion, the time to impact increases, making it easier for it to tip over.

The biggest impact of the displacement horizontally is the separation angle. The maximum displacement has an effect on the clearance required for the rover, which will be further explained in the following chapter 6.

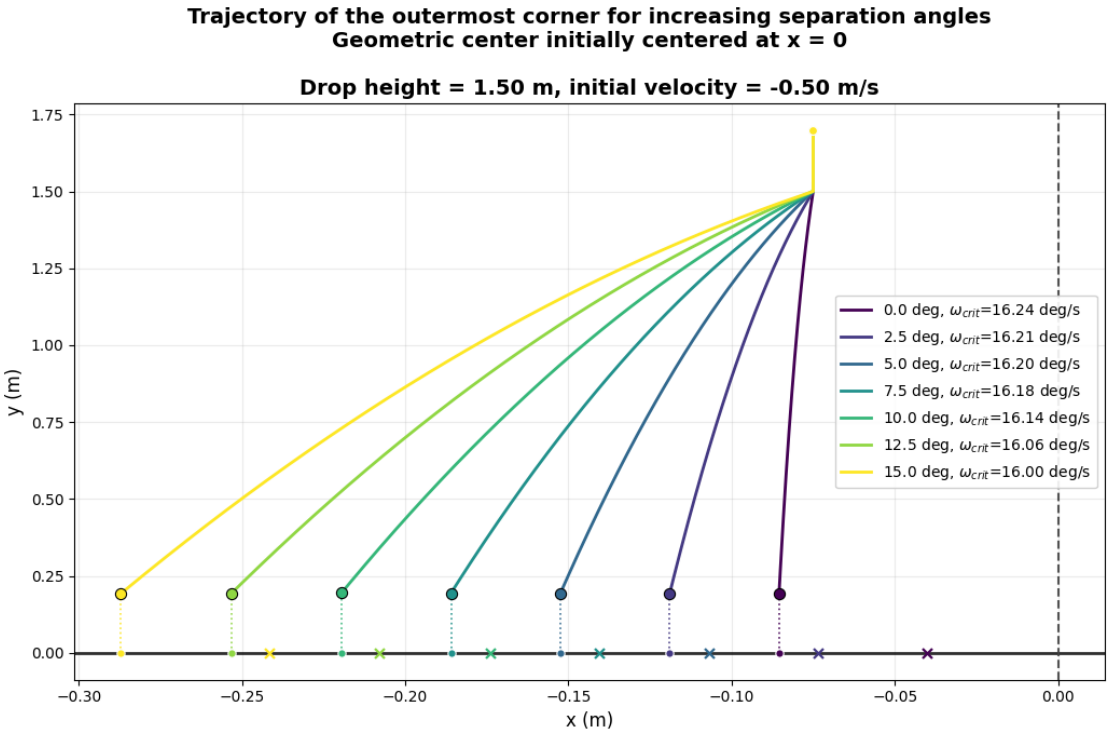

Figure 5.15: Outer-corner trajectory for increasing half-cone separation angles. Larger separation angles produce greater lateral displacement during free fall and slightly reduce the critical angular velocity for initial touchdown stability.

5.6.6. Combined results

The dominant physical effects behind the rover's free fall from the lander are the rotation and lateral motion. Rotation is a function of both time and angular velocity. Here, time is dependent on the initial height and velocity. Stability depends on the base of support and the position of the centre of gravity. Furthermore, lateral motion is determined by the separation angle and the exit velocity. None of these acts independently but influences different parts of the whole mechanism.

The main constraints identified are tip-over stability and the required lateral clearance. These can be described in Figure 5.16 and Figure 5.17.

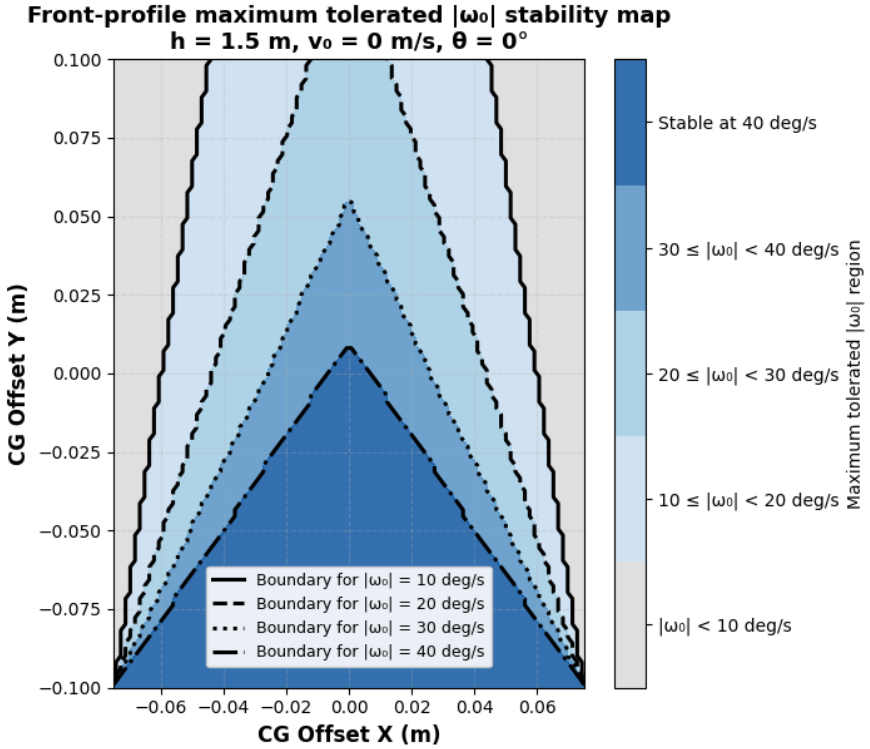

Figure 5.16: Initial touchdown stability map for the front-profile case. The colored regions show the interval of maximum tolerated absolute initial angular velocity $|\omega_0|$, for $h = 1.5m$, $v_0 = 0m/s$, $\theta = 0°$. The contour lines indicate the stability boundaries for the tested values of $|\omega_0|$. The darkest region is stable at the maximum tested value of $40\,°/s$, but higher angular velocities are not evaluated. Only initial touchdown stability is considered.

Figure 5.16 gives the centre of gravity envelope for the reference case per angular velocity. A lateral or upward shift in CG reduces stability and therefore lowers the angular velocity the rover can withstand without tipping over. Various envelopes are shown, indicating where the centre of gravity would need to be placed to be stable under its initial conditions. A very high initial angular velocity requires a narrower envelope to be stable. This would be useful for the preliminary standard, as it constrains the centre of gravity location for rovers once the deployment's initial conditions are known.

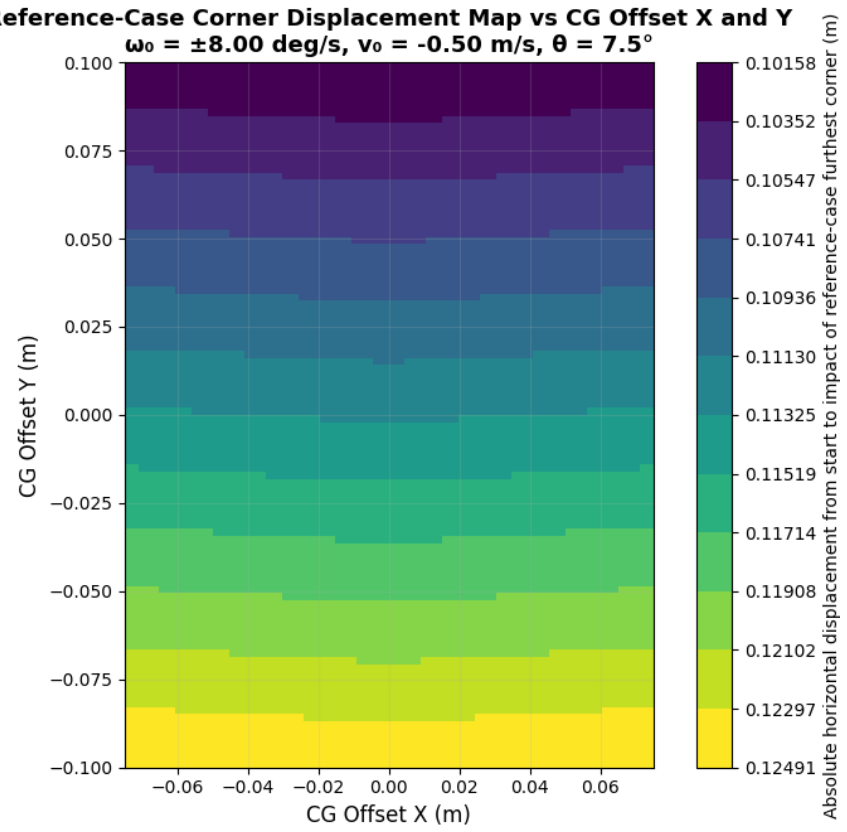

Figure 5.17: Maximum horizontal displacement of the outer rover corner as a function of centre-of-gravity position for the reference deployment case. The displacement is measured relative to the vertical drop position and includes the effect of rotation up to first surface contact.

Figure 5.17 displays the maximum horizontal displacement for the reference case over its entire centre of gravity envelope. It can be seen that, first of all, the displacement depends on the centre of gravity, and as it shifts downward, the displacement increases. This is the opposite of the stability criterion, as it gets more stable with a lower centre of gravity. This is because the rover rotates about its centre of gravity. Once the CG is placed lower, the arm is elongated over which it rotates. Therefore, the outer corners rotate faster and displace more. However, the difference between top and bottom placement is not as significant, only about 2 cm in displacement for the given case. The 2 cm is only a little compared to the 10 cm the rover might displace, but it does play a factor.

To quantify the constraints on tip-over stability and lateral clearance, a case study is conducted in the next chapter. It will link the design parameters to limitations and provide recommendations for the concept of the standardised rover.

6 | Case study

The purpose of this case study is to illustrate how the simplified deployment model can be applied to a representative rover geometry and assumed lander/deployer conditions. It is not intended as an experimental validation of the model or as proof of a complete rover standard. Instead, the case study demonstrates how the method can translate deployment assumptions into preliminary constraints on centre-of-gravity placement, lateral clearance and rover spacing.

6.1. Definition of case

This case study serves as a representative application of the proposed method for a small lunar rover concept, and as stated by the standardisation goals in chapter 3, is constrained to a mass of 10 kg and deployed as a secondary payload from a commercial lunar lander. The objective is not to validate a single rover design, but to assess how deployment drives constraints and how the design falls within the design boundaries for a possible configuration.

The case study is based on three elements: the lander and deployment conditions and the rover geometry. These define the initial conditions for the simplified model and allow for a first evaluation of touchdown stability and clearance constraints.

6.1.1. Lander condition and deployer assumptions

The deployment conditions are based on typical values derived from current commercial landers and CubeSat dispensers. Since detailed lander data is not publicly available, a representative drop height of 1.5 m is assumed. This corresponds to an approximate height of the Peregrine lander by Astrobotic, which is 2.0 m tall[28].

To model the deployment behaviour, characteristics of the EXOpod Cubesat deployer are used as a reference. This dispenser is widely used and should provide a basis for the release conditions. The parameters are shown in Table 6.1 and are conservative as a worst-case scenario.

Table 6.1: Lander and deployment assumptions for the case study, based on the EXOpod NOVA worst case[96]

Drop height	1.5 m
Tip-off rate / initial angular velocity	10 °/s
Half-cone separation angle	7.5 °
Initial velocity	$-0.5\,\mathrm{m\,s^{-1}}$
Rail length	13 cm

The tip-off rate and half-cone separation angle are taken from the EXOpod NOVA user manual, while the initial velocity and rail length are assumptions required for the model. The EXOpod NOVA user manual specifies exit velocities between 1.2 and $2.4\,\mathrm{m\,s^{-1}}$ for different CubeSat sizes [96]. In this case study, an initial downward

velocity of $-0.5\,\mathrm{m\,s^{-1}}$ is assumed. This leads to an exit velocity close to $1\,\mathrm{m\,s^{-1}}$ after the rover has travelled through the rails, due to the additional acceleration from lunar gravity. A lower initial velocity is preferred because it results in less energy upon impact. However, using a CubeSat-style deployer as a reference is considered useful because it provides realistic worst-case values for the tip-off rate and half-cone separation angle. The rail length is assumed to be equal to the rover body height, set at 13 cm.

6.1.2. Rover geometry

The rover geometry is based on a compact configuration inspired by both the CubeRover by Astrobotic and the previously studied TU Delft 3U CubeSat form rover by P. Ananwatanyoo [27] [98]. The latter was developed by the LUNEX-EuroMoonMars initiative, which explored the possibility of using a CubeSat as a rover [99].

Since complete data are not yet available for both designs, the available information is combined with assumptions to define a representative geometry for the case study shown in Table 6.2.

Table 6.2: Geometry of the rover, defining the body and wheel size for the case study.

Outer volume	$(34 \times 15 \times 18)$ cm
Geometry body(L x W x H)	$(30 \times 10 \times 13)$ cm
Wheel diameter	14 cm
Wheel width	2.5 cm
Wheel center spacing	20 cm
Surface clearance	5 cm

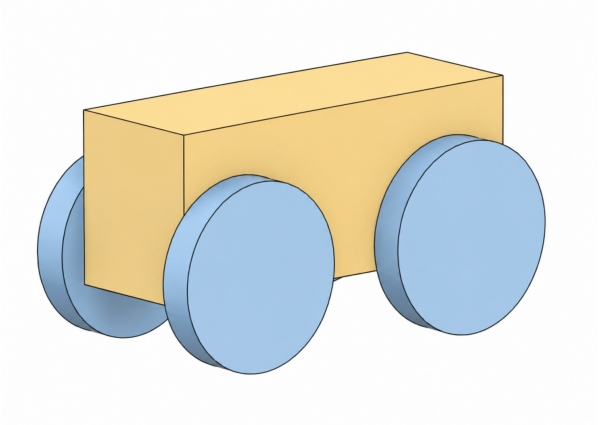

Figure 6.1: Isometric view of the representative rover

Using the defined lander conditions, deployer parameters and rover geometry, the study will evaluate the touchdown stability based on critical rotation angles. This could lead to an allowable centre-of-gravity envelope. Moreover, lateral displacement will be assessed to find the required clearance and spacing for multi-rover configurations.

6.2. Deployment constraints and design implications

This section applies the initial conditions imposed by the lander, deployment mechanism and geometry to the simplified model. To show what the constraints would be for this specific case and its accommodation inside the lunar lander. The main aspects considered are the centre of gravity envelope and the lateral displacement and its accompanying clearance required.

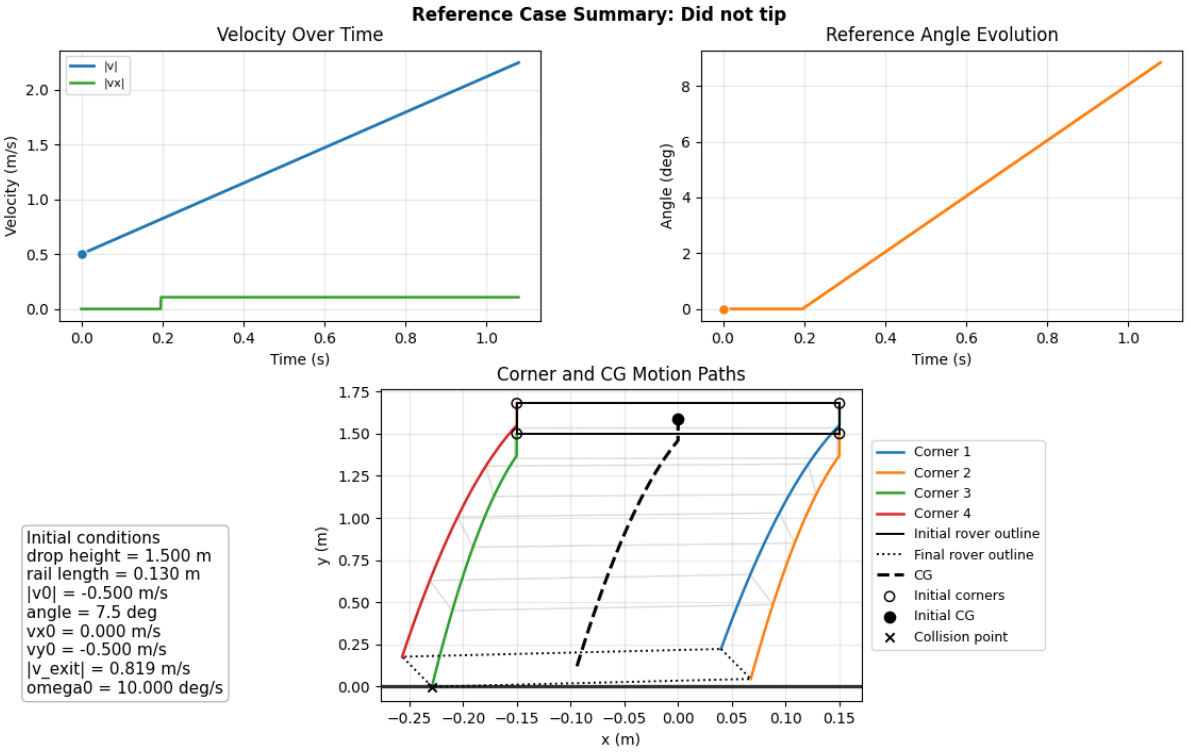

Figure 6.2: Reference free-fall trajectory of the case-study rover with the centre of gravity placed at the geometric centre. The plots show the velocity evolution, angular motion, and corner trajectories up to the first surface contact.

6.2.1. Centre of gravity envelope

The first constraint considered is the allowed position of the centre of gravity within the rover body. A lower, more central position would lead to greater stability by increasing the critical tipping angle. If it were to shift upwards and laterally it would worsen the stability margin.

For this case study, the centre of gravity is varied within the rover body. For each position, the critical rotation angle is compared with the rotation expected during deployment. This results in a first-contact stability envelope in which the rover does not exceed the geometric tipping criterion at touchdown. The analysis only considers the first-contact condition and does not include dynamics after direct impact, such as bouncing, sliding, or interaction with the surface.

Figure 6.3 and 6.4 display the envelopes of both the front and side views of the rover. These show that a large part of the internal body satisfies the first-contact stability criterion. For the front, it is almost fully stable. When considering a margin, where it,

for example, would be able to remain stable for twice the angular velocity, it is still mostly stable.

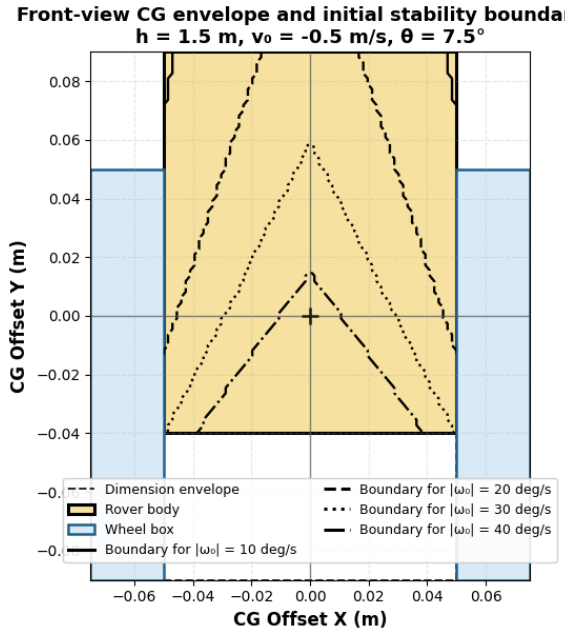

Figure 6.3: Front-view CG envelope for the case-study rover with initial touchdown stability boundaries. The rover geometry shows the representative body and wheel dimensions, while the contour lines indicate the limiting CG positions for selected values of $|\omega_0|$.

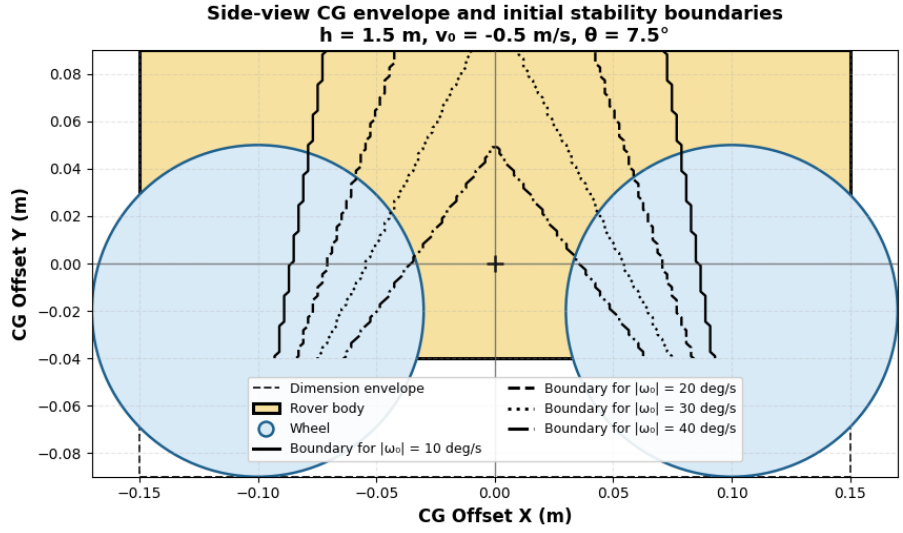

Figure 6.4: Side-view CG envelope for the case-study rover with initial touchdown stability boundaries. The rover geometry shows the representative body and wheel dimensions, while the contour lines indicate the limiting CG positions for selected values of $|\omega_0|$.

However, the results also show that the centre of gravity is preferably still low and close to the rover's centreline. This would give more robustness to the design and could be

required once the full dynamics are implemented. Therefore, heavy components like batteries should be placed as low as possible.

6.2.2. Lateral movement and clearance

The second constraint is the clearance required around the rover during deployment. Lateral movement and clearance can be assessed through the simulation and the deployment mechanism's imposed initial conditions. Since the model evaluates one plane at a time, the front and side views are assessed separately. The results should therefore be interpreted as a first estimate of displacement that could occur during deployment.

Upon release from the deployer, the rover may displace laterally due to inconsistencies in the release mechanism. Additionally, rotation about the centre of gravity changes the horizontal positions of the rover's outer corners. The combination of horizontal movement and rotation determines the maximum horizontal displacement at impact with the surface. This displacement is important because other payloads, rovers, or lander structures, such as landing legs, must remain outside the rover's free-fall trajectory.

The position of the centre of gravity also has an effect on the displacement, as described in subsection 5.6.5. Figure 6.5 and 6.6 display the maximum horizontal displacement for the given initial parameters. This can then be translated into the required clearance and spacing between rovers inside the lander when multiple rovers are placed next to each other.

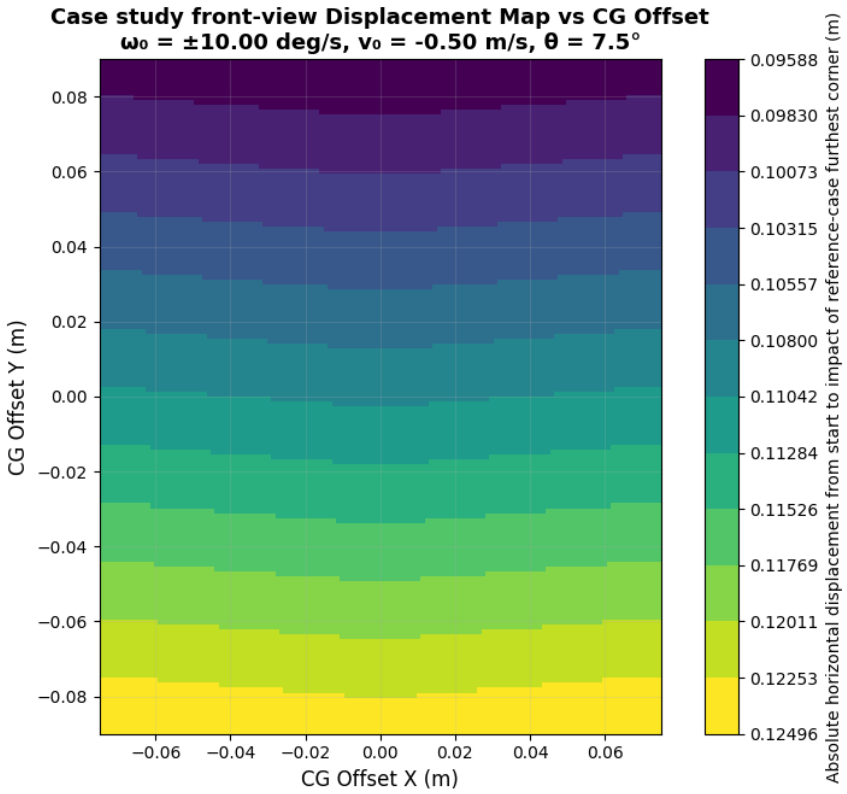

Figure 6.5: Front-view maximum horizontal displacement for the case-study rover as a function of centre-of-gravity position. The displacement of the outermost corner at first contact relative to the reference case is measured, showing that lower centre-of-gravity positions result in a larger clearance requirement.

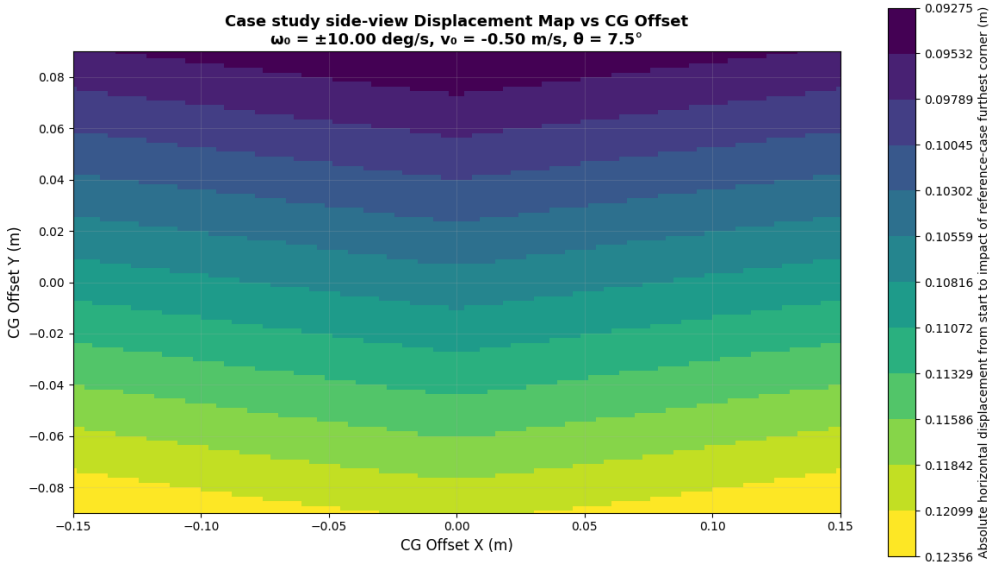

Figure 6.6: The centre of gravity envelope for the side view, showing the maximum horizontal displacement for the case study.

Table 6.3: The maximum horizontal displacement for the worst placement of the centre of gravity inside the body of the rover for the case study, additionally, the clearance zone projected underneath the geometric centre.

Max. horizontal displacement front	11.52 cm
Max. horizontal displacement side	11.46 cm
Clearance zone rover	64.4 cm × 49.6 cm

The current results for the case show a maximum displacement of 11.5 cm shown in Table 6.3. When the centre of gravity is placed at the bottom and in one of the corners, similar to the CG envelope, which would be the worst-case scenario. If a margin of 50% is added to account for modelling simplifications and uncertainties in the release conditions. This results in a required clearance zone of approximately 18 cm around the rover's initial projected position on the lunar surface. 50% is chosen because this is only a simplified model, and realistic cases are implemented with many assumptions. Furthermore, a margin of error would be preferable, as payloads could interfere and lead to mission failure. In the current case, the 18 cm would require an area of 64.4 by 49.6 cm to be cleared, projected underneath the rover.

This directly impacts the accommodation of multiple rovers inside the lander. If rovers were placed next to each other, their clearance zones should not overlap. For rovers of similar size, this would require approximately 36 cm spacing between neighbouring rovers. Although this is possible, it reduces packaging efficiency and therefore diminishes the attractiveness of a compact, standardised system that deploys multiple rovers.

To conclude, the assumed case is more constrained by horizontal clearance than by tip-over stability. The rover can remain stable for most realistic centre-of-gravity positions, but the projected clearance on the surface increases when conservative release conditions are used.

6.2.3. Design implications for the deployer

The clearance requirement is mainly driven by the deployer release conditions. In particular, the half-cone separation angle is important, as it induces lateral movement after release. The value of 7.5 ° used in this case study shows a worst-case value from a CubeSat deployer, which may not be optimal for a rover deployment system. Reducing this would directly make the clearance envelope smaller.

The initial velocity also affects the rover's trajectory. A higher exit velocity reduces the fall time, but increases the horizontal velocity component. Therefore, the deployer should avoid high exit velocities and lower it to have a more controlled release.

Several measures can reduce the rover's clearance zone. First, the drop height should be lowered to minimise the fall time and therefore horizontal motion and rotation. Secondly, the rails could be extended to constrain the deployment for longer. Thirdly, the deployer could be tilted away from neighbouring rovers or structures, then the rovers could be packaged more tightly inside the lander. Lastly, the release mechanism could be designed to reduce the angular velocity after release.

It should be noted that the present model does not yet include all relevant effects after

impact. The rover could bounce or slide to the side. These effects may further influence the required clearance and should be considered in future work. The current results already show that lateral movement can be a significant design driver and should be assessed to determine the viability of a standardised rover.

6.3. Summary of constraints for representative case

For the assumed case study, the main constraints are:

- The centre of gravity should remain low and close to the central line of the rover to ensure stability.
- The assumed initial angular velocity does not cause tip-over for most realistic centre of gravity positions for the simplified model.
- The maximum horizontal displacement is approximately 11.5 cm before any margins are applied.
- With the addition of 50% margin, a clearance of 18 cm would be required around the projected initial rover position.
- In case of multiple rovers, when standardised, a spacing of 36 cm with adjacent rovers is necessary if the rovers are of similar size.

The case study demonstrates how the proposed first-order method can be used to derive preliminary deployment-driven constraints for a representative small rover geometry. Under the assumed lander and deployer conditions, the simplified model indicates that lateral clearance is a stronger design driver than the geometric touchdown tipping criterion. These results should not be interpreted as validation of the deployment framework or proof of a complete rover standard. The case study should be used for clarification , since the model has not been validated experimentally or against flight data and does not include post-impact dynamics.

7 | Derived standardisation requirements and design rules

The standardisation considered in this thesis is meant for small lunar rovers with a mass up to 10 kg. At this stage, the rules are considered only for the lunar environment, as other planetary environments would require different rules. The rover is also considered a secondary payload. This means it should not occupy the lander's primary payload position and should not pose additional risk to the lander or other payloads.

The aim of the standard is not to fully define the rover design, but to provide an initial set of design rules and to demonstrate the implications of using deployment as a driver for rover standardisation. The main design philosophy is based on simplicity, flexibility, and ease of use. The deployment system should be reliable, require limited active control by the lander, and allow enough design freedom for different rover concepts.

7.1. Selected deployment concept

Based on the trade-off performed in this thesis, the drop/push deployment concept is selected as the baseline for deriving the standardisation rules. This does not mean that this method is universally the best deployment method, but that it is the most suitable baseline within the scope of this thesis, based on scalability, complexity, and implications for stakeholders.

For a standardised rover, the deployment method should be simple in operation and easy to integrate with various current commercial lunar landers. A rail-guided release is preferred, since it guides the rover during the first part of the deployment and reduces the freedom for unwanted rotation. This is especially important when the rover is connected to more than one point. If there is a delay between two release points, a rotation could be induced. For a rover, this rotation might become larger than what is normally seen in CubeSat dispenser systems. A guided release therefore helps to make the initial condition of the rover more controlled.

7.2. Deployer-side design rules

The main deployer-side variables are the drop height, exit velocity, tip-off rate, and separation angle. These variables define the rover's initial conditions after release and therefore directly influence the touchdown condition.

The drop height is mainly determined by the lander and by the location of the payload bay. If the landing legs are tall, the payload bay may start higher above the surface, which increases the drop height. If the deployer is not placed underneath the lander, the release height may also increase and the deployment becomes more complex. In general, a lower drop height is preferred because it reduces the time to impact and impact velocity. Based on the case study performed, representative drop heights of current commercial lunar landers, approximately 1 m to 1.5 m, are not a limitation for

initial touchdown conditions.

The exit velocity from the deployer should also be kept low. A higher exit velocity reduces the fall time but also increases the impact velocity, thereby increasing the loads at touchdown. Part of this energy may also be transferred into lateral motion after the rover leaves the rails. However, the exit velocity must still be high enough to overcome friction within the deployer. The minimum required exit velocity should therefore be determined for the specific deployer design.

The disturbances caused by the deployer, such as the tip-off rate and separation angle, should be minimised. Ideally, these values would be close to zero because they do not contribute to the rover's touchdown stability. In practice, small disturbances will remain, but the deployer should be designed to limit them.

7.3. Rover-side design rules

On the rover side, the most important design variable is the location of the centre of gravity. From the simulation, no single centre-of-gravity requirement can be defined, since the allowable location depends on the drop height and on the release conditions from the deployer. However, a low and central centre of gravity is preferred. This increases the critical tipping angle and gives the rover a better initial stability margin at touchdown.

A wider base of support is also preferred, as it increases the rover's stability. However, the rover will still be restricted by its maximum volume and by the available space inside the lander. The rover height itself is less important than the resulting centre-of-gravity height. As the rover becomes taller, it becomes more difficult to keep the centre of gravity close to the ground.

The minimum base of support depends on the rover's release conditions. For the investigated cases, a base of support around 10 cm gives a more favourable stability margin. A value close to 5 cm can be seen as a preliminary lower limit for the investigated drop heights of around 1 m and above. This should not be interpreted as a final general requirement, because the stability still depends on the centre-of-gravity location, drop height, exit velocity, tip-off rate, and separation angle. However, much smaller bases of support are not recommended, as the rover becomes unstable under several conditions that could occur during deployment.

7.4. Lander-side accommodation rules

The lander-side design should make the rover as accessible as possible for secondary payload use. The drop height should be reduced where possible, and the integration should remain simple. The deployer should provide a controlled release and should minimise the risk of collision with the lander or with other payloads.

Clearance zones should be included around the deployment path. This is needed to ensure the rover can leave the lander without hitting other structures. If multiple rovers are placed on the same lander, spacing between the rovers should also be considered. Each rover should have sufficient clearance during deployment, and the deployment of one rover should not interfere with another.

7.5. Use of the initial stability model

The model developed in this thesis should be used as an initial design tool for drop/push deployment concepts. It can be used to estimate how the drop height, centre-of-gravity location, release velocity, tip-off rate, and separation angle influence the initial touchdown condition. It can also be used to derive preliminary restrictions for the rover geometry and centre-of-gravity location.

The model should not be seen as a full validation of rover stability. It provides an initial indication of the effects of deployment conditions and rover geometry, but it does not capture the full touchdown dynamics. The rules derived from the model should therefore be interpreted as preliminary standardisation guidelines for the initial touchdown condition, rather than as complete rover design requirements.

7.6. Limitations

Several effects are not considered in the current model, as it is a simplified model intended to assess constraints for a preliminary standard. The model does not include the dynamics after the first impact, such as bouncing, sliding, or rolling after touchdown. It also does not include structural impact loads, although impact velocity could play an important role in the rover's mechanical design. As this thesis only includes the preliminary constraints and rules, it would go more into the detailed design and how the suspension, wheel design and placement of payload and subsystems.

Terrain effects are also not included. The rover is not evaluated on slopes, uneven terrain, or tilted initial contact conditions. These effects could reduce the stability margin and should be included in future work.

The derived rules should therefore be used as a first step towards standardisation. They show which parameters are important for a drop/push deployment concept and how these parameters can influence the initial stability of a small lunar rover. Further analysis and experimental validation are needed before these rules can be used as final standard requirements.

7.7. Future work

Several limitations could be reviewed or solved to strengthen the work presented in this thesis. The model currently stops at first contact with the with the lunar surface. The model could be extended to include full dynamics after touchdown, as roll, bounce or sliding could pose big constraints. The centre of gravity and the minimum base of support for certain drop heights might vary, as the stability constraint could be stricter. This is probably the most important future work to be done, as stability cannot be determined by investigating only up to touchdown.

The model could also be extended from a two-dimensional motion to full three-dimensional dynamics. The current approach addresses it one plane at a time, while the induced rotation could vary across planes depending on the case. A three-dimensional model would provide a more realistic estimate of the effects of roll and pitch, giving a better view of the trajectory and touchdown.

Terrain effects should be included in future work. The present model assumes a flat

surface, while the actual lunar surface will have an uneven terrain. Regolith could spread across the landing zone due to the landing procedure and rocks, craters and slopes as known uneven terrain. This could induce additional effects after touchdown, like roll. This could increase the risk of tip-over and will have a major impact, as this affects the dynamics. Including the variability would allow for a better evaluation of the stability and robustness of realistic conditions.

Another important step is experimental validation of the deployment concept. A CubeSat deployer could be modified to accommodate a rover and tested under representative conditions. These experiments could be used to measure the actual impact of exit velocity, angular velocity and lateral movement. This would allow for a better estimate of the larger disturbances on the geometry, mass and other design choices.

The accommodation of multiple rovers inside the lander could be refined. In the current work, clearance zones are taken as worst estimates, which reduces the efficiency of packaging the rovers inside the lander. Future work could investigate deployer orientation, for example, by deploying the rover under a slight tilt. This could reduce overlap between the trajectories to avoid collisions. Making the integration and spacing of the deployer for rovers easier.

The preliminary rules need to be extended to a broader standard for rovers. This thesis assesses only deployment-driven constraints, but other interfaces could also significantly impact the standard. So, including more specific mechanical interfaces, electrical/data connections, and thermal interfaces would move the work closer to a real standard, rather than only deployment guidelines.

Lastly, the Moon is not the only extraterrestrial body to be explored by rovers. To widen the scope, the Martian surface could also be included in the standard. The effects of a stronger gravitational force could be included to evaluate its impact on the rover's stability and implications for the rover standard.

8 | Conclusions

This thesis investigated how deployment constraints can be used as a starting point for the standardisation of a small lunar rover. The focus was on rovers with a mass below 10 kg, deployed as secondary payloads from a lunar lander. Since rover payloads and mission objectives can vary strongly between missions, deployment was treated as a common design driver that affects the rover geometry, centre of gravity position, landing stability and accommodation inside the lander. The main research question to be answered was:

> What design requirements and constraints does the selected deployment concept impose on a standardised small lunar rover (mass ≤ 10 kg) deployed as a secondary payload from a lunar lander?

The main research question was addressed by dividing it into three sub-questions. These sub-questions follow the structure of the thesis: selecting a suitable deployment concept, analysing its effect on touchdown stability, and assessing the accommodation and clearance constraints for multiple rovers.

Which deployment concept is most suitable as a baseline for a standardised lunar rover with a mass of up to 10 kg*, deployed as a secondary payload from a lunar lander, when assessed against defined criteria such as mass, stowed volume, mechanical complexity, reliability, scalability, and deployment risk?*

The deployment method found to be most suitable for a small standardised rover is the drop/push concept, where the rover is released from the lander and falls directly to the lunar surface. This method ranked highest mainly because of its low mechanical and operational complexity compared to the other methods of tethered-lowering and pod deployment. For a standardised concept, the deployment method should also be scalable in both rover size and number of rovers. Since there is no single rover design that suits every mission, the deployment concept should remain flexible while still allowing several rovers to use the same basic mechanism.

The main disadvantage would be the uncontrolled free fall of the rover. There are many unknowns to landing on the lunar surface, including terrain roughness or the lander's attitude. A During free fall, a rover would be able to adjust and make a soft landing. This can partly be designed for, but would impose restrictions on the geometry. But this was considered acceptable when compared with the added complexity of more controlled deployment methods.

For the selected deployment concept, how do drop height, centre-of-gravity location, release attitude, release velocity, and first-contact conditions affect touchdown stability of a standardised lunar rover with a mass of up to 10 kg*?*

For this specific deployment method, a simplified model for the touchdown stability has been created to gather the limitations on the design. As a baseline, the CubeSat deployer has been taken to give a first estimate for a similar mechanical system where a spacecraft is pushed out. The model is governed by the time to impact, the initial

angular velocity upon release and the critical tipping angle for the rover.

The time to impact is influenced by the drop height and initial velocity; the latter acts as the spring force that propels the rover out of the deployer, similar to the CubeSat dispenser. The critical tipping angle is determined by the position of the centre of gravity and the base of support of the rover. Together with the rotation induced by the inconsistencies of the deployment system, a centre of gravity envelope can be determined. A decrease in height and an increase in initial velocity decrease the time to impact, which makes the concept more stable as it has less time to rotate. As the centre of gravity is placed lower and closer to the centreline, the margin of stability increases because the critical tipping angles increase.

The guide rails have an important impact on the model because they constrain the early rotation. Therefore, inside the dispenser, the rover does not have the freedom to rotate, resulting in less rotation at impact.

For the case study, the rover remained stable for most realistic centre of gravity positions under the deployment conditions of the CubeSat. The angular velocity and drop height deployment assumptions did not create a critical tip-over condition in the simplified model, even when stability margins were considered. This indicates that for the investigated case, tip-over stability is not the main limiting constraint.

What stowed-volume, clearance, spacing and deployment-path requirements are imposed when multiple standardised lunar rovers, each with a mass of up to 10 kg*, are accommodated within a single lunar lander?*

The clearance and spacing requirements are dependent on the lateral movement induced during the deployment. In the simplified model, this lateral deviation is introduced through the half-cone separation angle after the rover exits the dispenser. Based on CubeSat deployment assumptions, a half-cone separation angle of 7.5° was used in the case study.

For this case study, with the goal of providing a representative case, estimating the implications of multi-rover accommodation based on the EXOpod NOVA dispenser and the CubeRover by Astrobotic resulted in a horizontal displacement up to 11.5 cm. With a 50% margin to account for modelling simplifications and release uncertainties, this led to a required clearance of approximately 18 cm around the projected rover position. If similar rovers had to be placed adjacent to each other, there would be a spacing required of 36 cm. This greatly reduces the packaging efficiency of the multi-rover configuration, which is one of the CubeSat dispenser's greatest strengths. The deployer mechanisms, regardless of this specific case, should therefore prioritise the separation angle, lower the exit velocity and lower the drop height as much as possible.

Design implications The rover should have a low and centrally placed centre of gravity. The base of support should be as wide as the volume envelope allows. The deployer should constrain the rover for as long as possible using rails and reduce velocity and lateral deviations to make the clearance envelope smaller. These parameters directly affect the stability margin and the required clearance around the rover.

Limitations As it is only a simplified model, it should be used as a first-order design tool only. The model considers in-plane rotation, so two-dimensional rigid body

motion and only until the first contact. It does not include any dynamics after first touch, so no bouncing, sliding, suspension behaviour, wheel deformation, slopes of the surface and rocks that could interfere with the mechanics. These effects may increase the required clearance and change the stability behaviour after touchdown. Therefore, the results are suitable for early-stage design and standardisation studies, but not yet for final deployment.

Overall, this thesis shows that deployment is a useful starting point for the preliminary standardisation of small lunar rovers. The drop/push concept was deemed the most attractive because it offers a simple and scalable deployment method with limited impact on the lander, making it suitable for a rover platform intended to be used as a secondary payload. However, the analysis also shows that this simplicity shifts the main design challenge from the deployment mechanism itself to the control of the release conditions. For the investigated case, initial tip-over stability was not the main constraint. Instead, the lateral clearance required during deployment became the main design driver, especially when multiple rovers are accommodated within a single lander. A practical standardised multi-rover deployer should therefore focus on controlling the separation angle, exit velocity, rail length and rover spacing. These parameters directly determine whether the concept's trajectory can be kept within a narrower and more predictable path. The main contribution of this thesis is therefore the identification of these deployment-driven constraints and their translation into preliminary design rules for a standardised small lunar rover concept.

References

[1] ECSS Secretariat / European Space Agency. *ECSS-S-ST-00C Rev. 1 (15 June 2020): Description, implementation and general requirements*. Tech. rep. Rev.1. European Cooperation for Space Standardization (ECSS), 2020. (Visited on 10/11/2025).

[2] Richard Forselius. *The Future of Aerospace Standardization*. Tech. rep. Aerospace Industries Association of America, Mar. 2022.

[3] European Space Agency. *CCSDS Standardization Committee*. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Onboard_Data_Processing/CCSDS_Standardization_Committee. 2024. (Visited on 10/11/2025).

[4] Bilal M M Bomani. *CubeSat Technology Past and Present: Current State-of-the-Art Survey*. Tech. rep. National Aeronautics and Space Administration (NASA), 2021. URL: http://www.sti.nasa.gov.

[5] The CubeSat Program, Cal Poly SLO. *CubeSat Design Specification Rev. 14.1 (1U–12U)*. Technical Document. CP-CDS-R14.1. Feb. 2022. URL: https://static1.squarespace.com/static/5418c831e4b0fa4ecac1bacd/t/62193b7fc9e72e0053f00910/1645820809779/CDS+REV14_1+2022-02-09.pdf.

[6] EO Portal. *CubeSat Concept*. 2025. URL: https://www.eoportal.org/other-space-activities/cubesat-concept (visited on 10/08/2025).

[7] Hywel Curtis. *Launch separation systems for CubeSats and microsatellites*. Last updated Oct 21, 2024. satsearch blog. May 2020. URL: https://blog.satsearch.co/2020-05-14-launch-separation-systems-for-cubesats-and-microsatellites (visited on 01/05/2026).

[8] Erik Kulu. *CubeSats & Nanosatellites-2024 Statistics, Forecast and Reliability*. Tech. rep. NewSpace Index, 2024, pp. 14–18. URL: www.newspace.im.

[9] Erik Kulu. *Nanosats Database — Figures*. Web page. 2025. URL: https://www.nanosats.eu/%5C#figures (visited on 10/06/2025).

[10] Space Inventor A/S. *Space Inventor — Satellite Manufacturing and Components*. https://space-inventor.com/. 2025. (Visited on 10/11/2025).

[11] Nodir Adilov. "An analysis of launch cost reductions for low Earth orbit satellites". In: *Economics Bulletin* 42.3 (2022), pp. 1623–1633. URL: https://www.accessecon.com/Pubs/EB/2022/Volume42/EB-22-V42-I3-P130.pdf (visited on 10/06/2025).

[12] Konstantinos-Panagiotis Bouzoukis et al. "An Overview of CubeSat Missions and Applications". In: *Aerospace* 12 (6 June 2025), p. 550. ISSN: 2226-4310. DOI: 10.3390/aerospace12060550.

[13] Alba Orbital, Delft University of Technology, and GAUSS Srl. *PocketQube Standard*. 2018. URL: https://www.albaorbital.com/pocketqube-standard (visited on 10/13/2025).

[14] Vittorio Franzese. "PocketQube picosatellites: survey of missions and technologies". In: *CEAS Space Journal* 17 (6 Nov. 2025), pp. 1007–1018. ISSN: 1868-2502. DOI: 10.1007/s12567-025-00603-0.

[15] TU Delft, Alba Orbital, GAUSS Srl. *The PocketQube Standard, Issue 1*. PDF document. Technical standard / specification. June 2018. URL: https://static1.squarespace.com/static/53d7dcdce4b07a1cdbbc08a4/t/5b34c395352f5303fcec6f45/1530184648111/PocketQube+Standard+issue+1+-+Published.pdf.

[16] Alba Orbital. *ALBAPOD INTERFACE CONTROL DOCUMENT*. Tech. rep. Alba Orbital, 2026. URL: www.albaorbital.com.

[17] Alex Ellery. *Planetary Rovers*. Springer Berlin Heidelberg, 2016. ISBN: 978-3-642-03258-5. DOI: 10.1007/978-3-642-03259-2.

[18] Yang Gao and Steve Chien. "Review on space robotics: Toward top-level science through space exploration". In: *Science Robotics* 2 (7 June 2017). ISSN: 2470-9476. DOI: 10.1126/scirobotics.aan5074.

[19] Alberto Della Torre et al. "AMALIA Mission Lunar Rover—The conceptual design of the Team ITALIA Rover, candidate for the Google Lunar X Prize Challenge". In: *Acta Astronautica* 67 (7-8 Oct. 2010), pp. 961–978. ISSN: 00945765. DOI: 10.1016/j.actaastro.2010.05.023.

[20] Inc. ispace. *ispace Releases Technical Cause Analysis for HAKUTO-R Mission 2*. https://ispace-inc.com/news-en/?p=7671. June 2025. (Visited on 10/14/2025).

[21] Mariam Alhammadi. *Lunar Rover Wheels Design & Analysis*. Tech. rep. Khalifa University, 2022.

[22] European Space Agency (ESA). *ESA to touch Moon from wheels of UAE Rashid rover*. ESA — Enabling & Support: Space Engineering & Technology. URL: https://www.esa.int/Enabling_Support/Space_Engineering_Technology/ESA_to_touch_Moon_from_wheels_of_UAE_Rashid_rover (visited on 11/06/2025).

[23] Joseph I Minow. "Impacts of the Space Environment on Lunar Exploration". In: *AIAA SciTech Forum*. 2023.

[24] Jeffrey S Parker and Rodney L Anderson. *LOW-ENERGY LUNAR TRAJECTORY DESIGN*. Tech. rep. NASA JPL, July 2013.

[25] K. L. Ryder and M. Campola. *The Lunar Radiation Environment*. Tech. rep. NASA GSFC, Apr. 2022.

[26] R. Kruzelecky et al. "MoonDust Lunar Dust Simulation and Mitigation". In: *40th International Conference on Environmental Systems*. American Institute of Aeronautics and Astronautics, July 2010. ISBN: 978-1-60086-957-0. DOI: 10.2514/6.2010-6023.

[27] Astrobotic Technology, Inc. *CubeRover Payload User's Guide*. Technical Report. Astrobotic Technology, 2024. URL: https://www.astrobotic.com (visited on 04/26/2026).

[28] Astrobotic. *ASTROBOTIC LUNAR LANDERS Payload User's Guide*. Tech. rep. Astrobotic, 2021.

[29] J. T. Karras et al. "Pop-up Mars Rover with Textile-Enhanced Rigid-Flex PCB Body". In: *International Conference on Robotics and Automation (ICRA)*. IEEE, June 2017, pp. 5459–5466. ISBN: 9781509046331.

[30] *The Transformable nano rover (Lunar Excursion Vehicle 2 (LEV-2), "SORA-Q") for space exploration*. LEV-2 (SORA-Q) overview. Japan Aerospace Exploration Agency, Space Exploration Innovation Hub Center (TansaX). URL: https://www.ihub-tansa.jaxa.jp/english/LEV2_en.html (visited on 11/06/2025).

[31] S. Nakajima, Ishihara K, and Terazono J. "MICRO ROVER, BIG OPPORTUNITY: YAOKI'S POTENTIALS FOR LUNAR SCIENCE". In: *56th Lunar and Planetary Science Conference*. Mar. 2025. URL: https://global.jaxa.jp/.

[32] Dymon Co., Ltd. *Lunar Rover "YAOKI"*. https://dymon.co.jp/en/yaoki/. (Visited on 11/06/2025).

[33] Gustavo Medina-Tanco. "Validation of the lunar mission Colmena-1 in deep space". In: *75 th International Astronautical Congress (IAC)*. IAF, Oct. 2024, pp. 14–18.

[34] Tetsuo Yoshimitsu and Takashi Kubota. "ASTEROID SURFACE EXPLORATION BY MINERVA-II SMALL ROVERS". In: *18th Annual Meeting of the Asia Oceania Geosciences Society*. WORLD SCIENTIFIC, Aug. 2022, pp. 180–182. ISBN: 978-981-12-6009-4. DOI: 10.1142/9789811260100_0061. URL: https://www.worldscientific.com/doi/10.1142/9789811260100_0061.

[35] Spacebit. *Spacebit — Official Website*. Company homepage. URL: https://spacebit.com/ (visited on 11/06/2025).

[36] Carnegie Mellon University — IRIS Lunar Rover Team. *IRIS Lunar Rover*. Official project website. URL: https://irislunarrover.space/ (visited on 11/05/2025).

[37] Lunar Resources Registry. *Hopper Rover, LEV-1, SLIM Mission*. Feb. 1, 2024. URL: https://lunarresourcesregistry.com/actual/hopper-rover-lev-1-slim-mission/ (visited on 11/06/2025).

[38] Japan Aerospace Exploration Agency (JAXA). *Result and Achievements of the Lunar Excursion Vehicle (LEV-1) on board Smart Lander for Investigating Moon (SLIM)*. https://global.jaxa.jp/press/2024/01/20240125-2_e.html. Press release. Jan. 2024. (Visited on 11/06/2025).

[39] *The ultimate goal is to deploy a swarm of mini moon rovers*. Innovation & Impact — Pioneering Tech. Delft University of Technology (TU Delft). URL: https://www.tudelft.nl/en/innovation-impact/pioneering-tech/articles/the-ultimate-goal-is-to-deploy-a-swarm-of-mini-moon-rovers (visited on 11/06/2025).

[40] European Space Agency (ESA). *Nanokhod*. ESA Automation and Robotics. URL: https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Automation_and_Robotics/Nanokhod (visited on 11/05/2025).

[41] Reinhold Bertrand, Michel van Winnendael, and Johannes Brückner. "The Nanokhod Micro-Rover - A Versatile Platform for Surface Exploration of Celestial Bodies". In: *Exploration and Utilisation of the Moon. Proceedings of the Fourth International Conference on Exploration and Utilisation of the Moon: ICEUM 4* (July 2000), pp. 149–154.

[42] Aaron Aupperlee. *Carnegie Mellon's MoonRanger Slated To Fly on 2029 Lunar Mission*. CMU News. Aug. 6, 2025. URL: https://www.cmu.edu/news/stories/archives/2025/august/carnegie-mellons-moonranger-slated-to-fly-on-2029-lunar-mission (visited on 11/06/2025).

[43] Louis-Jerome Burtz et al. "ispace Modular Rover Design". In: *70 th International Astronautical Congress (IAC)*. 2019, pp. 21–25. URL: https://www.researchgate.net/publication/344893028.

[44] J. Walker. *Flight System Architecture of The Sorato Lunar*. Tech. rep. Ispace.

[45] Smithsonian National Air and Space Museum. *Sorato Lunar Rover*. Collection object ID: nasm_A20220323000. URL: https://airandspace.si.edu/collection-objects/sorato-lunar-rover/nasm_A20220323000 (visited on 11/06/2025).

[46] Evan Ackerman. *Meet the Very First Rover to Land on Mars*. IEEE Spectrum. Aug. 2012. URL: https://spectrum.ieee.org/meet-the-very-first-rover-to-land-on-mars (visited on 03/04/2026).

[47] Leonard David. *Get an up-close look at China's Chang'e 6 farside moon rover (video)*. Space.com. July 2, 2024. URL: https://www.space.com/china-change-6-moon-far-side-minirover (visited on 11/06/2025).

[48] ispace EUROPE S.A. *ispace-EUROPE announces Completion of First European Designed, Manufactured, and Assembled Lunar Micro Rover*. Press release; rover name "TENACIOUS". July 25, 2024. URL: https://ispace-inc.com/news-en/?p=5593 (visited on 11/06/2025).

[49] Mustafa Mert Ankaralı et al. "Initial Design For Smart Micro Lunar Exploration Rovers For Intelligent Collaborative Tasking". In: *76 th International Astronautical Congress (IAC)*. IAF, Oct. 2025.

[50] *CHeRI Rover*. Official project website. Middle East Technical University (METU). URL: https://cherirover.metu.edu.tr/ (visited on 11/06/2025).

[51] *MoVe — System Sheet*. System sheet (flyer). Bremen, Germany: German Research Center for Artificial Intelligence (DFKI), Robotics Innovation Center. URL: https://robotik.dfki-bremen.de/fileadmin/content/ric/media/flyer/systemblaetter/Systemblatt_MoVe_engl.pdf (visited on 11/06/2025).

[52] Astrobotic. *ASTROBOTIC CUBEROVER Payload User's Guide*. Tech. rep. Astrobotic, Jan. 2024. URL: www.astrobotic.com.

[53] *CADRE — Cooperative Autonomous Distributed Robotic Exploration*. Mission overview page. NASA Jet Propulsion Laboratory (JPL). URL: https://www.jpl.nasa.gov/missions/cadre/ (visited on 11/06/2025).

[54] LUNA Analog Facility (DLR/ESA). *The first rover awaits its entry into LUNA*. News post. Nov. 8, 2023. URL: https://luna-analog-facility.de/en/the-first-rover-awaits-its-entry-into-luna/ (visited on 11/06/2025).

[55] Astronika Sp. z o.o. *Planetary exploration and ISRU*. Astronika — Portfolio. URL: https://astronika.pl/portfolio/planerary-exploration/ (visited on 11/05/2025).

[56] *Here's all you need to know about UAE's Rashid rover*. Science. Gulf News. URL: https://gulfnews.com/uae/science/heres-all-you-need-to-know-about-uaes-rashid-rover-1.88613619 (visited on 11/06/2025).

[57] Carrington Chun et al. "The Small Frontier: Trends Toward Miniaturization and the Future of Planetary Surface Rovers". In: *Actuators* 14 (7 July 2025), p. 356. ISSN: 2076-0825. DOI: 10.3390/act14070356.

[58] ELO2 Consortium. *ELO_2 — Official Site*. EPE + Lunar Outpost Oceania Consortium. 2024. URL: https://www.elo2.au/ (visited on 11/05/2025).

[59] Mawson Rovers. *Vehicles*. Official product page. URL: https://mawsonrovers.com/#vehicles (visited on 11/06/2025).

[60] Stephan Ulamec et al. "IDEFIX, THE MMX ROVER-IN-SITU SCIENCE ON PHOBOS". In: *55th Lunar and Planetary Science Conference*. Mar. 2024, p. 1878. URL: https://hal.science/hal-04782447v1.

[61] Adrian Beil. *IDEFIX Phobos rover sent to Japan ahead of mission to Mars*. NASA Spaceflight. Feb. 12, 2024. URL: https://www.nasaspaceflight.com/2024/02/idefix-interview/ (visited on 11/06/2025).

[62] Lunar Outpost. *Rovers*. Official product page. URL: https://www.lunaroutpost.com/rovers (visited on 11/06/2025).

[63] *Pragyan*. ROBOTS: Your Guide to the World of Robotics. IEEE Robots Guide. URL: https://robotsguide.com/robots/pragyan (visited on 11/06/2025).

[64] STELLS Space Corp. *First Ever Mobile Power Rover (MPR-1) Will Begin Providing Power on the Moon by 2025*. STELLS Space Corp. News & Updates. Nov. 2022. URL: https://stells.space/news-and-updates/details/4 (visited on 05/04/2026).

[65] Alberto Della Torre et al. "AMALIA Mission Lunar Rover—The conceptual design of the Team ITALIA Rover, candidate for the Google Lunar X Prize Challenge". In: *Acta Astronautica* 67 (7-8 Oct. 2010), pp. 961–978. ISSN: 00945765. DOI: 10.1016/j.actaastro.2010.05.023.

[66] NDTV. *Pakistan Joins China's Lunar Mission For Exploring Moon's South Pole*. Ed. by Sanstuti Nath. NDTV World News. Published: Feb. 7, 2025. Feb. 2025. URL: https://www.ndtv.com/world-news/pakistan-joins-chinas-change-8-lunar-mission-for-exploring-moons-south-pole-7655491 (visited on 05/04/2026).

[67] Space Applications Services. *LUVMI-M Lunar Rover*. Space Applications Services Moon. URL: https://moon.spaceapplications.com/lunar-rover/ (visited on 05/04/2026).

[68] Canadian Space Agency (CSA). *SPRP — Small Planetary Rover Platform*. Dec. 8, 2017. URL: https://www.asc-csa.gc.ca/eng/rovers/rover-fleet/sprp.asp (visited on 11/05/2025).

[69] Stephen Clark. *Chinese rover begins exploring far side of the moon*. Spaceflight Now. Jan. 5, 2019. URL: https://spaceflightnow.com/2019/01/05/chinese-rover-begins-exploring-far-side-of-the-moon/ (visited on 11/06/2025).

[70] Robert Lea. *Who is Astrobotic Technology and what do they do?* Space.com. Dec. 22, 2022. URL: https://www.space.com/astrobotic-technology (visited on 11/05/2025).

[71] Astrobotic Technology, Inc. *Polaris Rover*. Astrobotic Technology. URL: https://www.astrobotic.com/lunar-delivery/rovers/polaris-rover/ (visited on 11/05/2025).

[72] eoPortal. *Chang'e-3 Moon-landing Mission*. eoPortal Satellite Missions. Dec. 2013. URL: https://www.eoportal.org/satellite-missions/chang-e-3#spacecraft (visited on 05/04/2026).

[73] The Planetary Society. *Mars Exploration Rovers*. The Planetary Society. URL: https://www.planetary.org/space-missions/mars-exploration-rovers (visited on 05/04/2026).

[74] L. Ding et al. "Surface characteristics of the Zhurong Mars rover traverse at Utopia Planitia". In: *Nature Geoscience* 15 (3 Mar. 2022), pp. 171–176. ISSN: 1752-0894. DOI: 10.1038/s41561-022-00905-6.

[75] Japan Aerospace Exploration Agency. *Lunar Polar Exploration (LUPEX)*. JAXA Human Spaceflight Technology Directorate. URL: https://humans-in-space.jaxa.jp/en/biz-lab/tech/lupex/ (visited on 05/04/2026).

[76] National Aeronautics and Space Administration (NASA). *VIPER – Program of Record Technical Information to Inform Partnership Proposal Formulation*. Tech. rep. Volatiles Investigating Polar Exploration Rover (VIPER); Revision: DRAFT; Effective date: February 3, 2024. National Aeronautics and Space Administration, Feb. 2024.

[77] Astrobotic Technology. *Astrolab's FLIP Rover Joins Astrobotic's Griffin-1 to the Moon*. Press release. Feb. 2025. URL: https://www.astrobotic.com/astrolabs-flip-rover-joins-astrobotics-griffin-1-to-the-moon/ (visited on 05/04/2026).

[78] David A. Kring. *Lunar Mobility Review*. Lunar Exploration Initiative briefing. 2006. URL: https://www.lpi.usra.edu/science/kring/lunar_exploration/briefings/lunar_mobility_review.pdf (visited on 05/04/2026).

[79] National Aeronautics and Space Administration. *Mars Science Laboratory: Curiosity Rover*. https://science.nasa.gov/mission/msl-curiosity/. Page last updated: Apr. 21, 2026. 2026. (Visited on 05/04/2026).

[80] NASA Jet Propulsion Laboratory. *Mars 2020 Perseverance Launch Press Kit: Perseverance Rover*. https://www.jpl.nasa.gov/news/press_kits/mars_2020/launch/mission/spacecraft/perseverance_rover/. (Visited on 05/04/2026).

[81] National Aeronautics and Space Administration. *Commercial Lunar Payload Services*. 2026. URL: https://www.nasa.gov/commercial-lunar-payload-services/ (visited on 05/12/2026).

[82] ispace-U.S. *APEX Lunar Lander Payload User's Guide*. Payload User's Guide Revision 4. ispace-U.S., Mar. 2025. (Visited on 05/12/2026).

[83] Firefly Aerospace. *BLUE GHOST LUNAR LANDER Condensed Payload User's Guide*. Tech. rep. Firefly Aerospace, 2021.

[84] Kelli Mars. *25 Years Ago: Mars Pathfinder Launches to Mars to Deploy Sojourner, the First Planetary Rover*. Dec. 2021. URL: https://www.nasa.gov/history/25-years-ago-mars-pathfinder-launches-to-mars-to-deploy-sojourner-the-first-planetary-rover/ (visited on 04/17/2026).

[85] Akash A. Shetty et al. "Rover ramp deployment system for Chandrayaan-3: Concept, design, development and operations". In: *Acta Astronautica* 229 (Apr. 2025), pp. 1–12. ISSN: 00945765. DOI: 10.1016/j.actaastro.2024.12.014.

[86] Andrew Chaikin. "The Other Moon Landings". In: *Air & Space Magazine* (Mar. 2004). URL: https://www.smithsonianmag.com/air-space-magazine/the-other-moon-landings-6457729/ (visited on 04/17/2026).

[87] Middle East Technical University, Department of Aerospace Engineering. *CHERI Announcement*. https://ae.metu.edu.tr/announce/25/cheri_announcement.html. 2025. (Visited on 04/28/2026).

[88] Jet Propulsion Laboratory. *Here's How Curiosity's Sky Crane Changed the Way NASA Explores Mars*. NASA. Aug. 2024. URL: https://www.nasa.gov/missions/mars-science-laboratory/curiosity-rover/heres-how-curiositys-sky-crane-changed-the-way-nasa-explores-mars/ (visited on 04/19/2026).

[89] NASA. *Curiosity's Sky Crane Maneuver, Artist's Concept*. https://science.nasa.gov/photojournal/curiositys-sky-crane-maneuver-artists-concept/. NASA Photojournal, Image ID: PIA14839, Credits: NASA/JPL-Caltech. 2011. (Visited on 04/23/2026).

[90] Patrick McGarey et al. "How to Deploy a 10-km Interferometric Radio Telescope on the Moon with Just Four Tethered Robots". In: *2022 IEEE Aerospace Conference (AERO)*. IEEE, Mar. 2022, pp. 1–8. ISBN: 978-1-6654-3760-8. DOI: 10.1109/AERO053065.2022.9843745.

[91] German Aerospace Center (DLR). *MASCOT. Mobile Asteroid Surface Scout on board Hayabusa2*. DLR. 2025. URL: https://www.dlr.de/en/research-and-transfer/projects-and-missions/hayabusa2 (visited on 04/19/2026).

[92] NASA. *Mars Pathfinder*. NASA Science. 2024. URL: https://science.nasa.gov/mission/mars-pathfinder/ (visited on 04/20/2026).

[93] Gregory S. Parnell and Timothy E. Trainor. "Using the Swing Weight Matrix to Weight Multiple Objectives". In: *INCOSE International Symposium* 19 (1 July 2009), pp. 283–298. ISSN: 2334-5837. DOI: 10.1002/j.2334-5837.2009.tb00949.x.

[94] Jamie Fine. "Design, Analysis, Assembly, Integration and Testing of Mechanical Systems for Micro-Satellites and Micro-Satellite Separation Systems". Master of Applied Science thesis. Toronto, Canada: University of Toronto, 2014.

[95] Carnegie Mellon University Robotics Institute. *MoonRanger: Stowage and Deployment*. 2026. URL: https://labs.ri.cmu.edu/moonranger/stowage-and-deployment/ (visited on 04/27/2026).

[96] Michael Tolstoj and Till Siebert. *EXOpod Nova User Manual*. Revision 1.1. Exolaunch GmbH. Mar. 2024. URL: https://exolaunch.com/documents/EXOpod_Nova_User_Manual_September_2022.pdf (visited on 04/26/2026).

[97] Jinsheng Guo et al. "Modeling of the CubeSat deployment and initial separation angular velocity estimation". In: *Aerospace Science and Technology* 95 (Dec. 2019), p. 105477. ISSN: 12709638. DOI: 10.1016/j.ast.2019.105477.

[98] Panin Ananwatanyoo et al. "Structural Design and Analysis of a 3u Cubesat-Based Rover for Moon Surface Exploration". In: *IAF Space Exploration Symposium*. International Astronautical Federation (IAF), 2025, pp. 624–630. ISBN: 979-8-3313-2924-2. DOI: 10.52202/083076-0068.

[99] EuroMoonMars. *EuroMoonMars Programme*. 2026. URL: https://euromoonmars.space/ (visited on 04/26/2026).