Chair of Conveying Technology

Master's Thesis

Development of a conveying system for the moon

Andreas Taschner, BSc

August 2021

Affiliation:
Chair of Mining Engineering - Conveying Technology and Design Methods
Department Product Engineering
Montanuniversität Leoben

Title:
Development of a conveying system for the moon

Author:
Andreas TASCHNER, BSc

Field of study:
Mechanical Engineering - Heavy Machinery

Main Supervisor:
Univ.-Prof. Dipl.-Ing. Dr.mont. Nikolaus August SIFFERLINGER

Co-Supervisors:
Dipl.-Ing. Eric FIMBINGER
Dipl.-Ing. Dr.mont. Philipp HARTLIEB

Further Support:
Dipl.-Ing. Michael BERNER

Preface

At this point I would like to thank everyone who supported me in writing this thesis.

My biggest thanks go to my dear parents for their endless support, because without them this study would not have been possible for me. Furthermore, I would like to thank my entire family for their support during my studies.

In addition, I would like to thank my supervisors Prof. Sifferlinger, Dr. Hartlieb, DI Fimbinger, and DI Berner, who made this master thesis possible for me, and supported me when there were problems.

I would also like to thank my friends and fellow students, especially Peter Entfellner and Florian Fiedler, for the fun but also often learning-intensive time together. We shared the positive as well as the negative moments with each other, which resulted in an unconditional friendship for the rest of our lives.

Finally, I would also thank Dominik Höber for the excellent cooperation during our projects.

Statutory declaration

I declare on oath that I wrote this thesis independently, did not use other than the specified sources and aids, and did not otherwise use any unauthorized aids.

I declare that I have read, understood, and complied with the guidelines of the senate of the Montanuniversität Leoben for "Good Scientific Practice".

Furthermore, I declare that the electronic and printed version of the submitted thesis are identical, both, formally and with regard to content.

Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich diese Arbeit selbständig verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt, und mich auch sonst keiner unerlaubten Hilfsmittel bedient habe.

Ich erkläre, dass ich die Richtlinien des Senats der Montanuniversität Leoben zu "Gute wissenschaftliche Praxis" gelesen, verstanden und befolgt habe.

Weiters erkläre ich, dass die elektronische und gedruckte Version der eingereichten wissenschaftlichen Abschlussarbeit formal und inhaltlich identisch sind.

25.08.2021

Date/Datum

Signature/Unterschrift

Abstract

In recent years, space exploration missions to Mars and the Moon have become more attractive again. One reason for this is that it is possible to produce oxygen directly on the Moon using lunar resources. In-situ resource utilization (ISRU) aims to produce oxygen directly on the Moon using lunar resources without transporting resources from Earth to the Moon. It is the first step to enable independent life on the Moon. ISRU can be divided into four main stations: excavation, conveying, beneficiation, and processing. It is called the ISRU chain. The next goals in the future are to provide oxygen as fuel for rockets and to enable longer human space exploration missions. The conveyance of materials thus represents the second step of the entire ISRU chain. The unique and challenging environmental conditions and requirements, on the conveying system, lead to the fact that a conventional terrestrial conveying unit on the Moon does not work as desired. These environmental conditions and requirements include, for example, the thin atmosphere, the temperature fluctuations, the material to be conveyed (namely lunar regolith, abrasive and cohesive properties), and that the conveyor system must function completely autonomously since there are no humans on the Moon. Therefore, in the context of this work, a concept for a conveyor system is designed, which meets the challenging conditions of the Moon.

Various different basic conveying principles are available that can build a functioning lunar conveyor. After examining the feasibility and comparing the advantages and disadvantages of each conveying principle, it was decided that a ballistic conveying system had the greatest potential to operate as a lunar conveyor. This system has

crucial benefits: through the low gravity of the Moon, the conveying material flies over larger distances compared to the Earth, atmosphere resistance is low due to the thin atmosphere, and a flexible/mobile version of the conveyor is feasible. The ballistic conveyor is based on the functionality of a medieval ballista and is designed to be attached directly to the excavator, so no chassis is necessary. Before studying the conveying system in more detail, a first rough calculation is also made to theoretically estimate the maximum conveying distance. Furthermore, the ballistic conveyor system can be divided into three main assemblies: the machine loading system, the drive, and the swivel mechanism. The machine loading system is the interface between the excavator and the conveyor. It essentially consists of 2 industrial robots that transfer a total of 3 buckets, which are filled at the transfer chute of the excavator, between the transfer chute and the acceleration system, namely the drive. Furthermore, the drive ensures the acceleration of the material. The buckets are held by the drive, which pre-tensions springs that are then released and thus accelerate the bucket together with the material and finally abruptly decelerate the bucket so that the material flies to the desired destination. The swivel mechanism is responsible for the alignment and aiming of the conveyor unit. The target destination of the material is static and the conveyor is constantly in motion, so the drive must also be realigned in order to accelerate the material in the right direction.

After working out the individual principles of the assemblies and how they work together, a 3D model of the conveyor system was created. The main focus here is on the mechanical setup and that the conveyor system is functioning. The 3D model is certainly not the highest level of detail and only the most important parts were detailed, such as the drive or the industrial robots. The reason for this is that other aspects have to be taken into account, such as topology optimization. Before this conveyor system can be used on the Moon, other aspects must also be worked out in more detail, such as the energy supply or the automation of the system. These further challenges should be solved in interdisciplinary teams to generate a promising output.

The final conveying system presents a possible approach focusing on mechanical functionality. This system addresses the unique requirements of the lunar environment and presents basic mechanical concepts to overcome these requirements to enable lunar conveying, as well as providing opportunities for individual components to undergo further development and be used on other conveyors. Furthermore, this system can also be used for other tasks besides the transportation of material. Leveling the surface, transporting other materials besides lunar regolith, or using the industrial robots of the machine loading system for reparations and maintenance are some examples of other applications. Additionally, this system has also some capabilities for utilization in certain terrestrial applications.

Kurzfassung

In den letzten Jahren haben Weltraumforschungsmissionen zum Mars und zum Mond wieder an Attraktivität gewonnen. Ein Grund dafür ist, dass es möglich ist, Sauerstoff direkt auf dem Mond mit Hilfe von lunaren Ressourcen zu produzieren. Die In-Situ-Resource Utilization (ISRU) zielt darauf ab, Sauerstoff direkt auf dem Mond mit lunaren Ressourcen zu produzieren, ohne Ressourcen von der Erde zum Mond zu transportieren. Es ist der erste Schritt, um unabhängiges Leben auf dem Mond zu ermöglichen. ISRU lässt sich in vier Bereiche unterteilen: Abbau, Förderung, Aufbereitung und Verarbeitung. Man nennt das die ISRU-Kette. Die nächsten Ziele in der Zukunft sind die Bereitstellung von Sauerstoff als Treibstoff für Raketen und die Ermöglichung längerer bemannter Raumfahrtmissionen. Der Materialtransport stellt somit den zweiten Schritt der gesamten ISRU-Kette dar. Die einzigartigen und herausfordernden Umweltbedingungen und Anforderungen, an das Fördersystem, führen dazu, dass eine konventionelle terrestrische Förderanlage auf dem Mond nicht wie gewünscht funktioniert. Zu diesen Umgebungsbedingungen und Anforderungen gehören beispielsweise die dünne Atmosphäre, die Temperaturschwankungen, das zu fördernde Material (Regolith, abrasive und kohäsive Eigenschaften) und dass das Fördersystem völlig autonom funktionieren muss, da sich keine Menschen auf dem Mond befinden. Daher wird im Rahmen dieser Arbeit ein Konzept für ein Fördersystem entworfen, das den anspruchsvollen Bedingungen auf dem Mond gerecht wird.

Es gibt verschiedene grundlegende Förderprinzipien, die einen funktionierenden Mondförderer bilden können. Nach Prüfung der Realisierbarkeit und dem Vergleich der Vor-

und Nachteile der einzelnen Förderprinzipien wurde entschieden, dass ein ballistisches Fördersystem das größte Potenzial hat, als Mondförderer zu funktionieren. Dieses System hat wesentliche Vorteile: Durch die geringe Schwerkraft des Mondes fliegt das Fördergut über größere Distanzen als auf der Erde, der Atmosphärenwiderstand ist aufgrund der dünnen Atmosphäre gering und eine flexible/mobile Version des Förderers ist umsetzbar. Der ballistische Förderer basiert auf der Funktionsweise einer mittelalterlichen Balliste und ist so konzipiert, dass er direkt am Abbaugerät angebracht werden kann, so dass kein Fahrgestell erforderlich ist. Bevor das Fördersystem näher untersucht wird, erfolgt eine erste überschlägige Berechnung, um die maximale Förderstrecke theoretisch abzuschätzen. Des Weiteren kann das ballistische Fördersystem in drei Hauptbaugruppen unterteilt werden: das Maschinenladesystem, der Antrieb und der Schwenkmechanismus. Das Maschinenladesystem ist die Schnittstelle zwischen dem Abbaugerät und dem Förderer. Es besteht im Wesentlichen aus 2 Industrierobotern, die insgesamt 3 Becher, die an der Übergabeschurre des Abbaugeräts befüllt werden, zwischen der Übergabeschurre und dem Beschleunigungssystem, dem Antrieb, transportieren. Darüber hinaus sorgt der Antrieb für die Beschleunigung des Materials. Die Becher werden vom Antrieb gehalten, der Federn vorspannt, die dann losgelassen werden und so den Becher zusammen mit dem Material beschleunigen und schließlich abrupt abbremsen, so dass das Material zum gewünschten Zielort fliegt. Der Schwenkmechanismus ist für das Ausrichten und Zielen der Fördereinheit zuständig. Da der Zielort des Materials statisch ist und das Fördersystem ständig in Bewegung ist, muss auch der Antrieb neu ausgerichtet werden, um das Material in die richtige Richtung zu beschleunigen.

Nach der Erarbeitung der einzelnen Prinzipien der Baugruppen und deren Zusammenspiel, wurde ein 3D-Modell der Förderanlage erstellt. Das Hauptaugenmerk liegt hier auf dem mechanischen Aufbau und dass die Förderanlage funktioniert. Das 3D-Modell entspricht nicht dem höchsten Detaillierungsgrad und es wurden nur die wichtigsten Teile detailliert, wie zum Beispiel der Antrieb oder die Industrieroboter. Der Grund dafür ist, dass andere Aspekte berücksichtigt werden müssen, wie beispielsweise die

Topologieoptimierung. Bevor dieses Fördersystem auf dem Mond eingesetzt werden kann, müssen auch andere Aspekte detaillierter ausgearbeitet werden, wie die Energieversorgung oder die Automatisierung des Systems. Diese weiteren Herausforderungen sollten in interdisziplinären Teams gelöst werden, um ein erfolgversprechendes Ergebnis zu erzielen.

Das finale Fördersystem stellt einen möglichen Ansatz dar, der sich auf die mechanische Funktionalität konzentriert. Dieses System geht auf die besonderen Anforderungen der Mondumgebung ein und stellt grundlegende mechanische Konzepte zur Bewältigung dieser Anforderungen vor, um eine Förderung auf dem Mond zu ermöglichen, sowie Möglichkeiten zur Weiterentwicklung einzelner Komponenten und deren Einsatz auf anderen Förderanlagen. Darüber hinaus kann dieses System neben dem Materialtransport auch für andere Aufgaben eingesetzt werden. Die Ebnung der Oberfläche, der Transport von anderen Materialien als Mondregolith oder der Einsatz der Industrieroboter des Maschinenladesystems für Reparaturen und Wartung sind einige Beispiele für weitere Anwendungen. Zusätzlich hat dieses System auch einige Anwendungsmöglichkeiten für bestimmte terrestrische Anwendungen.

Further publications

The author of this master thesis has already done several publications in this subject area. These were worked through in a team, and are listed below:

Challenge

NASA Bucket Drum Design Challenge – April 2020 [45]
Powered by NASA Lunar Surface Innovation Initiative (LSII) and grabcad
Fourth place
Project: NASA Bucket Drum Double-Helix
Team members: Andreas Taschner, Eric Fimbinger, Stephan Weißenböck and Dominik Höber
Link: https://grabcad.com/library/nasa-bucket-drum-double-helix-1

Article

"Excavation and Conyeving Technologies for Space Applications" [19]
Published in January 2021
BHM Berg- und Hüttenmännische Monatshefte
Authors: Dominik Höber, Andreas Taschner and Eric Fimbinger
DOI: 10.1007/s00501-020-01073-z

Presentation

SONet Talks 2021
Date: 9th of April 2021
online
Presenters: Andreas Taschner and Dominik Höber
Link: https://youtu.be/y5z4kOHajhc

Poster

Space Resources Week 2021 [17]
powered by LSA, ESA and LIST
19.04.2021-22.04.2021
virtual
Title: "Excavation and Conveying for Lunar Missions: System developments for the two fundamental steps of the ISRU chain"
Authors: Philipp Hartlieb, Eric Fimbinger, Dominik Höber and Andreas Taschner
DOI: 10.5281/zenodo.4707306

Cooperation Höber/Taschner

Due to the publications, two different master theses are being conducted. Dominik Höber deals with a mining unit for the Moon, and Andreas Taschner with the associated conveying unit. Since these topics have the same fundamentals, chapters 1-7 were divided and each was prepared by one person. So these chapters will be equal in both theses. This was done that each work is readable on its own. The following chapters have already been published in Dominik Höber's master thesis 'Development of an Excavation Concept for Lunar Reglith'.

The following chapters were written by Dominik Höber:

- Introduction (Chapter 1)
- The Moon (Chapter 2)
- Existing Robots (Chapter 4)

The following chapters and subsections were written by Andreas Taschner:

- ISRU Chain (Chapter 3)
- Transportation Systems (Chapter 5)
- Design Materials (Chapter 6)
- Boundary Conditions (Subsection 7.2)

The related part refers only to the introduction and the basic informations, the actual task is completely different in both theses. Thus, each work is independent and will be assessed individually.

Contents

1 Introduction **2**

2 The Moon **4**

- 2.1 Overview 4
- 2.2 The Lunar Landscape 5
  - 2.2.1 Structure 6
  - 2.2.2 Environmental Conditions 10
- 2.3 Regolith 13
  - 2.3.1 Chemical Composition 13
  - 2.3.2 Physical Properties 15
  - 2.3.3 Dust 16

3 ISRU Chain **18**

- 3.1 Excavation 19
- 3.2 Material Handling 20
- 3.3 Beneficiation 23
- 3.4 Processing 25

4 Existing Robots **29**

- 4.1 Mars Rover 29
  - 4.1.1 Spirit and Opportunity 29
  - 4.1.2 Curiosity 31
  - 4.1.3 Perseverance 33

4.2 NASA Rassor 35

5 Transportation Systems 37

5.1 European Large Logistics Lander (EL3) 38
5.2 NASA Lunar Lander 39
5.3 Peregrine 40
5.4 Starship 41
5.5 Blue Moon 43

6 Design Materials 45

7 Task Definition and Boundary Conditions 48

7.1 Task 48
7.2 Boundary Conditions 49

8 Conveying principles 52

8.1 Problems 52
8.2 Functional principles 54
  8.2.1 Lunar trucks 54
  8.2.2 Belt conveyor 56
  8.2.3 Tubular drag and trough chain conveyor 57
  8.2.4 Flexible screw conveyor 58
  8.2.5 Vibratory conveyor 59
  8.2.6 Mobile system on rails 60
  8.2.7 Ropeway conveyor 64
  8.2.8 Pneumatic conveyor 65
  8.2.9 Electromagnetic conveyor 66
  8.2.10 Ballistic conveyor 67
  8.2.11 Discussion 69

9 Concepts for the ballistic conveying system 73
9.1 Ballistic acceleration principles . . . 74
9.1.1 Blast wheel . . . 74
9.1.2 Cylinder-piston system . . . 75
9.1.3 Rotational slingshot with cylinder . . . 76
9.1.4 Rotational slingshot . . . 77
9.1.5 Bucket wheel . . . 78
9.1.6 Acceleration wheel with pre-tensioned spring . . . 79
9.1.7 Four-bar linkage . . . 80
9.1.8 Spring drive with toothed rack . . . 81
9.1.9 Spring drive with a linear cylinder . . . 83
9.1.10 Discussion . . . 86
9.2 Swivel mechanism . . . 87
9.2.1 Rope or cylinder . . . 89
9.2.2 Worm gear . . . 90
9.2.3 Curved telescopic cylinder . . . 91
9.2.4 Linear cylinder . . . 92
9.2.5 Eccentric mechanism . . . 93
9.2.6 Direct mechanism . . . 94
9.2.7 Gear wheel . . . 95
9.2.8 Tiltable plate . . . 96
9.2.9 Fork system . . . 98
9.2.10 Discussion . . . 99
9.3 Machine loading system . . . 100
9.3.1 Intermediate storage with rotary feeder . . . 101
9.3.2 Drum type bucket storage . . . 102
9.3.3 Circular type bucket storage with pusher . . . 104
9.3.4 Rotary system on 2 levels . . . 105
9.3.5 Vertical loading system . . . 107

9.3.6 Robot system with intermediate bucket storage 107
9.3.7 Loading system with linear cylinders 109
9.3.8 Rotating plate with gates 110
9.3.9 Loading system with 3 robots 112
9.3.10 Loading system with 2 robots 113
9.3.11 Discussion 114

10 Estimated calculation 117

11 Final design 121

11.1 Overview of the system 121
11.2 Major Subsystems 122
11.2.1 Ballistic acceleration system 122
11.2.2 Swivel mechanism 127
11.2.3 Machine loading system 128
11.2.4 Bucket 129

12 Operation cycle 132

12.1 Excavation area 132
12.2 Material flow 134
12.3 Working cycle 136
12.4 Material collection 139

13 Further developments 144

13.1 Range extension 144
13.2 Pre-processing of conveying material 145
13.3 Automation 146
13.4 Design materials 146
13.5 Manufacturing and assembling 147
13.6 Dust protection 148
13.7 Error handling and maintenance 149

13.8 Energy 149
13.9 Interface between excavator and conveyor 150

14 Conclusion **152**

List of Figures **159**

List of Tables **164**

Bibliography **166**

Beginning of the fundamental chapters

The following chapters are the result of a collaboration between Andreas Taschner and Dominik Höber and have already been published in Dominik Höber's master thesis 'Development of an Excavation Concept for Lunar Reglith', but Andreas Taschner contributed to it in equal parts as Dominik Höber. The exact split of who wrote which chapter can be seen before the table of contents in 'Cooperation Höber/Taschner'. The main part of this thesis, on which the focus lies, has been worked on completely independently by Andreas Taschner and starts with chapter 8.

1 Introduction

The universe has inspired mankind for many decades. Since the first success in reaching outer space, researchers from all over the world have been working on new technologies, for example, to position a robot precisely on Mars.

Space missions have experienced a resurgence, especially in recent years. Since private companies such as SpaceX or Blue Origin have been involved in inventing new technologies, the public interest is increasing steadily. More and more countries are launching missions into space, such as the United Arab Emirates or China. This mission mostly targets Mars because it can be a future planet for mankind, according to many researchers. [15]

The biggest problem with travelling to Mars is the long distance and the large fuel consumption. Due to the latter, another celestial body comes to the fore, the Moon. There is a chance to obtain fuel for rockets from the oxygen-containing surface material, the regolith. Thus, for example, a spaceship could fly from the Earth to the Moon, refuel and then continue its flight to Mars. This would be a great advantage because the Moon‘s atmosphere is much thinner than that of the Earth, and the gravitational acceleration is lower. Therefore, less energy is needed to escape from the lunar atmosphere, which would significantly increase the range of a rocket.

The abundant raw material Regolith on the Moon, due to additive manufacturing processes, can also be used as a building material for lunar bases and protection shields.

Another potential of the lunar surface material regolith is to produce oxygen for Moon bases, first for exploration missions and later for possible life on the Moon.

There are a lot of research projects ongoing to get the oxygen out of the material. They use in-situ resource utilization (ISRU), which describes a process chain from excavation to processing at the same place. However, the crucial step of this process is the excavation. Without a good mining system, the manufacturing processes cannot work. Another important step is materials handling because the medium must be brought to the manufacturing plant.

Therefore, we have made it our mission to advance this research to contribute to our knowledge of the universe.

The major task of this thesis is the development and conzeptualization of an approach for a conveying unit for the use on the Moon. The main focus is on the mechanical funtionalization. Initially, various topics must be covered in the literature review, for instance, the lunar landscape and the ISRU chain, to define boundary conditions (chapter 7) and to obtain a knowledge about the particular environmental conditions on the Moon. An overview is also given of various robots that are already developed for use on extraterrestrial bodies, as well as transportation systems that are developed for transporting payloads to other celestial bodies.

In chapter 8 different conveying principles are described with advantages and disadvantages, followed by a discussion comparing the different principles and selecting the concept with the highest potential. Afterward, in chapter 9 different approaches for the main assemblies of the conveying unit are presented, compared, and the approach with the highest potential is chosen. After that, approximate calculations were carried out in chapter 10. In chapter 11 the final design of the conveying unit is presented and described. Finally, the operation system of the developed conveying concept is presented in chapter 12 and further developments which are necessary in order to maintain a error-free operation of the conveying concept are described in chapter 13.

2 The Moon

The Moon is the nearest celestial body to the Earth, with a distance between 356,000 km and 406,000 km. Because of its proximity in relation to other terrestrial bodies, mankind sees great potential in it. Due to this enthusiasm, the first missions to the Moon were already started in 1959. The first spacecraft to reach this celestial body was the Russian Lander 9 on the 3rd of February 1966, but the most famous mission was the first manned landing on the Moon on the 24th of July in 1969, during the Apollo 11 mission. The last people on this celestial body were Eugene Cernan and Harrison Schmitt of the Apollo 17 mission at the end of 1972. [51, 55]

2.1 Overview

Before starting with the main part of this thesis, it is important to take a look at the environmental and geological conditions at the Moon because these conditions lay the foundation for the development of the concept as they further set relevant boundary conditions. In Table 2.1, there is a fore comparison of some basic properties of the Moon and the Earth.

Table 2.1: Overview of properties Moon and Earth [51]

	Moon	Earth
Diameter	3,476 km	12,756 km
Mass	$0.7x10^{23}$ kg	$59.8x10^{23}$ kg
Gravitational acceleration	1.622 m/s^2	9.8 m/s^2
Temperature range	-258 °C (at the poles) to 127 °C (at the equator)	-89.2 °C (at the poles) to 60 °C (at the equator)
Atmospheric pressure at surface	1x10^-12 torr = 1.333224x10^-14 bar	760 torr = 1.01325 bar

Due to the fact that the Moon rotates around the Earth and also its axes within a month, it is always the same side that can be seen from the Earth. This gives the impression that the Moon is locked in its place. Therefore, we differentiate between "near side" and "far side". The Moon can reflect only a fraction of the incident light, but it appears bright in the sky. The reason for this is the contrast between the Moon and the night sky, which is deep black. Actually, the brightness of the Moon is similar to the brightness of coal dust. [51]

2.2 The Lunar Landscape

Compared to the Earth on which the mountains result from an active plate tectonic process, highlands on the Moon were only created by differently sized meteorite impacts. These impacts formed not only the lunar surface over a timespan of four billion years, but also created the main subsurface material, the lunar regolith. This material will be discussed in Chapter 2.3. The core of the Moon consists of iron, with a temperature of about 1400°C, which is heated by the energy of radioactive elements. [51, 4, 11]

For the project covered in this thesis, only the surface conditions are relevant, so the inner conditions of the Moon are not mentioned further.

2.2.1 Structure

The surface structure of the Moon can be divided into two different types of landscape. On the one hand, there are dark lunar mares, and on the other hand, lighter highlands (Figure 2.1), which have a lot of craters. These hollows are characteristic for the Moon. The impacts are differentiated into craters and basins, depending on their diameters. [60]

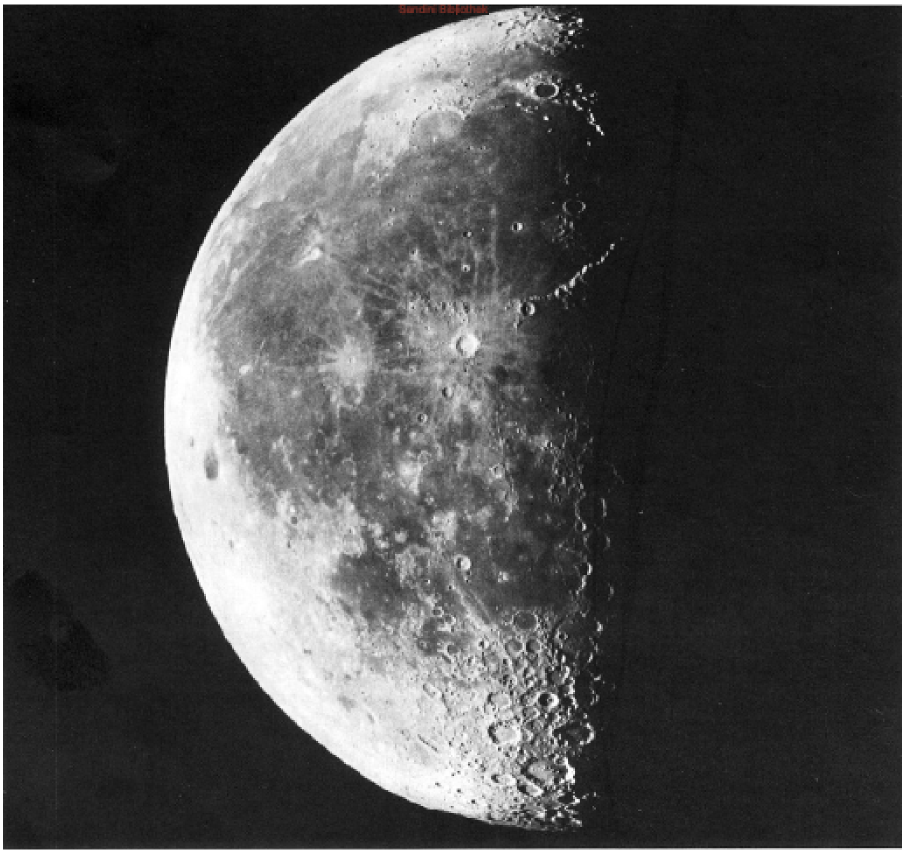


Figure 2.1: The Moon surface with mares and highlands [60]

Maria

A long time ago, people believed that the Moon has oceans and continents, as on Earth. But today, it is known that it is impossible for big oceans to ever exist because the gravity on the Moon is too low. These so-called lunar seas are just large patches of dark lava rock.

These mares, as shown in Figure 2.2, are not as old as the white highlands, so only a few craters can be found there because of fewer meteorite impacts since then. There are two classes of structure in the mare field, the mare ridges and the arcuate grabens. [60, 64]

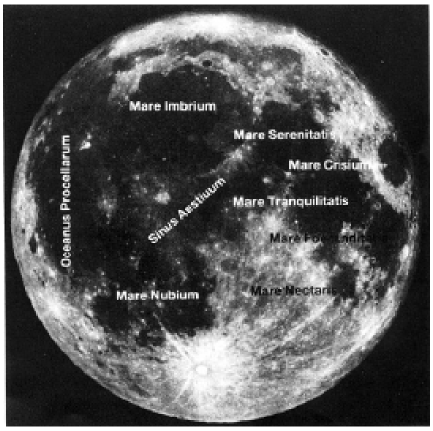


Figure 2.2: Moon mares [60]

Figure 2.3: The Apennines on the Moon [60]

Highland

Besides the craters, there are also long mountain ranges on the Moon. They were named after well-known regions on the Earth, such as the Alps and the Apennines. However, these peaks are not comparable with those on Earth, because they are only accumulations through meteorite impacts.

With their span of over 1,000 km, the Apennines (Figure 2.3) are the largest mountain range on the Moon. The peaks are up to 6,500 m high in relation to their surrounding valleys. [60, 18]

Crater

As already mentioned, the craters were created by the impact of meteorites. They have a diameter of up to 250 km. There are over 30,000 craters visible from the earth (Figure 2.4), but there are many smaller ones as well (from the Earth only those larger than 400 m in diameter are visible).

Figure 2.4: Crater landscape [60]

The crater formations can be divided into three types:

- The small craters with a diameter of 20 km
- The ring mountains (20 to 100 km)
- The wall levels (greater than 100 km)

The walls of big craters are often higher than 3,000 m, in exceptions up to 10,000 m. And because there is no water and wind, these craters remain as they are (except until the next impact of meteorites).

The biggest one is the Clavius crater with a diameter of 240 km and the highest one is the Letrone crater with a hight of about 10,000 m. Other popular ones are Archimedes, Aristoteles, Copernicus, Grimaldi, Theophilus and Tycho. [60, 64]

Basins and basin rings

The large basins are an important characteristic of the Moon, which can be seen from the Earth as black circles. These bowls were created by meteorite impacts, but unlike craters, these pools have a diameter of at least 300 km. This limit is an attribute for central rings instead of central crater peaks.

The most popular ones are the Orientale Basin (Figure 2.5), the Imbrium Basin, and the South Pole-Aitken Basin. The Orientale Basin has a diameter of 930 km and four rings. Unlike the Orientale Basin, the Imbrium Basin was filled with lava. The South Pole-Aitken Basin is the largest Basin on the Moon with a diameter of 2,500 km. In addition to the large diameter, it also has a depth of 12 km. [51, 18]

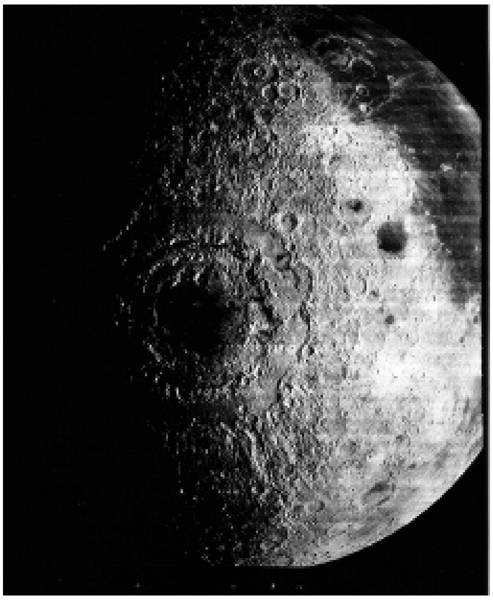


Figure 2.5: Orientale Basin [51]

Water

Evidence of hydrogen has been found on the Moon, and it is believed that there is water ice at the poles of this celestial body. Figure 2.6 shows the suspected occurrences. Water resources would be a big advantage for further missions on the Moon. [51]

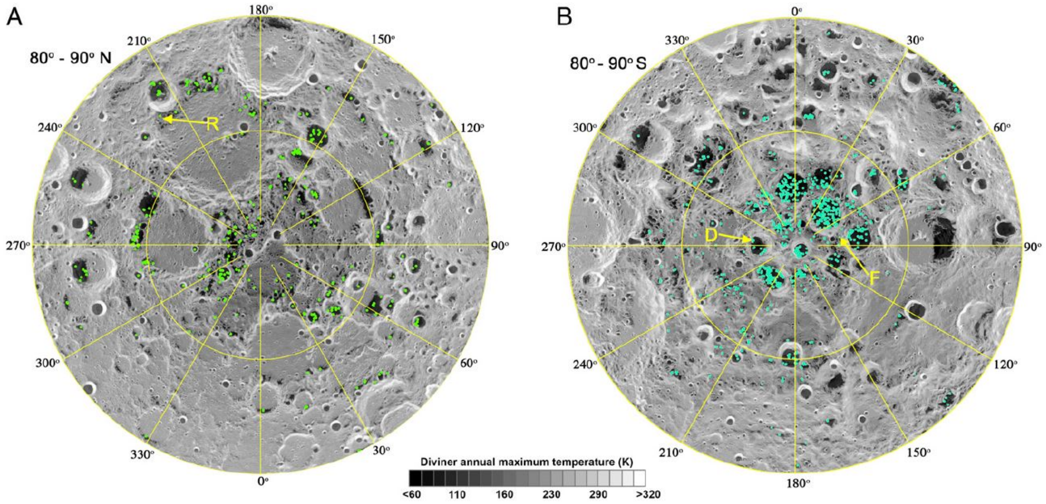


Figure 2.6: Distribution of water ice at the northern and southern polar regions [29]

2.2.2 Environmental Conditions

The environmental conditions are in many aspects different from those on Earth, notably to name the most important ones: gravity, atmosphere, temperature and cosmic radiation. Those conditions are further described on the following pages. [51]

Gravity

As already mentioned in the overview, the gravitational acceleration is only about a sixth of that on Earth. Exemplarily transferred to Earth conditions, this means that a weight of 120 kg results in a weight force on the Moon that can be compared to a weight force of only 20 kg on Earth.

$$g=\frac{G*M}{R^2} \tag{2.1}$$

The gravitational acceleration (g) depends on the gravitational constant (G), the respective radius of the Moon (R), and its total mass (M). The gravitational constant has a value of 6.673×10^{-11} m^3/kgs^2. [59]

Atmosphere

Many people think that the Moon has no atmosphere while in fact, it has a very tenuous one. The atmosphere at the Moon has a gas concentration of about $2\text{x}10^5$ molecules per cubic centimetre, which is only about one-fourteenth (1/14) of the Earth. In the following Table 2.2, there is the composition of the lunar atmosphere. The values are given in molecules per cubic centimetre (molecules/cm^3).

Table 2.2: Gas composition of the lunar atmosphere [18]

Gas	Chemical nomenclature	Daytime	Nighttime
Neon	^{20}Ne	$4\text{x}10^3$ - 10^4	10^5
Helium	He	$8\text{x}10^2$ - $4.7\text{x}10^3$	4 - $7\text{x}10^4$
Hydrogen	H2	2.5 - $9.9\text{x}10^3$	10^4 – 1.5 x 10^5
Argon	^{40}Ar	$2\text{x}10^3$	10^2
Methane	CH4	$1.2\text{x}10^3$	
Carbon dioxide	CO2	10^3	
Ammonia	NH3	$4\text{x}10^2$	
Hydroxide+water	OH+H2O	0.5	

The composition also depends on the time of the day because there are differences between daytime and nighttime. [18]

Length of day

A day on the Moon lasts about 709 hours, which corresponds to about 29.5 Earth days, so it is nearly a month. This is a challenge and a problem for missions as there are big temperature fluctuations at night, which can also be seen in the following paragraph. [51]

Temperature

Conditions of +127°C to -173°C prevail at the equator of the Moon. These large temperature fluctuations are caused by the day and night phases on the Moon. In Figure 2.7, the temperature curve at the equator is shown. It can also be seen that an approximately constant temperature of around 240 K (-33°C) has set one meter below the surface. [51]

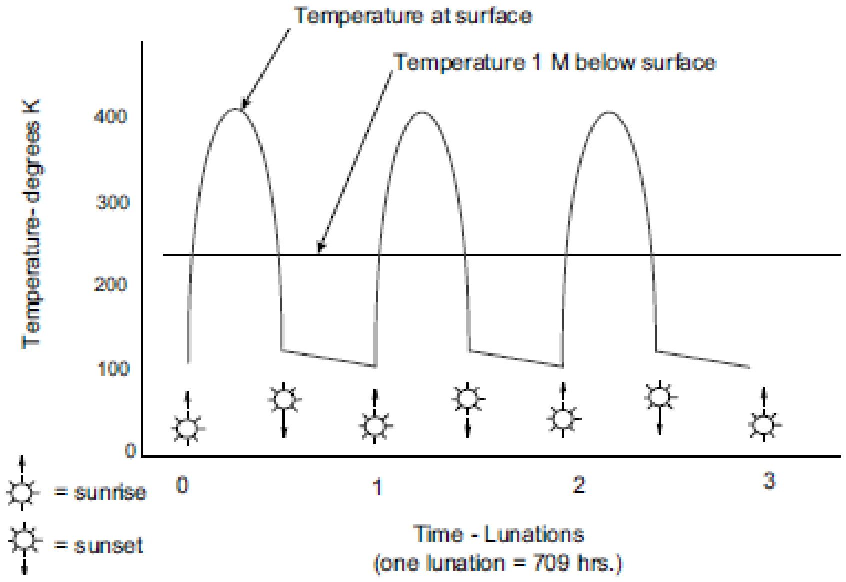


Figure 2.7: Temperature profile at the Moon´s surface [51]

Ionizing radiation

There are three major types of radiation in the lunar environment, the solar wind, the solar cosmic rays, and the galactic cosmic rays. Each of them has different effects on the lunar environment. The influence of these radiations on the Moon depends on their energy and composition; for instance, the solar cosmic rays leads to ionization energy loss in the top millimetres or centimetres of the lunar surface. [18]

2.3 Regolith

There are many different minerals and rocks, which occur on the Moon, but for this application, the lunar regolith is of major importance; thus, others will not be mentioned further. Regolith results from meteorite impacts to the lunar surface. These meteorites were shattered by the impact and covered the Moons top surface layer with a fine powder: the regolith. Due to this, regolith can only be found on the surface of a celestial body, such as specifically the Moon. On the Moon, this layer covers almost the entire surface and has a thickness of four to five meters in the mare areas, and between ten and fifteen meters in the highland regions.

Regolith has two great potentials: On the one hand, it can be used as a building material because it protects against radiation, and on the other hand, it can be used to generate oxygen. The exact process of oxygen generation is described in the ISRU chapter. [51, 4]

2.3.1 Chemical Composition

The lunar regolith contains of a lot of different elements. These elements can be divided into two groups, the major elements and the trace elements. The lunar surface consists of a mixture of basaltic and anorthositic materials. It is also notable that more than a quarter of the particles on the top appears in the form of agglutinates (fused soil).

Agglutinates are composed of regolith particles and glass, which is created by the impact of the meteorites and the resulting energy conversion from the kinetic energy to heat. The unmelted fragments stick to the melted ones and thus create a new form of grain. As can be seen in Figure 2.7, these agglutinate have a very sharp shape, which is responsible for the increased wear on contacting components, such as mining equipment. [51, 10]

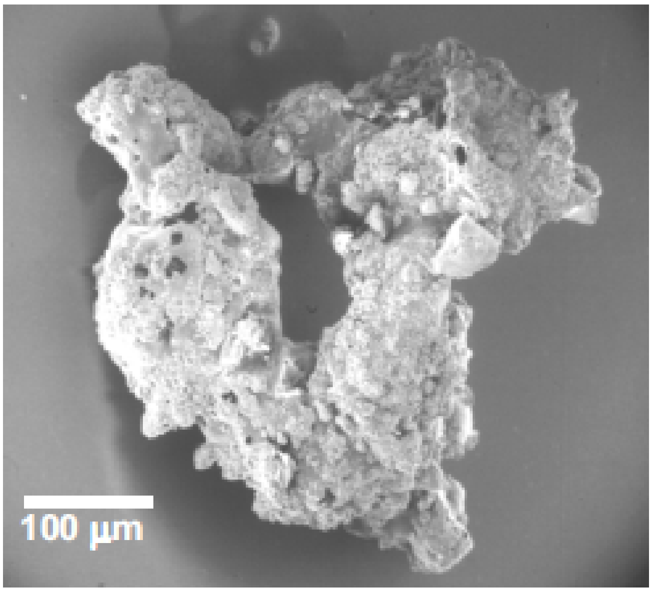


Figure 2.8: Lunar agglutinate [51]

For the listed values (Table 2.3), the average occurrence is described. The metallic components occur in the form of metal oxides. The major elements are given in the unit of percents of atoms (%) and the trace elements in grams per cubic metre (g/m^3). [51]

Table 2.3: Major and trace elements of regolith [51]

Major elements	Percent of atoms	Trace elements	Grams per cubic meter
Oxygen (O)	60.9	Sulfur (S)	1,800
Silicon (Si)	16.4	Phosphorus (P)	1,000
Aluminum (Al)	9.4	Carbon (C)	200
Calcium (Ca)	5.8	Hydrogen (H)	100
Magnesium (Mg)	4.2	Nitrogen (N)	100
Iron (Fe)	2.3	Helium (He)	20
Sodium (Na)	0.4	Neon (Ne)	20
Titanium (Ti)	0.3	Argon (Ar)	1
		Krypton (Kr)	1
		Xenon (Xe)	1

2.3.2 Physical Properties

In general, the regolith has very specific characteristics, which will be explained here, for instance, different properties due to different grain sizes.

As can be seen in Table 2.4, some properties depend on the depth. These are indicated by their average values, like the cohesion, the internal friction angle and the bulk density. High cohesion means the particles attract each other strongly and this leads to the fact that the grains can form lumps. It is also interesting that the internal friction angle, which is a parameter for the friction between the particles, changes significantly even at a depth of a few centimetres. The increase in the bulk density can be explained by the increasing compaction with depth. [18, 30]

Table 2.4: Cohesion and internal friction angle of regolith [18, 30]

Depth	Cohesion c (kPa)	Internal friction angle (°)	Bulk density (g/cm^3)
0-15 cm	0.52	42	1.45-1.55
0-30 cm	0.9	46	1.53-1.63
30-60 cm	3.0	54	1.69-1.79
0-60 cm	1.6	49.5	1.61-1.71

Grain shape

There are various shapes of lunar regolith, from spherical to extremely angular. Most of the particles have an elongated shape, so the grains tend to form a denser packing. Due to this compaction, they are preferably arranged somehow parallel, along their longitudinal axes. This leads to some physical properties showing anisotropic behaviour. [51]

Grain size

The average grain size of regolith on the surface is between 60 and 80 μm. In the examined soil sample, grain sizes between 40 and 800 μm were founded. Most of the particles are glass bonded aggregates, rocks, and minerals. [18]

Another source has shown the following particle size distribution, as can be seen in Table 2.5. The values are given in percent, but the total is not 100%, because some particles were undefined and therefore not assigned.

Table 2.5: Particle size distribution in lunar soil [10]

	Size (μm)						Sample
	250-500	150-250	90-150	75-90	45-75	20-45	weighted
Weight percentage	11.91	13.13	15.99	5.48	14.45	17.37	average 78.33

Of course, there are also some bigger particles, also in the form of rocks, but these are not included in the grain size distribution because they do not appear regularly and are therefore not dealt with as part of the bulk material regolith.

It can be recognized, that there are differences between those two sources. This is because of the fact, that the distribution on the Moon is not the same everywhere. [10]

2.3.3 Dust

Particles with diameters less than 20 μm are generally called dust (in lunar context), and they can cause serious problems. Due to electrostatically loading, these small particles adhere to various surfaces. This could already be seen in the manned moon missions. They were stuck, for instance, on helmet visors, and attempts to wipe them off, scratches the visor. Furthermore, it is getting hotter and hotter inside the overall space suit, because of the dark dust and following absorption of the solar radiation. Another issue was lower traction of the lunar rovers than initially expected. [51, 10]

Electrostatic charging

Because there is no moisture in the lunar regolith and the thin atmosphere, there is an interaction between the different radiations and the particles. Due to this influence, the regolith is electronegatively charged on the night side and positively charged on the daylight side. [51, 10]

3 ISRU Chain

In-Situ Resource Utilization, or ISRU, is defined as follows:

„In-Situ Resource Utilization is the collection, processing, storing and use of materials encountered in the course of human or robotic space exploration that replace materials that would otherwise be brought from Earth to accomplish a mission critical need at reduced overall cost and risk.“ [49]

In this section, ISRU is only considered for lunar missions, although this process chain as a whole normally includes every planet on which it is possible. ISRU includes the production with native resources as raw materials used for goods and products, which are necessary for a human being on the Moon, or space and exploration missions. For instance, ISRU contains topics like the production of life support gases, propellants, spare and wear parts, and the construction of infrastructure on the lunar surface. One essential aim, among others, is to reduce the logistics from Earth and move them to the Moon, so that rockets do not need to transport essentials to this celestial body for each consumable. Instead of delivering these from Earth to the Moon, it is better to use raw materials that exist there. Moreover, the escape velocity from the lunar atmosphere is 2 km/s, whereas the escape velocity on the Earth is about 5 times higher, 11 km/s. Thus, the reduced logistics lead to a reduction in costs. Additionally, ISRU enables long-term missions such as lunar soil excavations, where energy supply is essential. These last points describe the importance of ISRU very well and explain why so many research projects focus on it. [49, 51]

A difficult challenge is the multidisciplinarity of this process chain. For a functional and successful ISRU, it is necessary to consider all stages – from excavation to storing the produced goods, similar to the terrestrial mine-to-product process. Therefore, many specialists from several different fields of research are required. To illustrate, for the development of an excavation robot and a chemical extraction process, different types of knowledge are needed. Furthermore, it is also crucial to link the stages properly, because without a connection between the stages, ISRU won't work.[26]

One approach is to structure ISRU into a process chain. Figure 3.1 gives a brief overview of the ISRU process chain.

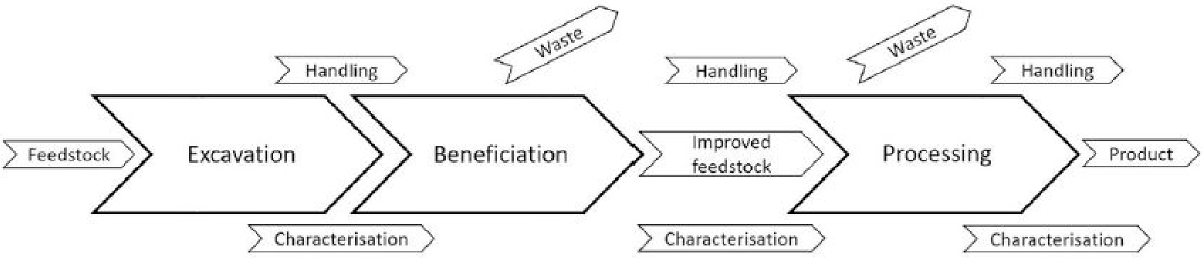


Figure 3.1: ISRU process chain [25]

It can be introduced in many different ways, but the main parts are always the same. The essential chain links are excavation, material handling, beneficiation, and processing.

3.1 Excavation

First, the lunar soil consists of regolith. Regolith is the feedstock for ISRU on the Moon. The properties and composition (e.g. ores, chemical elements) are described in Section 2.3. Regolith contains chemical elements, which can be used for mission support or to support human life on the Moon. For instance, approximately 40% of oxygen by weight is contained in the regolith. [25]

Although excavation is the initial step in the ISRU process chain, only a few research projects, compared to other steps such as chemical processing, are about the excavation on the Moon. It is currently difficult to specify the exact requirements because data about the lunar soil (e.g. composition, possible ice content) is not sufficiently available. In particular, two main issues occur when it comes to mining, conveying, and to the beneficiation of lunar regolith: First, the properties of regolith such as chemical composition and mineralogical makeup, and second, the gravitational force on the lunar surface, which is significantly different compared to the gravity force on Earth. Due to the harsh environment on the Moon, these are not the only issues that arise; for example, energy supply and tribological aspects will also be challenging. [25]

The tractive force depends on the mass of the mining unit and increases with the mass of the machine. Terrestrial excavators are designed for large vertical and lateral excavation forces without loss of traction. Therefore, almost every mining machine on Earth is a heavyweight solution. The transport of a large amount of payload from the Earth to the lunar surface leads to high financial costs and risks to deliver the payload to the Moon safely. As a result, excavators, which are operating on the surface of the Moon, have to be designed for low excavation forces and with low masses. Figures 3.2 and 3.3 are examples for this step of the ISRU chain that are under development. [25]

3.2 Material Handling

After regolith is excavated, it has to be transported to the production plant, where it goes through further steps. The material has to be delivered from the excavator, which usually operates a few hundred meters away from the base or processing plant, to the production plant as well as transported in the production plant between the individual steps. The different tasks require different conveyors. [51, 4]

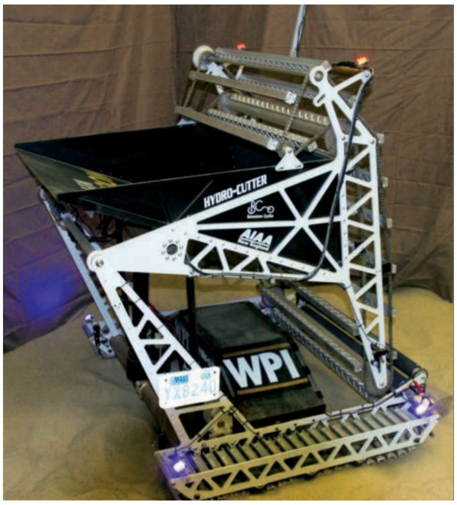


Figure 3.2: Moonraker robot [34]

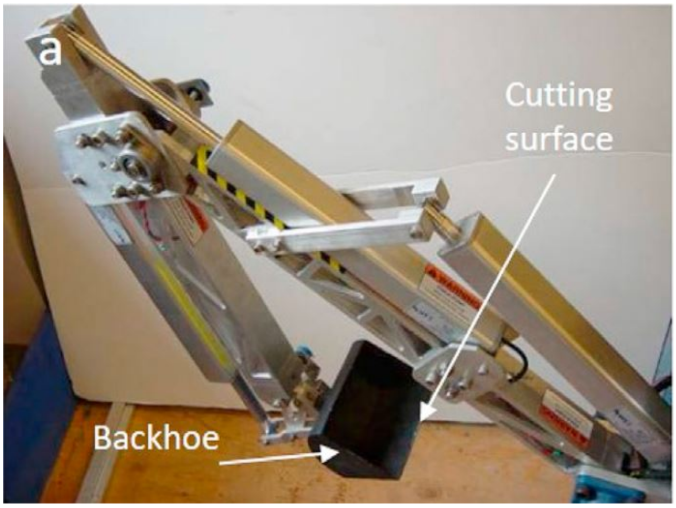


Figure 3.3: Backhoe as an excavator system [25]

There are also some major challenges in the conveying of Regolith that need to be overcome. Cohesiveness is an important property when it comes to material handling. On Earth, when the particle size decreases, the material is more cohesive. In addition, gravity also has a large influence on the powder movement and cohesiveness. Decreasing gravity level leads to an increase in cohesiveness. If, for example, a certain gravity level drops to 1/4, there will be a huge change in powder behaviour. The result of a growing cohesiveness is that the material acquires other characteristics like clumping, difficulty in fluidizing, poor flowability, and avalanching. Furthermore, electrostatic effects have also an influence on material behaviour. On the Moon, electrostatic effects occur more often than on the Earth due to the hard vacuum and the lower gravity. The lunar surface, which is exposed to the lunar environment, receives a surface charge straight from space or even from ultra-low density plasma. Moreover, on the Moon, the particles cannot discharge themselves by the atmosphere. Besides, fine dust is part of the regolith. Dust concerns problems with mechanical machineries, such as moving parts and seals. [4]

For the transport of regolith within the production plant, there are different types of mechanical conveyors under development. Besides, pneumatic conveyors are possible on the Moon. Figure 3.4 is a graphic of the pneumatic conveying system.

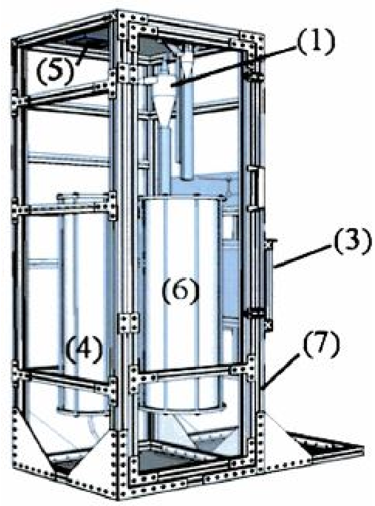


Figure 3.4: Graphic of pneumatic conveyor [35]

The delivery of regolith over longer distances is more difficult. Various types of conveying systems are being developed and studied, such as pneumatic conveying, electromagnetic conveying, railway systems, and conveyor systems. Figure 3.5 illustrates an approach for a future design of a pneumatic conveyor system. [51]

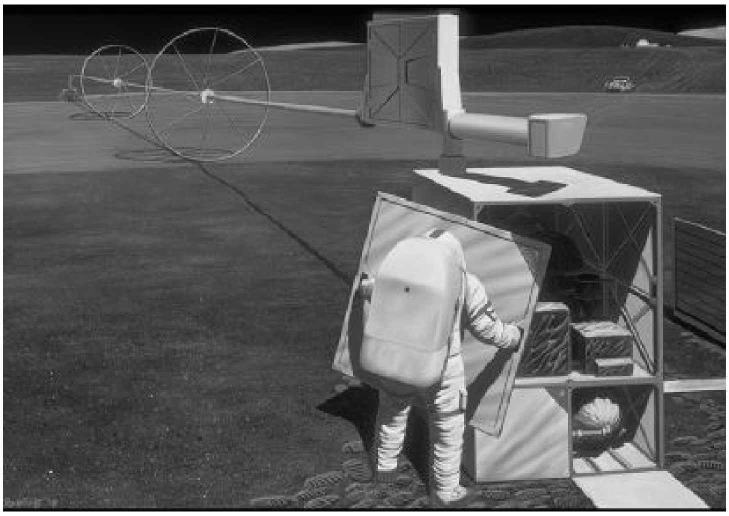


Figure 3.5: Future design of a pneumatic conveyor [51]

3.3 Beneficiation

After the transport of lunar soil to the plant and before the processing begins, the regolith has to be beneficiated or separated. Almost every processing operation requires a certain type of feedstock material. Therefore, a reliable beneficiation process, including size classification and material enrichment, is crucial for further steps. In particular, the beneficiation step ensures a consistent feedstock. Furthermore, with an appropriate raw material, no mechanical problems occur in the processing step. To illustrate, the hydrogen reduction process using ilmenite, which is patented by Gibson & Knudson, needs a feedstock containing between 80 and 90% ilmenite. [47]

Many separation and beneficiation systems on Earth use large amounts of water like density separation by spirals, jigs, froth flotation, and shaking tables. These technologies are unsuitable for beneficiation on the Moon. Every enumerated technology uses differences in physical properties to separate minerals from waste, for example, density, electromagnetic characteristics, and surface properties. As a result, beneficiation technologies without using a process fluid for separation have to be considered for lunar applications. [47]

Separation technologies based on gravity use the differences in density, particle's mass, and volume of the particles contained in the mixture. These methods, such as the shaking table, are well-known solutions for terrestrial applications. However, it would be a huge technical problem to implement such technologies for lunar separation. Instead of gravity-based separation, electrostatic and magnetic techniques are studied because they have a higher potential for beneficiation on the Moon. [47]

In electrostatic separation, changes in the Coulomb and/or dielectrophoresis forces are exploited. Both approaches have proven to be useful for generating material enrichment from several mixtures in lunar applications. Electrostatic separation, which is based on the manipulation of these two forces, has thus gained the most attention for lunar separation technologies. Due to the different surface charges of the particles, the Coulomb force separates them. Further, in a non-uniform electrostatic field, the particles are polarized and the dielectrophoresis force is generated. Coulomb force methods require two things: charged particles and an electrostatic field. The charged particles pass through an electrostatic field. Particles, which have a positive charge, are attached to the negative side of the electrostatic field, and vice versa. Some examples of Coulomb separation techniques are Ion Bombardment, Electron Bombardment, and UV Charging. Figure 3.6 shows another technique based on Coulomb force technology called Tribocharching and Free Fall Separation. [47]

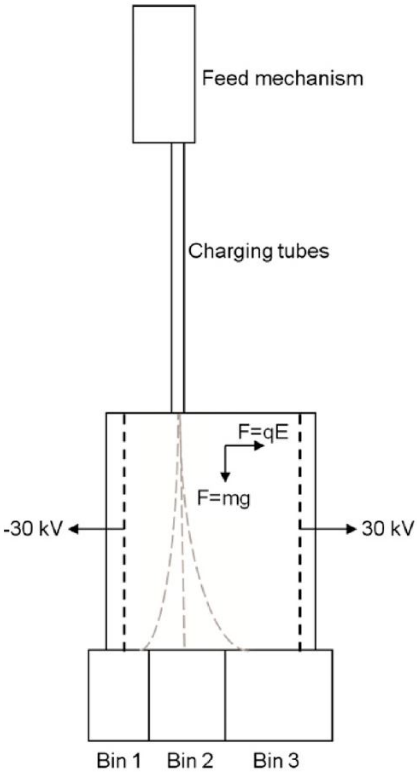


Figure 3.6: Diagram of a free fall type separator [47]

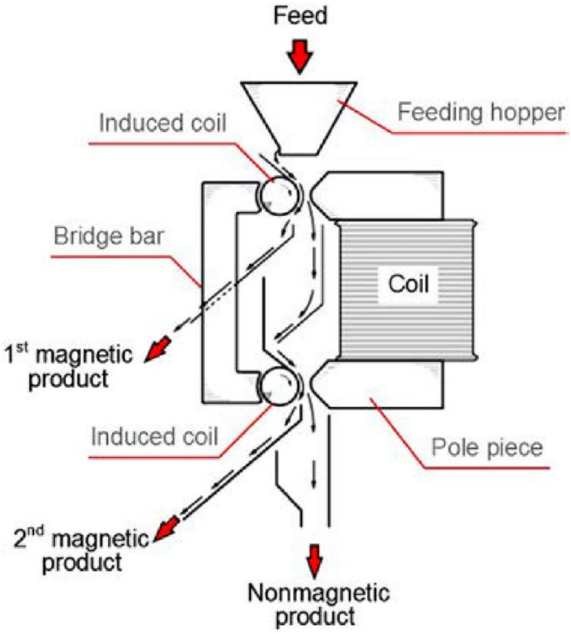


Figure 3.7: Diagrammatic representation of an IRMS [47]

Another beneficitation technique is magnetic separation. In terrestrial processing operations, magnetic separation is used. In particular to remove tramp iron from other minerals. Materials can be divided into three different magnetic behaviours: Diamagnetism, Ferromagnetism, and Paramagnetism. Diamagnetic materials, like quartz, only oppose the magnetic field if the field is very strong, whereas ferromagnetic materials, such as iron, can be highly magnetized. For example, ilmenite is a paramagnetic material, and without an applied magnetic field, the atoms have unaligned magnetic moments, and this results in a net-zero magnetization. But, the magnetic moments react to applied magnetic fields. Overall, the separation of paramagnetic materials from the other feedstock requires strong magnetic fields, a minimum of 2 T. In Figure 3.7, there is a high-gradient magnetic separation (IRMS) application. [47]

3.4 Processing

The production of oxygen on the Moon is a main point of ISRU. In many different types of lunar missions, oxygen is crucial, such as for ensuring human life on the lunar surface or for refuelling a rocket before launching again. As an example: 80% of the takeoff weight of Apollo 11 consisted of fuel and liquid oxygen. So, if liquid oxygen is available on the Moon, as by ISRU, the launch weight of a rocket can be significantly reduced. There are different types of experiments to produce oxygen on the lunar surface, and they can be divided into chemical reduction, pyrolysis, aqueous solvent processing, and electrochemical reduction. [4]

For feedstocks, which have a large proportion of iron ore like ilmenite, hydrogen reduction is suitable. This process works at approximately 900°C and is relatively simple.

$$FeTiO_3 + H_2 \longrightarrow Fe + TiO_2 + H_2O \tag{3.1}$$

The water is in a gaseous state after the process and is afterwards condensed. Subsequently, the water goes into an electrolysis process, and the hydrogen returns to the reduction process. The iron ore oxide content in the feedstock is decisive for the oxygen yield and depends on where the raw material was located so that a beneficiation step prior to reduction is necessary. [4] Figure 3.8 shows two different types of reduction reactors called ROxygen, developed by NASA, and PILOT, developed by Lockheed Martin Astronautics (LMA). [50]

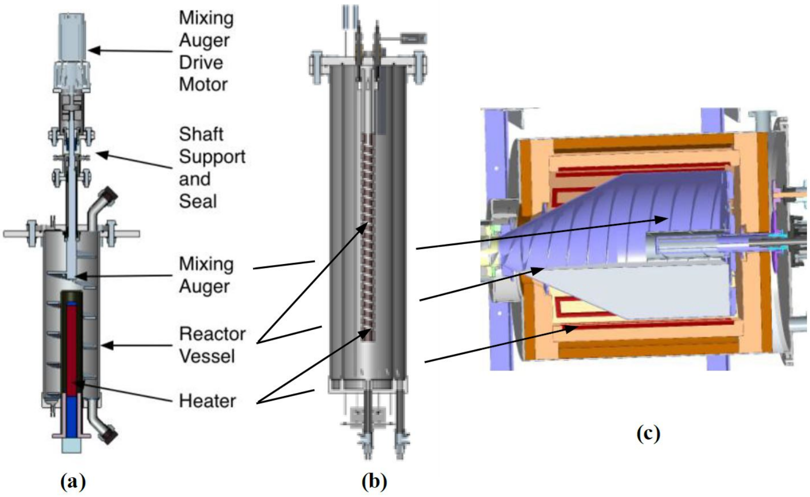


Figure 3.8: ROxygen Gen I Reactor (a), ROxygen Gen II Reactor (b), PILOT Rotating Reactor (c) [50]

Carbothermal reduction with methane is significantly different from the hydrogen reduction because it is appropriate to a bulk regolith feedstock including silicon oxide. Furthermore, this process can reach higher reduction levels. The crucial step starts at a temperature of about 1600°C:

$$FeTiO_3 + CH_4 \longrightarrow Fe + TiO_2 + CO + 2\,H_2 \tag{3.2}$$

$$MgSiO_3 + 2\,CH_4 \longrightarrow Si + MgO + 2\,CO + 4\,H_2 \tag{3.3}$$

$$CaSiO_3 + 2\,CH_4 \longrightarrow Si + CaO + 2\,CO + 4\,H_2 \tag{3.4}$$

Figure 3.9 illustrates a sketch of the carbothermal reduction of lunar regolith.

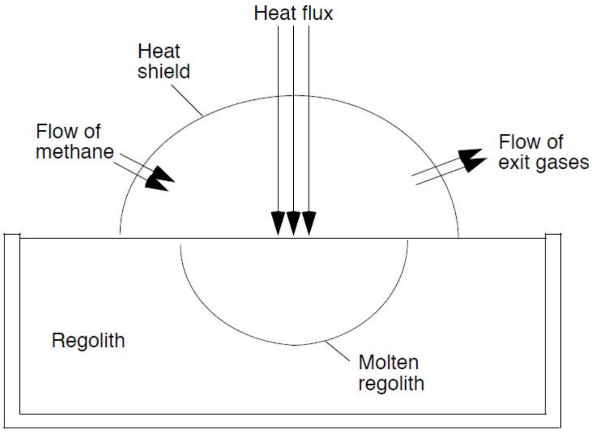


Figure 3.9: Sketch of the carbothermal reduction of lunar regolith [5]

The next step produces water over a nickel catalyst:

$$CO + 3\,H_2 \longrightarrow CH_4 + H_2O \tag{3.5}$$

Then the methane is reused, and the water goes forward to electrolysis. Although ESA stated this process as their preferred way to generate oxygen, there are some disadvantages. The carbothermal reduction process requires multiple processing steps and high operating temperatures. [4]

Similarly, the vapour phase pyrolysis also works with a bulk regolith feedstock, but this process requires an operating temperature above 2000°C to decompose the strong metal-oxide bonds:

$$FeTiO \longrightarrow Fe + TiO_2 + CO + \frac{1}{2}O_2 \tag{3.6}$$

$$MgSiO_3 \longrightarrow SiO + MgO + \frac{1}{2}O_2 \tag{3.7}$$

$$CaSiO_3 \longrightarrow SiO + CaO + 2\,CO + \frac{1}{2}O_2 \tag{3.8}$$

It is possible to reach oxygen yields up to 50% depending on some process factors such as temperature and duration. The rapid cooling and condensation of the oxygen obtained is an essential step in preventing the recombination of oxygen with the remaining suboxides. The major drawback is certainly the high operating temperature. [4]

There are other processes to produce oxygen, for instance, sulphuric acid reduction and the magma process, which is the simplest approach, but these processes are here not discussed in detail.

Water ice on the Moon could become a ‚gamechanger' due to water is the most important substance for mankind. NASA's mission called LCROSS detected water ice in the polar regions in acceptable quantities in October 2009. According to the LCROSS mission, the lunar soil in the polar regions, especially in the permanently shaded craters, contains about 5.6% water ice, but this is a model-based estimation, so it must be confirmed first. If the prediction is correct, the astronauts will be able to extract up to 100 litres of water from one cubic meter of lunar soil. The presence of water ice on the Moon represents a great opportunity for lunar missions; nevertheless, many challenging problems are still ahead. For instance, ice-mining operations will be technically problematic because of the low temperatures to -230°C and below. Moreover, the extraction of water ice will be energy-consuming, expensive, and the transportation of the extracted water ice will also be problematic due to the mountainous terrain and the rough environment. [4]

4 Existing Robots

The following pages will describe some existing robots which were already used in space or are planned to start soon. The structure of the robots is the most important aspect of this research; hence, a selection of modern robots used in space exploration (therefore also including Mars) is being examined in more detail in the following.

4.1 Mars Rover

The Mars rovers from the National Aerospace and Space Agency (NASA), are the most popular space robots, and even if they aren´t/weren´t mining robots, there is a lot of knowledge for further use. For example, the drive or the energy supply. The Mars Rover project consists of several missions: the missions Spirit and Opportunity are already considered completed. [42]

4.1.1 Spirit and Opportunity

These robots (Figure 4.1) were structurally identical, and they investigated the geological circumstances on Mars. The landing sites Gusev Crater and Meridani Planum were specifically selected because water was suspected there most. [44, 42]

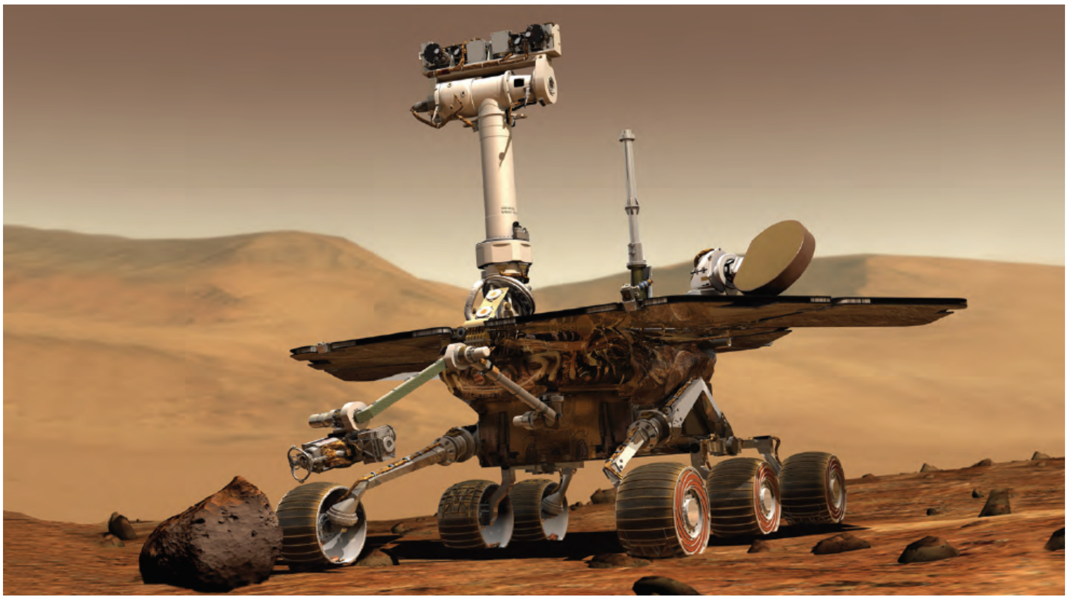


Figure 4.1: Spirit and Opportunity [44]

Table 4.1: Facts about the missions Spirit and Opportunity [44]

	Spirit	Opportunity
Launch	10th of June 2003	7th of July 2003
Arrival	4th of January 2004	25th of January 2004
Landing place:	Gusev Crater, Mars	Meridiani Planum, Mars

While NASA lost the connection to Spirit on the 22nd of March 2010, the mission of Opportunity lasted until the 10th of June 2018. On the 12th of February, the mission was finally declared finished (Table 4.1). [44, 42]

Structure

The rover was 1.6 m long with a width of 2.3 m. The total height of the robot was 1.5 m, and it had a total weight of 175 kg. It also had a robot arm with three instruments to remove rocks and brush surfaces. [39]

The core structure was made of composite material in a honeycomb setup, and the energy supply was realized by solar panels, with a total area of 1.3 m^2. The panels could

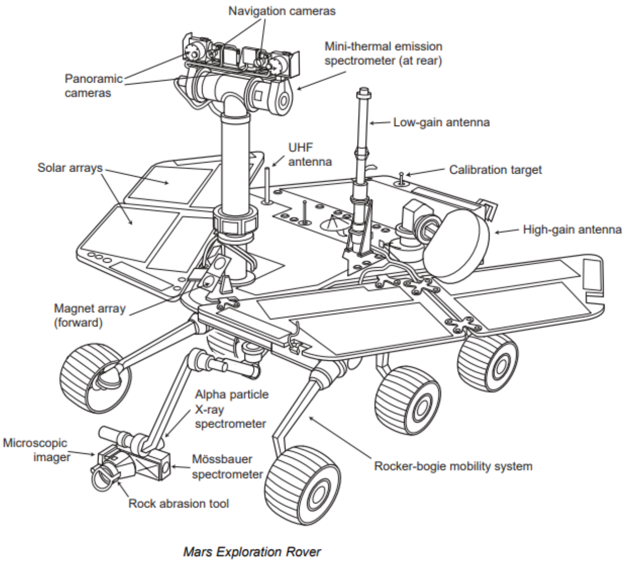


Figure 4.2: Structure of Spirit and Opportunity [39]

produce up to 900 Wh of energy by martian day. The rover also had six wheels (figure 4.2) and a special system for driving over relatively big rocks. Sensitive components such as the battery were stowed in a warmed box so that they survived the cold Martian nights. The rover was also equipped with a few cameras for navigation and collecting data. [38]

4.1.2 Curiosity

Curiosity (Figure 4.3) is the follow-up development of the rovers Spirit and Opportunity. The main mission is to deal with the question if there were ever viable conditions on Mars. Curiosity is especially looking for moist climatic conditions as well as rocks and minerals. The mission (Table 4.2) still continues today.

Unlike its predecessors, it does not use solar panels for power supply. Curiosity uses a Multi-Mission Radioisotope Thermoelectric Generator that provides about 2,700 Wh per sol (Martian day). [41, 40]

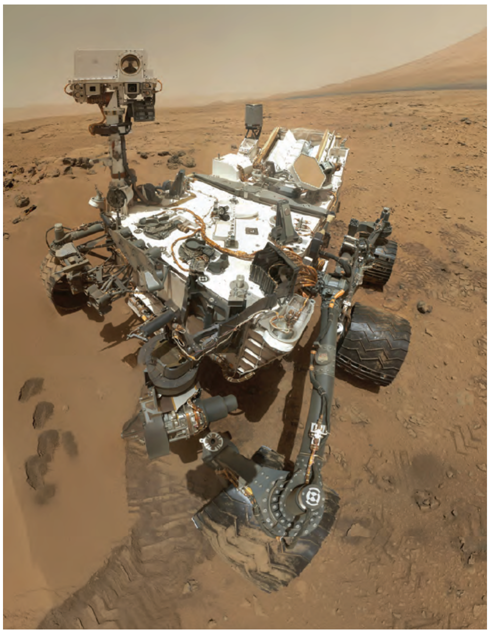


Figure 4.3: Curiosity [41]

Table 4.2: The Curiosity mission [41, 40]

Mission		Structure	
Launch	26th of October 2011	Length	3 m
Arrival	8th of August 2012	Width	2.8 m
Landing place	Gale Crater, Mars	High	2.1 m
		Mass	899 kg

The robotic arm is probably the most important tool for Curiosity. It is 2.1 m long and is constructed like a human arm to ensure maximum flexibility. The hand at the end is called turret (Figures 4.4 and 4.5) and has many functions. These include a drill, for collecting powdery rock samples, a brush, and a shovel (DRT) for collecting surface samples. Furthermore, an Alpha Particle X-ray Spectrometer (APXS) is used for the identification of chemical elements, and a subsystem named Collection and Handling for In-Situ Martian Rock Analysis (CHIMRA) that is used for sample processing, is located there. Another equipment is a camera called Mars Hand Lens Imager (MAHLI). With this, Curiosity can research the geological conditions on Mars. [41, 40]

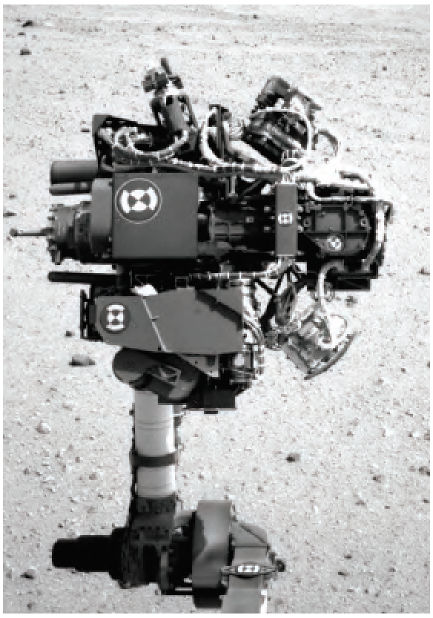


Figure 4.4: Curiosity´s turret [41]

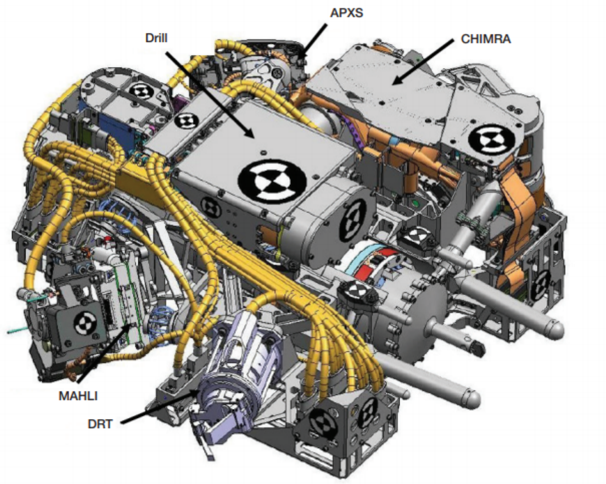


Figure 4.5: Structure of Curiosity´s turret [40]

4.1.3 Perseverance

Perseverance (figure 4.6) is the latest Mars rover landed on Mars. This mission can be divided into four goals, which are defined as follows.

- Determine whether life ever existed
- Characterize the climate
- Characterize the geology
- Prepare for human exploration

With its launch on the 31st of July 2020, Perseverance landed on the 18th of February 2021 in the Jezero Crater. With a length of 3 m, a width of 2.7 m, and a height of 2.2 m, it is quite similar in size to its predecessor Curiosity. Although in terms of weight, this rover is about 126 kilograms heavier (total 1025 kg). For its power supply, a Multi-Mission Radioisotope Thermoelectric Generator, like the last generation of Mars rovers, is used. [37, 32]

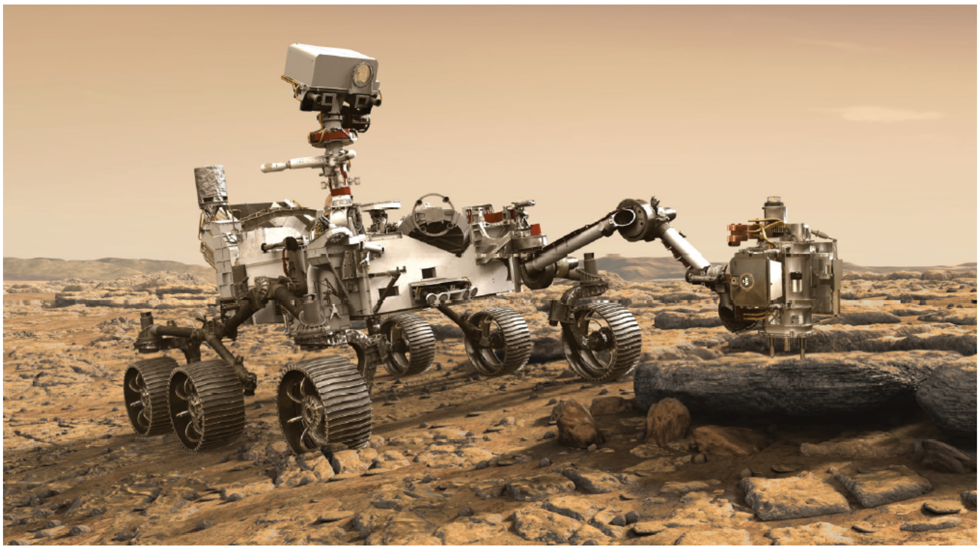


Figure 4.6: Perseverance [37]

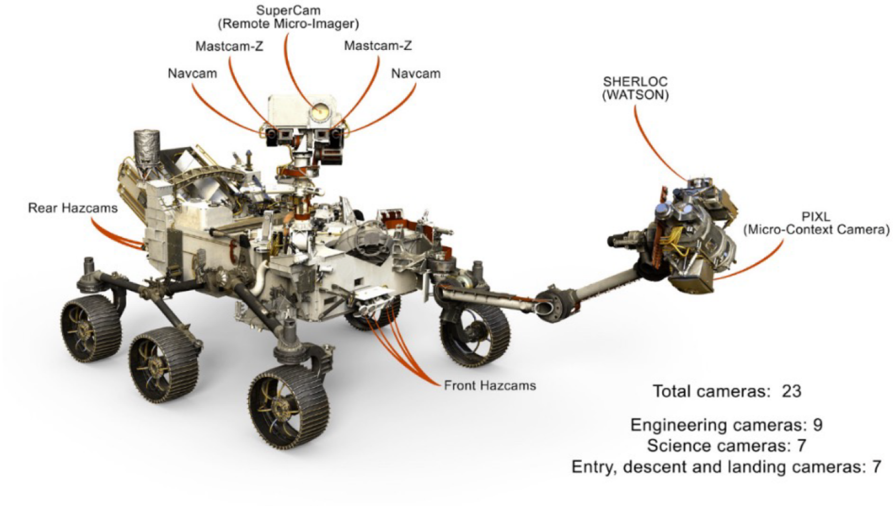


Figure 4.7: Perseverance and its cameras [37]

As can be seen in Figure 4.7, Perseverance has a total of 23 cameras for taking pictures and for orientation on Mars surface. Nineteen of them are located directly on the rover, three on the back shell, and one on the descent stage. There is also a lot of other scientific equipment for various purposes. In addition to its robot arm, it is also equipped with numerous sensors and detectors to examine every movement in the best possible way. [37, 32]

Ingenuity

The remarkable thing about this mission is that the Mars rover is hosted by a helicopter for the first time. This helicopter is called Ingenuity (Figure 4.8). Aside from its exploration mission, it is mainly used to plan the best route for the Mars rovers.

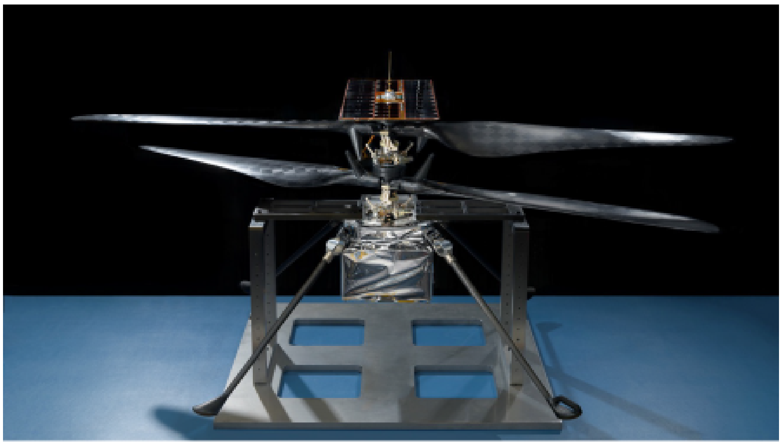


Figure 4.8: Ingenuity [37]

Ingenuity weighs 1.8 kg, is 0.49 m high and the span of its two pairs of rotors is 1.2 m. It is equipped with two different cameras, and it gets its energy from a solar panel that charges lithium-ion batteries With this power supply, it can fly 90 s per Martian day. [37]

4.2 NASA Rassor

The Regolith Advanced Surface Systems Operations Robot (RASSOR) Excavator is a robot, which should be used on the Moon to mine and transport regolith. It consists of four drums (Figure 4.9), which take up and store the regolith until it is dropped out at the unloading point. The mining takes place by rotating the drum in one direction and the discharge by changing the direction of the rotation. Therefore four drums are used so that the forces cancel each other out as good as possible. [36, 43, 53]

Figure 4.9: NASA Rassor [43]

The RASSOR should meet the following requirements:

- Mining of 700 kg regolith in 24 h
- Equipped with a camera
- Recharging its batteries at the lander
- Lifespan of minimum 5 years
- Ability to improve itself

[36]

The expected weight of the RASSOR will be about 100 lb which ensures 45 kg. But this low weight is also problematic because if the robot is lighter, the excavation process is more difficult. This is because the drums can not be pressed into the regolith with relatively high forces; the robot would lift itself while digging.

The robot is currently still in the planning phase; a start date is not known yet. [53]

5 Transportation Systems

In this chapter, lunar landers are described, which would be able to transport the mining and conveying unit to the Moon. Before the transportation from the Earth to the Moon starts, the mining and conveying unit is housed in the lunar lander until its arrival on the lunar surface. The whole lunar lander is a part of the launch vehicle. For illustration, the lunar lander of the mission Apollo 11 "Eagle" was placed in the tip of the rocket Saturn V. Launch vehicles consist of several stages; the majority of launch vehicles have three stages. After a certain amount of time after launch, the first stage gets disconnected from the rest of the vehicle. The other stages also disconnect from the vehicle until the lunar lander is close to the Moon. The remaining distance is covered by the lunar lander itself – until arrival at the lunar surface.

Commercial rocket launch companies are developing rapidly. Nowadays, there are already about 100 companies working on solutions for rocket launches, such as SpaceX or United Launch Alliance (ULA), a joint venture of Boeing Defense, Space and Security (BDS), and Lockheed Martin Space Systems. As an example, Figure 5.1 shows the rocket Vulcan Centaur, which is developed from ULA. The first launch of Vulcan Centaur is planned for June 2021. Soon, rocket launches are going to be different from them today: There will be launch providers with reusable first stage engine compartments, reusable first stages, and completely reusable two-stage launch vehicles. [12]

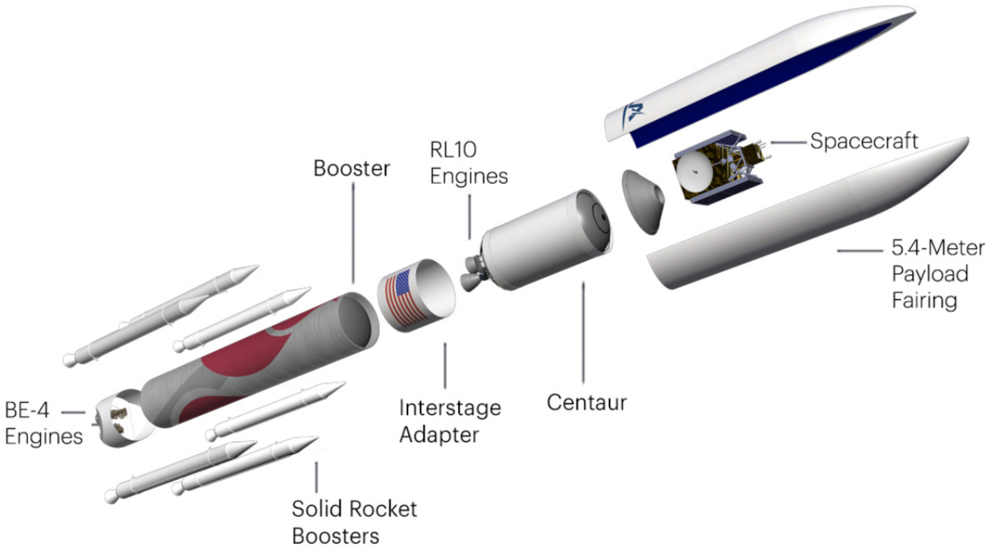


Figure 5.1: Vulcan Centaur [61]

5.1 European Large Logistics Lander (EL3)

The European Large Logistics Lander, which is shown in Figure 5.2, is a project of the European Space Agency (ESA). At this time, the EL3 is in an intensive study and development phase. If the project proves, it becomes a complete space project [14]

Although EL3 is not yet a full-fledged project, it is important for Europe to take part as an essential organization in various research topics related to the Moon. In particular, the goal of the Artemis program, which is a collaboration of ESA, the US government and NASA, is to bring people to the Moon in 2024, including the first woman ever.

As the name suggests, it is a lunar lander that is mainly developed to transport cargo. First, two payload options were approved: delivering logistics to support human expeditions on the lunar surface; and second, autonomous science missions without humans on board to return samples from the lunar soil. For the future, certain missions should be combined, like technology demonstration and cargo delivery. One main goal is to have a wide variety of mission, which can be done by EL3. Furthermore, EL3 is designed to survive the lunar night. [14]

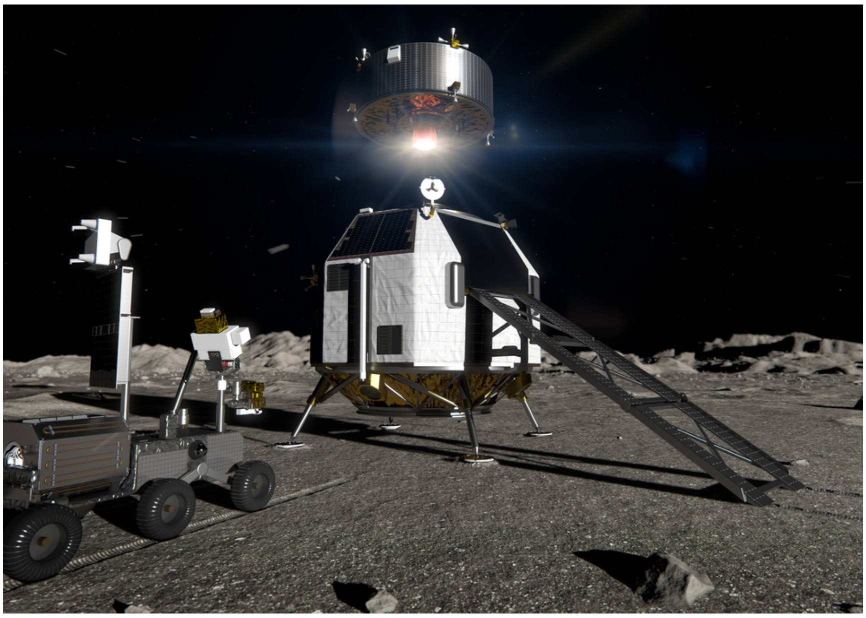


Figure 5.2: European Large Logistics Lander [14]

In the following, the essential properties of EL3 are listed [14]:

- Size: 4.5m in diameter, up to 6m tall
- Mass on Earth: 8500kg
- Mass of delivered cargo: 1500kg
- Mission types: cargo, science rover, in-situ resources, and more
- Launcher: Ariane 64
- Launch Site: Kourou, French Guiana

5.2 NASA Lunar Lander

The NASA Lunar Lander (Figure 5.3) is a pallet concept to transport mainly robotic mobility systems, like rovers, to the lunar surface. The design is not complete and several subassemblies are at different levels of development.[28]

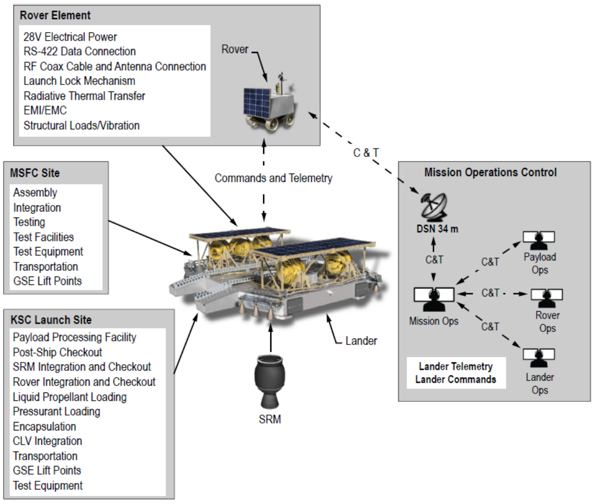


Figure 5.3: NASA Lunar Lander [28]

This lander will deliver medium-sized payloads, up to 300 kg, to the polar regions of the Moon. Shortly after the landing, power will be provided to the payload by the lunar lander. Additionally, this lunar lander is not able to survive the lunar night. One essential target in the development amongst others was to design a lander that is simple and affordable. So the requirements were set to a minimum. In other words, the main parameters risk, mass, and performance were weighed lower than cost. [28]

5.3 Peregrine

Peregrine is a lunar lander from the company Astrobotic. In general, Astrobotic is a company, which works in the field of lunar logistics and provides delivery services from the Earth to the Moon. Figure 5.4 shows the lunar lander. [2]

The maximum payload delivery capacity is 100 kg. Peregrine is designed for a surface mission duration of 192 h. Almost every kind of payload is able to get to the lunar surface with Peregrine. 1 W power and 10 kbps bandwidth per kilogram is provided

Figure 5.4: Peregrine [2]

for the payload by this lunar lander. From the lunar poles to the lunar equator – Peregrine can bring payloads to several locations on the Moon. Like the NASA lunar lander, Peregrine flies the missions autonomously, in other words, without humans on board. [2]

Astrorobotic already offers commercial cargo flights to the lunar orbit and lunar surface for various institutions, for instance, governments, companies, individuals, and universities. Transportation of the payload to the lunar orbit costs $300,000 per kilogram, delivery to the lunar surface $1,200,000 per kilogram. In addition, for mobility on the lunar surface, every customer can book a delivery rover, which transports a certain payload to the target location. [2]

5.4 Starship

Starship is a spacecraft system of the company SpaceX, which was founded by Elon Musk. It is a two-stage vehicle, composed of the "Super Heavy" rocket as the launch vehicle and the spacecraft called Starship. The whole system is a completely reusable delivery system for missions to the Moon and Mars as well as for Earth orbit delivery missions. As shown in Figure 5.5, both types of missions, crewed and uncrewed, are possible with the different configuration types of the Starship. [56]

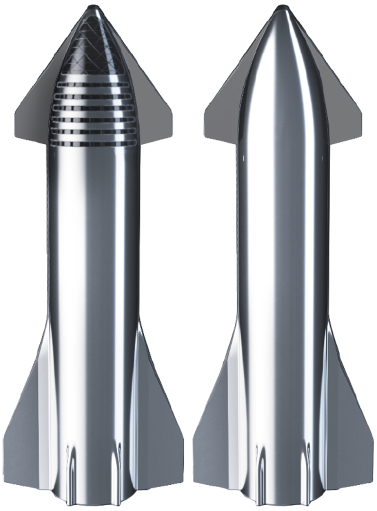


Figure 5.5: Crew configuration (left) and uncrewed configuration (right) [56]

Starship can do a wide variety of transportation missions without humans in the spacecraft. It has the ability to deliver satellites, cargo, large observatories, refueling tanks, and many more. This spacecraft has the capability to transport more than 100 t of cargo to the Moon and Mars fully autonomously. Additionally, this system is available to transport cargo from one location on Earth to another location on Earth very quickly. Figure 5.6 illustrates the dimensions of the Starship payload volume. [56]

Moreover, another target of the Starship design, among others, is to make life multi-planetary. So, the crew configuration of the Starship can transport up to 100 people from Earth to the Moon and Mars. [56]

According to SpaceX vice president of commercial sales, Jonathan Hofeller, launching satellites by 2021 is the firm's goal. There are two launch sites: Kennedy Space Center, and Boca Chica launch pad. [56, 33]

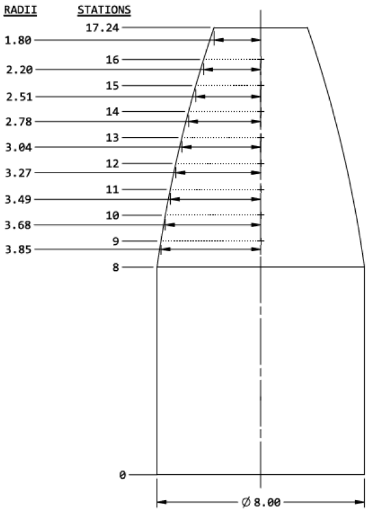


Figure 5.6: Starship payload volume [56]

5.5 Blue Moon

Blue Moon (Figure 5.7) is a lander from the company Blue Origin. The founder of Blue Origin is Jeff Bezos, who also founded Amazon. This lunar lander also has two configurations: as a fully autonomous cargo lander and as a human landing system. Blue Moon can be launched with multiple launch vehicles, for instance, Blue Origin's New Glenn, or the Vulcan Centaur from the company ULA. [7]

Figure 5.7: Blue Moon [7]

This lander has a 23 ft (about 7 m) payload bay, which provides much space for the cargo. The bay stays about 4 m above the ground on the four landing legs. Blue Moon weighs about 16.5 t in total, with the maximum amount of fuel and cargo. It is possible to load about 4.5 t of payload into the lander. [16]

Furthermore, Blue Moon is capable of conducting different types of missions, such as science, in-situ resource utilization, and infrastructure development missions. The unloading system of the lunar lander uses a crane to drop off certain payloads. This davit system is able to drop up to four lunar rovers onto the lunar surface simultaneously. Also, cargo missions with the Blue Moon lander will be available for different institutions, like universities, government, and commercial customers. [7, 16]

6 Design Materials

In this chapter, the requirements for the design materials, and which materials are suitable for the excavation and conveying system, are discussed.

The harsh lunar environment leads to a variety of requirements for the design materials. The following essential factors lead to large differences in material requirements between terrestrial and lunar applications:

- Temperature
- Radiation
- Atmosphere and Pressure
- Meteorites
- Gravity
- The length of the lunar day
- Dust
- Electromagnetism

Especially the points Pressure, Temperature, and Electromagnetism are essential in terms of mechanical equipment/materials. [20]

The low pressure on the Moon leads to outgassing effects in the design materials. Outgassing is the release of molecules into a vacuum, which were closed on or in a material. Outgassing can occur in different types of mechanisms: desorption, evaporation, and diffusion. This (in this particular case) negative process often appears with polymeric materials. As a result, outgassing cause structure distortion, change in properties, loss of dimension stability, loss of mass, and surface contamination. On the Apollo 8 mission, for example, the silicone rubber seals of the observation window were outgassed during the first lunar orbital flight. Subsequently, the large window was contaminated, and the astronauts couldn't take pictures and videos from this window and had to use another one. [1, 13, 23]

Another important difference among others is the temperature. One lunar day lasts for about 28 Earth days, including about 14 Earth days of lunar night and 14 Earth days of the lunar day. Due to the thin atmosphere and the long days/nights, the temperature has a large variation of approximately 140 K in the equatorial zone of the Moon. Therefore, the design materials for lunar missions must have high thermal resistance. Also, the thermal expansion of the design materials must be taken into account, as the thermal expansion can lead to problems, e.g. with bearings or seals. [20]

If lunar mission objects rove on the lunar surface, charge differences relative to the lunar surface occur. The reason for this is an additional charge source: triboelectric charging. Triboelectric charging appears at the regolith-wheel junction. Atmospheric static discharge is not possible due to the lack of atmosphere. Moreover, dust with an electrostatic charge has a high tendency to adhere to exposed surfaces. For instance, the adhesion of lunar dust could be the reason for a not feasible lunar mission. Dust adhesion to solar panels on the moon can decrease the efficiency of the solar panels. [8, 21]

In table 6.1, some materials, which are possible for lunar applications, are compared. [63]

Aluminium is one of the most commercial structure material in aerospace application. It has a low density relative to steel and low costs in fabrication. Furthermore, there is a large variety of aluminium alloys, so this material has a broad range of essential properties. [63]

Table 6.1: Design materials for lunar applications [63]

Material	Density [kg/dm3]	Melting Point [°C]	Thermal Expansion [10-6/K]	Youngs' Modulus [GPa]
Aluminium	2.7	660	23.8	71
Beryllium	1.7	1287	11	293
Titanium	4.5	1668	8.2	108
Steel	7.85	900-1500	11-13	210
CFRP	1.6	-	0.2	140

Although pure beryllium does not fit the requirements of space applications, beryllium-aluminium alloys are some of the rare light metals with a high melting point, relatively high strength, and high ductility. It is used particularly in space and aircraft applications. [54]

Titanium is a high-strength structural material, characterised by good stiffness, lightweight, and high-temperature capabilities. Similar to aluminium, there is a variety of alloys with titanium, so the properties are also different depending on the alloy. Drawbacks are the high costs and difficulties to manufacture, especially welding. [63]

Steel is the material with the broadest range of applications in all areas of technology. Specific alloys, such as stainless steel, which are appropriate for lunar missions, are also possible for lunar systems.

Carbon fibre reinforced plastic (CFRP) is also appropriate for lunar missions. It has high strength and high stiffness with the graphite fibres. In addition, it is a lightweight material. The properties, especially stiffness and strength, are depending on the direction of the fibres. The main disadvantages are outgassing and complicated manufacturing. [65]

7 Task Definition and Boundary Conditions

In this chapter, the task and the boundary conditions are defined. Some of the boundary conditions are considered rather as a recommendation or as an additional (nice-to-have) aspect, since especially the maximum weight can only be achieved by ultralight construction.

7.1 Task

The task of this thesis is to conceptualize and design a conveyor system for the use on the Moon. The main focus of the thesis is on the mechanical functionality of the conveyor system. The thesis should contain a content research, different conveyor concepts, a design proposal with the focus on the mechanical functionality, and further steps that still have to be done to make the conveyor system applicable for lunar applications. The conveying material is lunar regolith.

In the beginning, a literature review should be conducted to define the requirements for the conveyor system. After the literature research, several different basic conveying principles will be identified with their advantages and disadvantages. Based on this, a discussion should be held and a decision made as to which conveying principle has the greatest potential for use on the Moon. After that, the main assemblies of the conveyor system should be defined, and for each assembly again concepts should be presented with advantages and disadvantages with a final discussion to determine again the concept with the greatest potential. In the next step, the conveyor system should be designed and the functionality of the system should be explained. It should also be considered that the conveyor system has to work directly and interact with an excavator, which is also designed for lunar use, in order to realize the mining and conveying of lunar regolith. This excavator was designed within the master thesis of Dominik Höber 'Development of an Excavation Concept for Lunar Regolith'. Finally, further necessary development steps should be explained, which are necessary for the application on the Moon.

7.2 Boundary Conditions

Initially, the maximum dimensions and weight of the system are specified. In chapter 5, several lunar landers, which can deliver both units to the lunar surface, are described. These transportation systems are either built by commercial companies (i.e. Blue Moon, SpaceX) or space agencies, such as NASA or ESA. Although there are only a few lunar landers offering a delivery service to the moon compared to terrestrial delivery services, there is a wide variety of maximum weights and maximum dimensions of the payload compartment of the transporters. To illustrate, SpaceX's Starship will deliver a maximum weight of about 100 t, whereas the maximum payload delivery capacity of Astrobotic's Peregrine is 100 kg. After studying various lunar landers in Chapter 5, ESA's European Large Logistics Lander (EL3) is defined as the delivery unit for the two systems. EL3 has a maximum payload capacity of 1.5 t. The maximum weight of the excavation- and conveying system is respectively about 750 kg, or 1.5 t in total, so both systems can be transported to the moon simultaneously. The maximum dimensions of each system are 6 m in length, 4 m in width, and 2 m in height.

Furthermore, the volume flow rate is also defined. The first step is the search for the annually required oxygen mass. About 10,000 kg of oxygen is needed for initial human lunar missions. Additionally, the same amount of oxygen is required for two launches from the lunar surface. Assuming the least efficient oxygen extraction method, a volume of 660 m^3 is required, which corresponds to an area with the size of 8,250 m^2 (about one soccer field) excavated 8 cm deep. As a result, the mining target is set to 2 m^3 per Earth day (equals 0.083 m^3/h). [49, 50]

Ending of the fundamental chapters

The following chapters are the main part of this thesis and were worked out and developed completely independently by Andreas Taschner.

8 Conveying principles

In order to meet the requirements of the ISRU-chain, conveying regolith between certain points is essential. The distance over which the material has to be transported is crucial for the decision of a suitable conveying unit. Regolith has to be transported between each step: from the mining area to a temporary storage facility, on to the beneficiation plant, and finally to the processing plant. Further, delivery distances differ significantly. The distance from the mining unit to the storage is many times larger than the distance within the Moon base between the beneficiation and the processing unit. As a result, for these different requirements, different conveying technologies are necessary. In this master thesis, the focus is on conveying technologies for long transportation distances. In the next sections, several topics are described. First, problems and challenges of the lunar environment are introduced, then various concepts are presented including advantages and drawbacks, and finally, the different concepts are discussed and the concept which has the highest potential is selected.

8.1 Problems

Although the conveyor technology is well developed for Earth applications, there are completely different requirements for conveying on the Moon, which can be challenging and lead to major problems.

First of all, there are several reasons why regolith is probably cohesive. The lower gravitational forces on the particles cause an accumulation of the material and the bulk behavior appear more cohesive. Furthermore, the lunar regolith contains a large proportion of fine particulates. As a consequence, cohesion increases more than other forces that influence material behavior. Additionally, the lunar atmosphere with its hard vacuum has left the lunar soil more chemically reactive. As a result, the surface energy is higher than in terrestrial operations. Moreover, the lack of aerodynamic forces leads to a large inter particular cohesion, which is a main difference between lunar and terrestrial bulk material behavior. [62]

Secondly, regolith is sharp and abrasive which can lead to major problems at open joints or bearings. In particular, the fine fraction of the lunar soil is a problem for joints at the machine. Similarly, the abrasiveness of lunar regolith causes high friction and wear on parts that are in direct contact with regolith. For example, rovers that transport the mined material to the base suffer under the abrasiveness of regolith because they have to cover large distances from the mining side to the lunar base. This phenomenon popped up at the Mars rover called Curiosity which can be seen in Figure 8.1. [27]

Figure 8.1: Wheel damage on Curiosity [27]

Thirdly, the excavation unit would excavate the top centimeters of the lunar soil, so the mining machine is mobile and changes its location after the specific area has been excavated. Subsequently, the conveying unit must be also mobile. However, the majority of conveyors that are well known in terrestrial operations, for instance, belt conveyors, have a fixed conveying path. So the beginning and the end of the conveyor are at a fixed position and can only be changed with a large effort. [19]

Lastly, in the initial step of conveying regolith on the Moon, no human is on the Moon. As a result, the conveying unit has to work completely autonomous from the moment it arrives at the lunar surface. For example, there are no mechanics on the Moon who assemble the different parts of the machine; rather, the machine must be ready for operation without human assistance upon arrival. Additionally, there will be no maintenance support on the Moon, so the machine has to be designed that only minor issues can occur while conveying, otherwise the machine loses its function and cannot convey any further material. Furthermore, the dimensions of the conveying unit are limited by the fact that the payload capacity of a specific lander is also finite. [19]

8.2 Functional principles

In this section, various concepts are described including conveyors which are already well known in terrestrial operations. The function of the concept is briefly outlined as well as advantages and drawbacks are listed.

8.2.1 Lunar trucks

Trucks are applicable for delivering raw material on the Moon. Similar to the skips in the terrestrial mining industry, the discharge skip of the lunar truck is filled with raw materials, afterward, the material is transported by the lunar truck and finally, the truck unloads the transported material at a desired location, for example in front of the beneficiation process building. In detail, the truck can be loaded directly at the excavator by using a transfer chute, and when unloading, the truck tilts the discharge skip so that the raw material is moved into a bunker. Figure 8.2 illustrates a draft of a lunar truck.

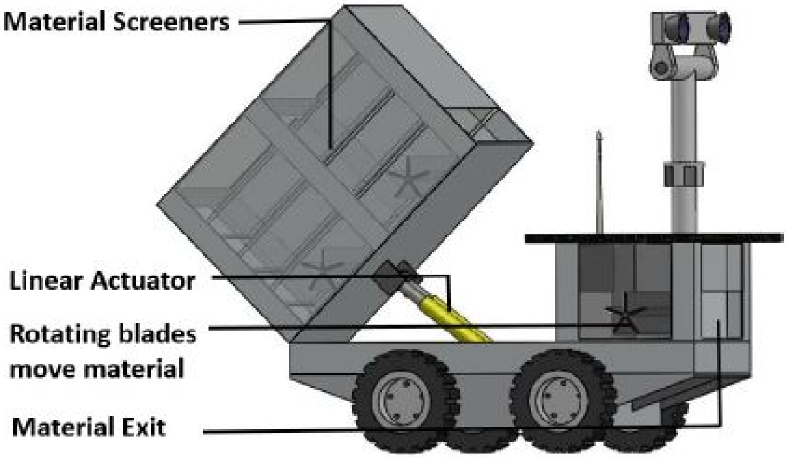


Figure 8.2: Regolith Processing Rover [22]

Advantages

- High mobility and flexibility
- Easy scalable
- Comparable known solution on Earth

Disadvantages

- Limited range
- Relatively low speed
- Less efficient
- Small-medium payload capacity
- Wheel damage will occur due to abrasive lunar regolith

8.2.2 Belt conveyor

In general, the belt conveyor is the most commonly used conveyor and is applicable in almost any industry, such as the food industry or the mining industry. Belt conveyors are continuous conveyors that have high productivity compared to energy consumption. They can transport bulk material or general cargo over a long or short distance and they are mostly used as stationary conveyors. [46]

Advantages

- Continuous transport
- High payload capacity and high mass flow rate
- energy efficient
- Comparable known solutions on Earth

Disadvantages

- No or almost no mobility or flexibility
- Large mass
- Many moving parts, for instance, idlers
- Difficult to implement on the Moon, as this system should be usable without human intervention after landing

One idea is to combine the two previously mentioned concepts, rover and conveyor belt. It could be designed as a continuous haulage system. Conveyor belts with a limited conveying distance are mounted on a chassis. Several of these systems could be positioned in one path, thus forming a longer conveying distance. Figure 8.3 shows a comparable solution on Earth that is already in use. This application still has some disadvantages, such as the large mass of the system.

Figure 8.3: FCT flexible conveyor train from the company Komatsu [24]

8.2.3 Tubular drag and trough chain conveyor

Tubular drag conveyors (Figure 8.4) consist generally of a closed pipe in which the chain including the carriers is driven. The chain with the flights, which are about the same size as the circular cross-section of the pipe, transports the bulk material in horizontal, slightly inclined, but also in steep and vertical direction. This type of conveyor is only suitable for bulk material and is frequently used for granular material like grains. [57]

Similar to the tubular drag conveyor, trough chain conveyors also have carriers that are mounted on the chain which is the traction device. This system is enclosed with metal sheets except for the feeding and the discharging point. The main difference to the tubular drag conveyor is the different shapes of the carriers. The carriers (Figure 8.5) convey the material forward. Generally, trough chain conveyors are used for granular and powdery bulk material.

Advantages

- Continuous conveying systems
- Easy to automate
- 3-dimensional conveying path possible

Disadvantages

- High friction and wear between bulk material and vonveyor parts
- Low flexibility
- Large mass
- Many moving parts
- Only short conveying distances possible

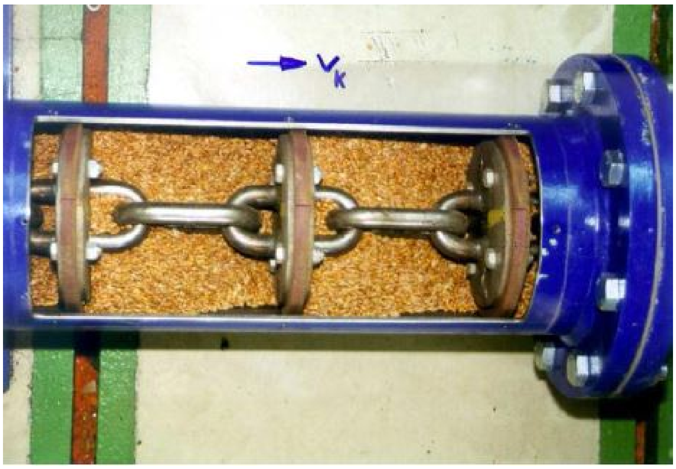


Figure 8.4: Tubular drag conveyor [57]

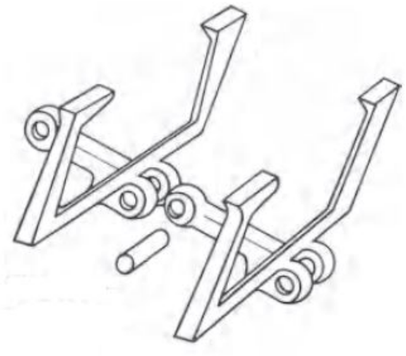


Figure 8.5: Carriers of a trough conveyor [46]

8.2.4 Flexible screw conveyor

Screw conveyors are among the oldest systems of conveying. Archimedes described the principle more than 2000 years ago and used it in the form of a water pump. The conveying element corresponds to a full or interrupted screw surface, which is turned around its axis and pushes the material to be conveyed forward into a trough or pipe.

Flexible screw conveyors consist of a band screw that has no shaft. Therefore the screw can be used in curved pipes. The screw is guided over the inner wall of the pipe. Figure 8.6 shows different screws one with a shaft and one without a shaft. [57, 46]

Advantages

- Continuous conveying systems
- Easy to automate
- 3-dimensional conveying path possible

Disadvantages

- High friction and wear between bulk material and conveyor parts
- Only short conveying distances possible

Figure 8.6: Different types of screws [52]

8.2.5 Vibratory conveyor

Vibratory conveyors are very robust and low-maintenance conveying systems for the horizontal, inclined, or vertical transport of bulk materials of various grain sizes. The stiff conveyor trough of the vibratory conveyors is set into stationary oscillations by a drive system, which transfers mass forces to the conveyed material during the trough suspension and moves it forward during the trough return. In general, vibratory conveyors can be divided into 2 categories, depending on their work principle: shaking trough (Figure 8.7 (a)) and vibrating trough (Figure 8.7 (b)). [57, 46]

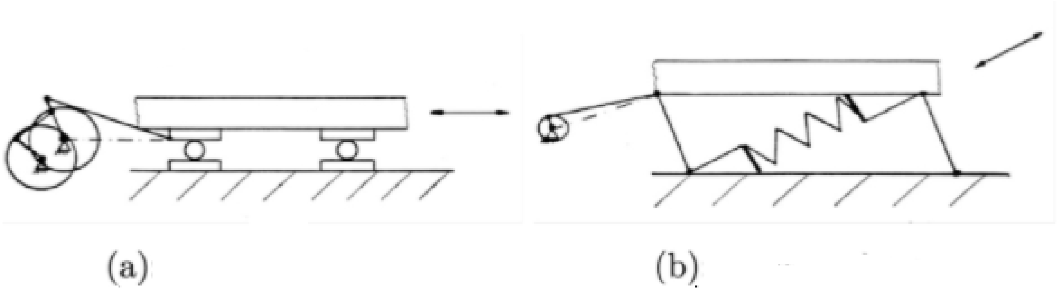


Figure 8.7: Different working principles of vibrating conveyors [46]

Advantages

- Continuous conveying system
- Easy to automate
- combination of conveying and separation technique applicable

Disadvantages

- large mass
- Only short conveying distances possible

8.2.6 Mobile system on rails

An alternative approach is to use mobile systems on rails. The elevated track, on which the carriers convey the material, reduces regolith stirring. As a result, less friction and wear occur at the railroad assemblies and therefore, it is a reliable system for conveying materials across the Moon. Furthermore, the power supply and the navigation are easier to implement. The railroad system will be an effective transportation system for long-distance transportation of raw materials. It is suitable for large quantities, long distances, and at high speeds. Figure 8.8 shows an approach for an elevated railway. [27, 51]

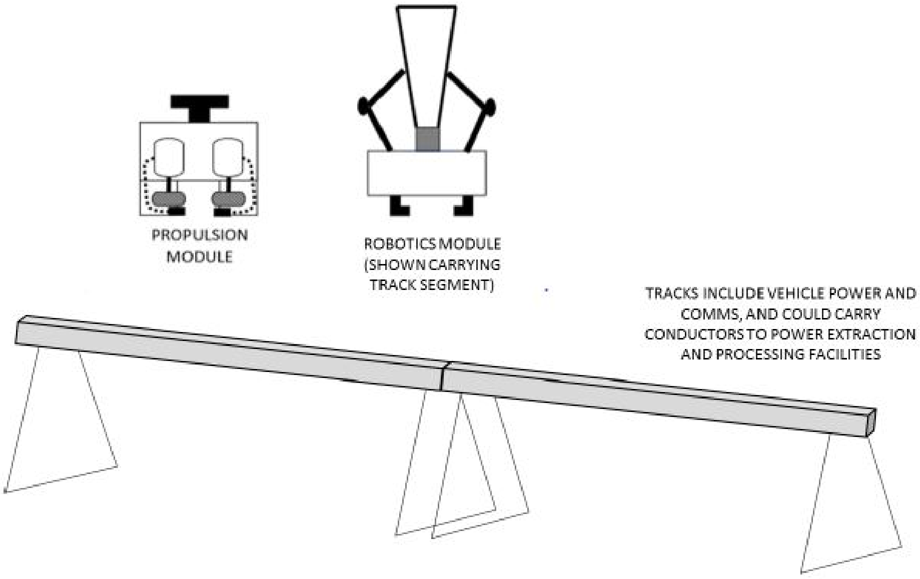


Figure 8.8: Elevated track for long-term transportation [27]

Advantages

- Conveying track has no contact with lunar soil leading to less wear
- Semi-flexible conveying path is possible (mobile supports)
- High payload capacity
- Carriers without wheels are possible, due to low gravity
- Navigation is easy to implement

Disadvantages

- Infrastructure is required
- Maintenance and wear protection is necessary at the contact surfaces
- Large mass of the whole system

Concepts for railway solutions are briefly described.

Telescopic railway rover

The rover has two operation modes: One when the rover drives and gets to the desired place (Figure 8.9) and the other when its rails are extended and the rover stands still (Figure 8.10). When the rover stands still, it is ready that the carriers convey raw materials on its rails. Many telescopic railway rovers in a row can build a conveying path. In addition, the conveying path is completely flexible, because each rover can navigate on its own. In comparison, commercial railway solutions are completely inflexible on Earth. Nevertheless, there are some drawbacks. Many rovers are necessary for a long conveying path. Furthermore, it is difficult to automate all rovers, so that they work on their own without disturbances.

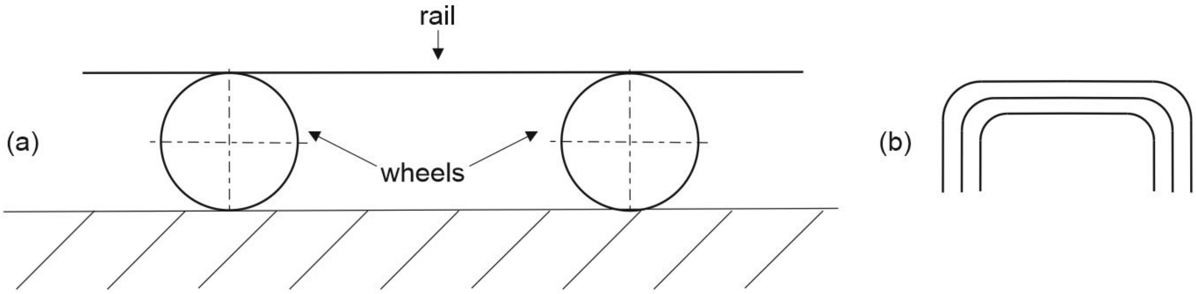


Figure 8.9: (a) Telescopic railway rover in mobile mode; (b) cross-section of the rails

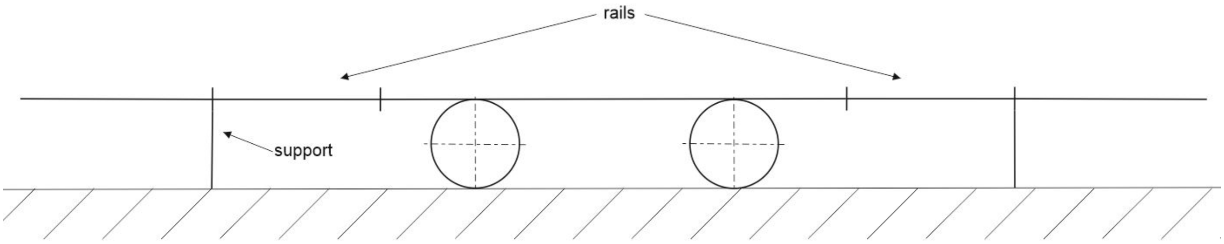


Figure 8.10: Telescopic railway rover in working mode

Track-laying vehicle

This concept is shown in Figure 8.11. Similar to a certain military vehicle, this vehicle lays the rails on the ground, forming a transport route for other carriers. Subsequently, the conveying path is also flexible. Another advantage over the telescopic railway rover is that this solution does not require as many rovers as the telescopic rover solution. Thus, the track-laying vehicle is not as flexible as the telescopic railway rover. Moreover, it is difficult to implement elevated rails.

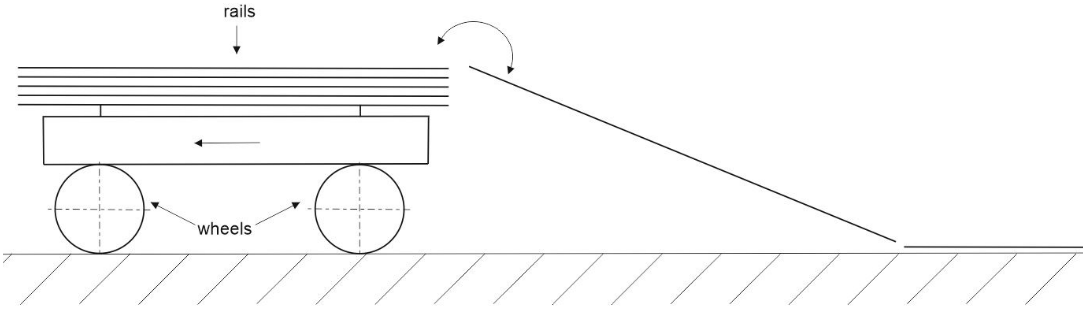


Figure 8.11: Track-laying vehicle

Flexible railroad

The flexible railroad system is elevated by mobile supports. Therefore, the conveying path is flexible and the whole system is mobile. Figure 8.12 shows a system that is already developed for applications on Earth and is usually used as a logistic conveyor. The conveying path consists of a scissor system. Pulling leads to lengthening of the conveyor and pushing leads to shorten. Besides, the conveyor can convey around curves. The scissor system is susceptible to dust, so it is difficult for this system to work safely without maintenance.

Figure 8.12: Scissor roller conveyor [48]

8.2.7 Ropeway conveyor

Ropeways are a well-known solution on Earth, both for passenger and cargo transport. In general, a ropeway connects two locations by a single rope. This rope circulates between the two locations and is supported by a certain number of masts that are built at specific intervals. Carriers are attached to the rope which holds and conveys the raw material. Furthermore, at one or both ends of the ropeway, there are electric motors mounted which provide the required force to drive the rope. [58]

Advantages

- Low maintenance effort
- High payload capacity
- Energy efficient
- Easy to automate
- Comparable known solution on Earth

Disadvantages

- Infrastructure is necessary
- Inefficient for small workload
- The mass of the rope would lead to a major problem

8.2.8 Pneumatic conveyor

On Earth, pneumatic conveyors are usually used to transfer dry, bulk granular materials along a pipeline by the mineral and chemical industries. The necessary energy for material transport is provided by a storage of compressed gas. Pneumatic conveying systems for material transport within a lunar production plant are already in the testing phase. In particular, the system was tested at a low gravity flight. (the airplane flies within a specific path so that the low gravity level is realized). Besides, the pneumatic conveying technology can be used for transporting raw materials over long distances, for example, from the mining side to the production plant. Thus, several problems will occur for long conveying distances. There is an essential difference to the mechanical conveyors: This approach has no moving parts which can lose their functionality due to lunar dust. Moreover, this technology can be coupled with a gas classifier. As a result, the pneumatic conveyor can be used as a conveyor and as a separator. Figure 8.13 shows an illustration of how a pneumatic conveyor could be realized on the Moon. [51, 31]

Advantages

- No mechanical parts, which can be damaged by lunar dust
- Reusable gas with appropriate lifecycle
- Low maintenance effort
- Low friction of raw materials within the transportation pipe
- No dust development

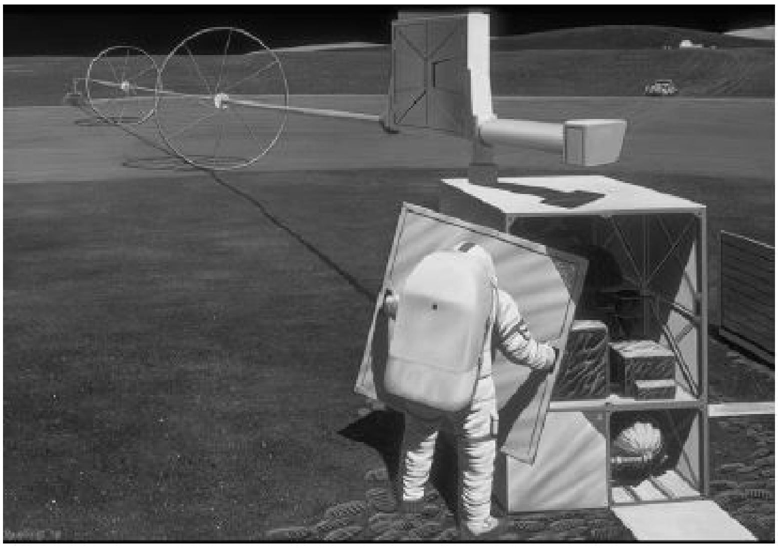


Figure 8.13: Approach of a pneumatic conveyor in the future [51]

Disadvantages

- Generally complex system
- Difficult to protect the system from leaks and escaping gas
- Temperature fluctuations will lead to several essential problems with the transport gas

8.2.9 Electromagnetic conveyor

The problem with the lunar dust could be overcome by utilizing its ferromagnetic properties. It should be possible to suck up the regolith using magnetic forces. One proposal is the Lunar Soil Magnetic Collector (LSMAC), shown in Figure 8.14. The most essential parts of this conveyor are the wound coils. The coils are controlled individually to generate magnetic fields in sequence. The regolith is picked up with the front coil and gets through it due to the magnetic potential. Afterward, the front coil is powered down and the next coil is powered up to attract the material. Powering down the coil before and powering up the next coil leads to a "caterpillar" effect, transporting the material along the electromagnetic conveyor. [51, 3]

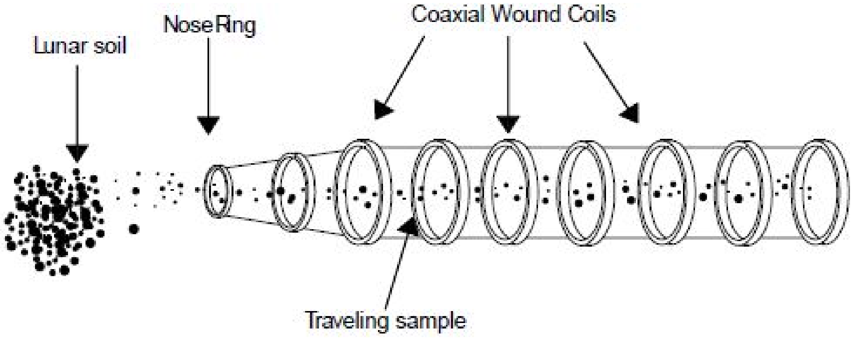


Figure 8.14: Electromagnetic conveyor [3]

Advantages

- No dust development
- Low maintenance
- No friction and wear between regolith and the conveying system
- No mechanical parts
- Long conveying distances are possible

Disadvantages

- Magnetic fields have to be strong enough
- Sufficient speed to carry regolith
- All chemical propositions which are contained in regolith are not conveyable

8.2.10 Ballistic conveyor

Technology that was used by the Romans to hurl stones or flaming missiles over enemy fortifications, can also be used for material transport on the Moon. Such a system can be implemented for conveying raw materials from the mining side to the production plant. In addition, it would be possible to throw the raw materials from the ground of a crater to the lunar surface. Although ballistic conveying systems are not often used for terrestrial operations, there are several reasons that this technology can work on the Moon. The gravity is only 1/6 compared to the Earth, so the thrown material can cover a larger conveying distance. Furthermore, there will not be air resistance on the lunar surface and there are no weather hazards too. In Figure 8.15 you can see an illustration of a ballistic conveying concept. [51]

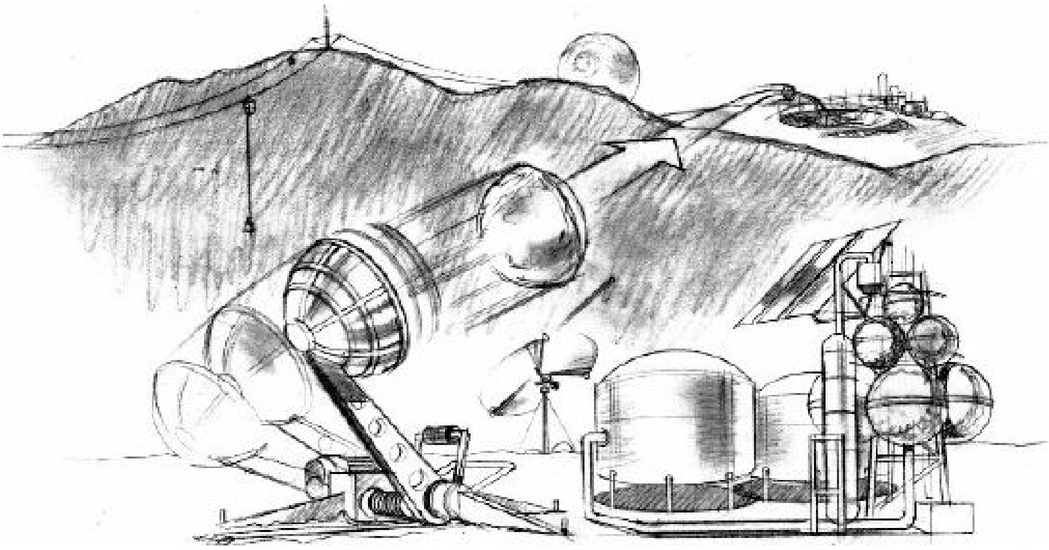


Figure 8.15: Concept for a ballistic conveyor [51]

Advantages

- Large conveying distances are possible due to low gravity and no air resistance
- Flexibility, usable at different locations because a mobile design is realizable
- Only a few moving parts
- Cohesiveness of regolith is an advantage for throwing

Disadvantages

- Difficult to automate, especially that regolith arrives at the desired place

8.2.11 Discussion

In general, rovers would meet most requirements on the Moon and there are already comparable known solutions on Earth. Thus, there is one main disadvantage among others, such as the relatively low speed and energy consumption: maintenance would be necessary, especially on the wheels of the rover due to the abrasive lunar regolith. As a result, the rover is not able to operate fully autonomously for an extended period of time which makes the rover as a conveying system unsuitable over long distances. Moreover, the navigation and the automation of the rover are more difficult compared to other conveyors, for example, railway systems or belt conveyors. Nonetheless, they are flexible, so they can fulfill individual missions

When it comes to belt conveyors, they are also commonly used on Earth. They are easy to automate, have a high payload capacity, and energy-efficient. Despite the mentioned advantages of belt conveyors, they have crucial disadvantages, for instance, no flexibility and they are difficult to implement as a fully autonomous conveyor. Another approach is to combine both rovers and belt conveyors, but they would be really difficult to automate and has also a large mass. These drawbacks are the cause that these concepts will have difficulties working on the Moon. Nevertheless, they can be advantageous when it comes to transport a large amount of raw material between two stationary process plants over a short distance.

Tubular drag, chain trough, vibratory, and flexible screw conveyors have almost the same advantages and drawbacks, with the main disadvantage of short conveying distances. Long conveying distances require are powerful engine and the equipment would have a high mass. Another crucial drawback is the high friction and wear between the conveyor and the abrasive lunar regolith. So, similar to rovers, there will occur maintenance problems, since maintenance would be difficult to realize. These conveyors are not feasible with respect to the long conveying distance, however, they have the capability to feed other systems like storages. Furthermore, vibratory systems are applicable to discharge processes, due to the cohesion of the lunar regolith. Additionally, they can be used for dosage tasks on the Moon, such as conveying a certain amount of material in a process chamber.

Alternatively, a railway system for conveying tasks on the Moon is also practicable. Different railway concepts are described in section 8.2.6 Even though the railway systems on Earth are stationary, a quasi-dynamic solution is possible for lunar applications, but it is difficult to realize. Since the excavating machine always changes its location, it may not be completely stationary. Compared to other conveyors, such as the tubular drag conveyor mentioned before, there is no relative velocity between the transported raw material and the conveyor, because the raw material is in carriers that are guided over rails, resulting in less friction and wear. Moreover, the lower gravity on the Moon compared to Earth causes less frictional forces between the rails and carriers. Though, there are some significant drawbacks. The complex infrastructure which is necessary has a large mass, therefore, it is difficult to transport it to the Moon. Furthermore, it is challenging to implement this transportation system without human assistance. In addition, the desired flexibility is not achieved with this concept. Similar to belt conveyors, they can be implemented as conveyors between stationary lunar bases.

Likewise, transportation systems based on ropeways have almost the same benefits and drawbacks as railway approaches. The main difference between ropeway and railway is the system of how it works: in the case of ropeway conveyors, the carriers are attached to a rope and the rope is driven by an engine. Nevertheless, ropeway systems have similar major drawbacks: the infrastructure and equipment needed have a large mass and the whole system has insufficient flexibility.

Another proposal is a pneumatic conveyor. Compared to the other conveyors, the pneumatic transportation system works in a completely different way resulting in divergent advantages and disadvantages. Unlike other conveyors, the pneumatic conveyor has not any mechanical parts, which are in contact with lunar regolith, leading to friction, wear, and a higher failure probability. Only a low level of friction will occur between the transportation pipe and the raw material. Additionally, there is no dust generation due to the conveyance of the material within the pipe. However, there are critical disadvantages which cause that this system is not feasible as a flexible conveying system. Undoubtedly, the hard vacuum on the Moon is the most challenging boundary condition, because a transport gas is necessary for the system. As a result, leaks in the system cause a complete failure of the whole system.

Electromagnetic conveyor systems are also suitable for lunar applications. They also contain no moving mechanical parts. In addition, there is no dust generation, no friction between raw material and conveying system, resulting in low maintenance effort. Nonetheless, this system cannot convey every fraction present in the lunar regolith. Regolith contains materials, that are not attracted by magnetic forces, therefore, they cannot be conveyed by this system.

Although ballistic conveying systems are barely used on Earth, for instance in woodchip machines, they have some significant benefits regarding lunar conveying applications. Basically, the low gravity and the thin atmosphere are major difficulties for almost every conveying system mentioned so far, but in the case of ballistic conveying, they are advantageous, allowing a long conveying distance to be covered. Besides, this system can transport the raw materials over topological hurdles, such as craters or big rocks, which is not possible with another presented conveying system. Furthermore, it has a few moving parts and a mobile or flexible design of the system is feasible. Moreover, the cohesiveness of regolith is a challenge for the majority of the introduced transportation systems, however, for this system, the cohesiveness is an advantage because it requires that the thrown bulk material is held together during the flight phase. The difficulty of the system is automating the throwing process so that the conveyed material arrives at the desired location.

Finally, one system is selected from those presented. The conveyor system with the highest potential is the ballistic conveying system. The benefits outweigh the disadvantage of this system completely. Even though ballistic conveyors are not often used for terrestrial transportation tasks, they have some unique advantages which can be used on the Moon.

9 Concepts for the ballistic conveying system

Generally, based on the basic principle chosen in chapter 8, in this chapter the development of a design concept for a conveying unit is presented. The following subsections consist of the different main assemblies which contain several basic concepts, and the discussion and decision which works best for the required environment. The first subchapter contains the ballistic acceleration principles. The ballistic acceleration system is the main drive of the conveyor. Afterward, different swivel mechanisms for the drive are presented. Lastly, different machine loading systems are explained.

Basically, some clarifications must be made to avoid significant misunderstandings. The final design is not a complete, fully detailed mechanical design. All parts are designed without topological aeronautical optimizations and without other optimization, for instance, finite element analysis or mass optimization. Purchased parts, like linear cylinders, which are used in the design, are commercial parts for terrestrial applications. Consequently, these parts must also be adapted for deployment on the Moon. In addition, automatization of the machine, such as remote control, is not examined and developed within this thesis. Furthermore, this design is one approach that can work on the Moon for a certain type of operation with predefined requirements. For example, for subsurface mining, a completely different conveying machine could be beneficial compared to this proposal or when humans are settled on the Moon, there could be also another machine advantageous, because maintenance is available with humans on the Moon.

9.1 Ballistic acceleration principles

In this subsection principles for the drive of the machine are described with advantages and disadvantages, followed by a discussion of which principle fits the requirements best.

9.1.1 Blast wheel

The blast wheel principle (shown in Figure 9.1) is used in terrestrial units, for instance, wood chip machines or mobile harvesters. The wheel is driven by an engine and rotates at a constant velocity. Regolith flows into the inlet of the blast wheel and is afterward accelerated by the blades attached to the blast wheel. Finally, the material leaves the spinning wheel and is directed into a tube that has a specific shape to achieve the desired trajectory.

Advantages

- Continuous motion
- Continuous volume flow rate
- No loss energy

Disadvantages

- High friction and wear
- Large dust generation
- Relative velocity between the conveyor and conveyed material

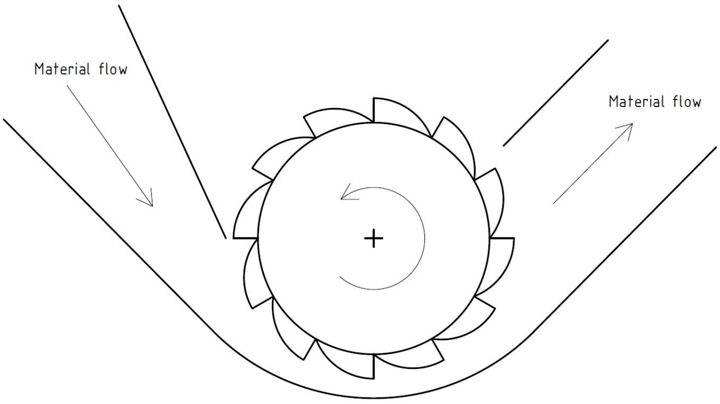


Figure 9.1: Blast wheel

9.1.2 Cylinder-piston system

The piston rod is mounted on the crankshaft. The crankshaft rotates continuously resulting that the piston oscillates within the cylinder. When lunar regolith is filled into the cylinder, the piston accelerates the raw material and throws it away. Finally, new regolith is filled in the cylinder and the process starts again. Figure 9.2 illustrates this working principle.

Advantages

- Continuous motion
- No loss energy

Disadvantages

- High friction and wear
- Large dust generation
- Relative velocity between the conveyor and conveyed material
- Filling process would be complex
- Difficult to control
- Sinusoidal acceleration, but linear acceleration is desired

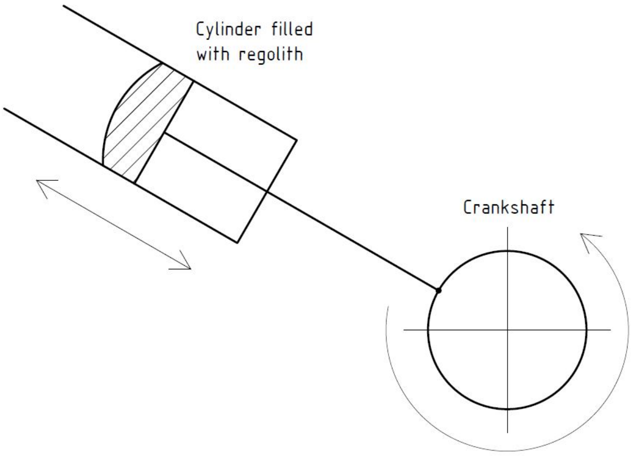


Figure 9.2: Cylinder-piston system

9.1.3 Rotational slingshot with cylinder

The slingshot is at one end attached to a rotational joint and on the other end, there is a bucket where the conveying material is placed. Further, a linear cylinder is connected to the slingshot. When regolith was filled into the bucket, the cylinder accelerates the slingshot and the slingshot rotates around the joint until the cylinder stops the rotation due to its size limitation. As a result, lunar regolith leaves the bucket and flies to the desired location. Basically, various arrangements of the cylinder are possible. Using an intelligent arrangement of the cylinder is beneficial to exploit the leverage effect and thus quickly accelerate the material to be transported. Figure 9.3 and Figure 9.4 show different examples of the scheme.

Advantages

- Low friction and wear
- Less dust generation compared to blast wheel
- No relative velocity between the conveyor and conveyed material
- Filling process is simple

Disadvantages

- Discontinuous motion
- Loss of energy due to abrupt deceleration
- High stress on parts because of quick acceleration and deceleration

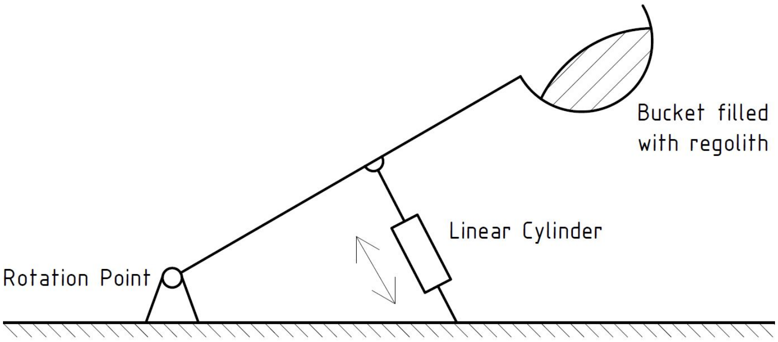


Figure 9.3: Slingshot example 1

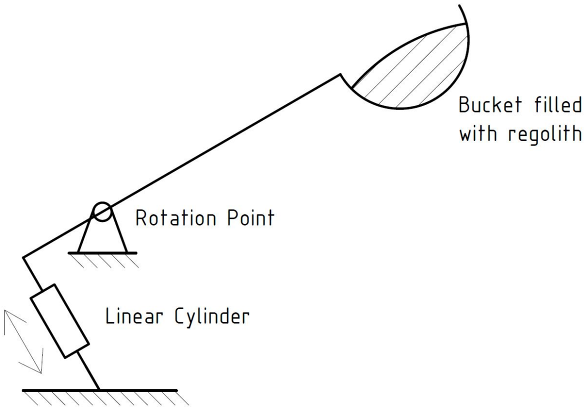


Figure 9.4: Slingshot example 2

9.1.4 Rotational slingshot

This concept (represented in Figure 9.5) is similar to the previously mentioned concept, but there is a significant difference. No linear cylinder is applied for generating velocity. Instead, a drive at the rotation point is used to achieve the required acceleration. Moreover, the slingshot is able to rotate several cycles, to reach a satisfying velocity, before it is slowed down instantly. Another proposal is to apply a torsion spring that is pre-tensioned with a drive. However, the filling process is almost the same as at the rotational slingshot with a cylinder. Generally, this type of slingshot has the same benefits and drawbacks as the previously mentioned principle.

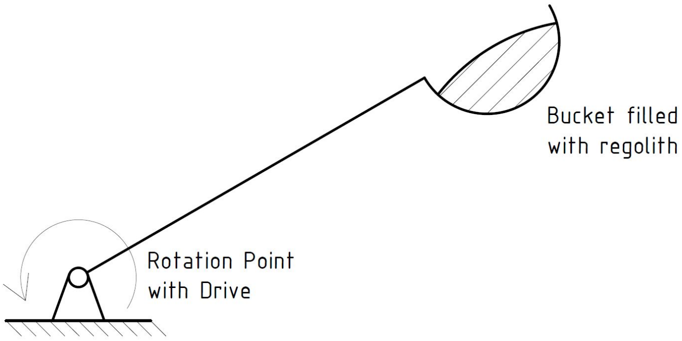


Figure 9.5: Rotational slingshot

9.1.5 Bucket wheel

Basically, the bucket wheel (Figure 9.6) consists of a center wheel where the buckets are attached. Each bucket is filled with raw material. Further, the wheel rotates and thus the buckets are rotating around the center. When the acceleration of a bucket is sufficient, its bottom opens in a certain position, resulting in the release of the raw material. Subsequently, regolith flies to the desired location.

Advantages

- Barely relative velocity between conveyor and material
- Continuous motion
- Low dust development

Disadvantages

- Many moving parts

- In general complex system and complicated filling process is necessary
- Difficult to control

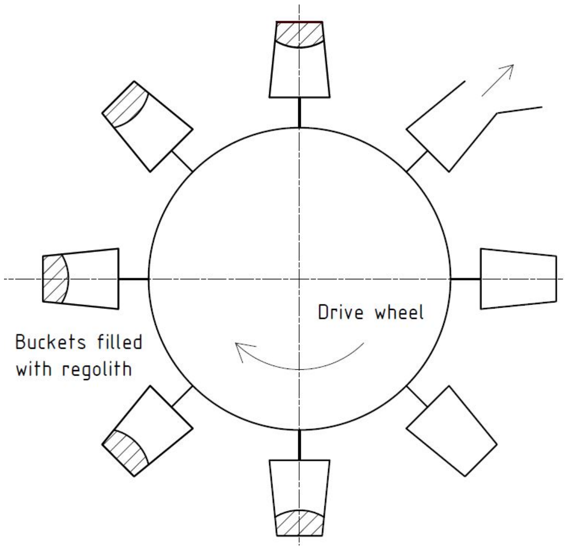


Figure 9.6: Bucket wheel

9.1.6 Acceleration wheel with pre-tensioned spring

In the case of this scheme (Figure 9.7), also a driven wheel is applied for continuous motion. Additionally, at the outer radius of the wheel, a spring is attached to that wheel. The other end of the spring is mounted at a fixed point. Consequently, when the wheel is rotating counterclockwise continuously, the spring is pre-tensioned between the bottom and top position of the attachment point. Afterward, when the attachment point reaches the top, the spring accelerates the wheel with the saved potential energy instantly. This acceleration causes regolith to be thrown away.

Advantages

- Continuous motion combined with a large acceleration
- Barely relative velocity between conveyor and material
- Low dust development

- Low friction and wear

Disadvantages

- Special spring material, which fits the requirements of the lunar environment, is necessary
- Complicated system required to disconnect drive and wheel during the acceleration phase
- The driven wheel must also be accelerated
- Complex filling process

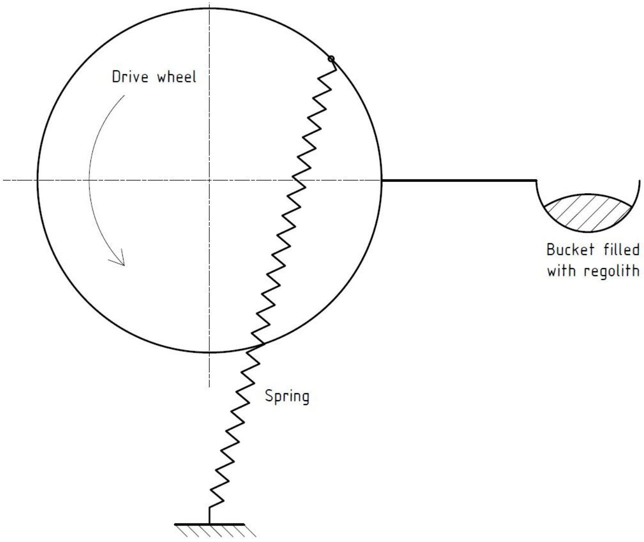


Figure 9.7: Acceleration wheel with pre-tensioned spring

9.1.7 Four-bar linkage

The four-bar linkage is an already well-known principle. It must be adapted for use in the lunar conveying unit. In one joint, a bucket is mounted to deposit regolith in it. Furthermore, the drive of the system has to be adjustable to achieve different levels of accelerations. During the filling process, the velocity is slowed down, and when it is desired to throw regolith to a certain location, the drive accelerates the bucket quickly. Figure 9.8 illustrates the adapted four-bar linkage.

Advantages

- Basically continuous motion
- Barely relative velocity between conveyor and material

Disadvantages

- Many moving parts with joints
- Complex filling process

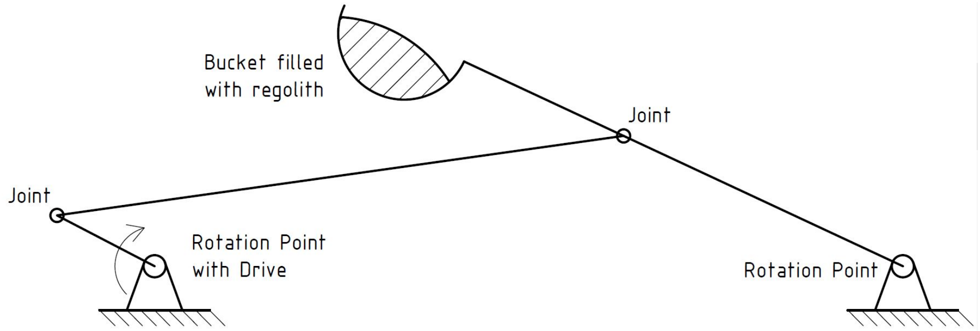


Figure 9.8: Four-bar linkage

9.1.8 Spring drive with toothed rack

Figure 9.9 shows the work cycle of this approach. The main part is first the spring drive. The gear is connected to a rack that preloads the springs of the drive. Above the rack is a bucket in which the regolith is deposited. The working cycle operates as follows: First (Figure 9.9 (a)), regolith is filled into the bucket, the gear wheel rotates constantly and manipulates the rack, which results in tensioned springs. Second (Figure 9.9 (b)), one half of the gear is without teeth, so when the last tooth leaves the rack, the tensioned springs can release their stored energy and abruptly accelerate the material being conveyed. Finally (Figure 9.9 (c)) the springs are unstressed again and the operation starts again.

Advantages

- Constant working cycle
- Barely relative velocity between conveyor and material
- Low dust generation
- Large accelerations are feasible compared to other drive concepts

Disadvantages

- Special spring material, which fits the requirements of the lunar environment, is necessary
- Gear and rack must be protected, otherwise, they will wear out under the abrasive regolith

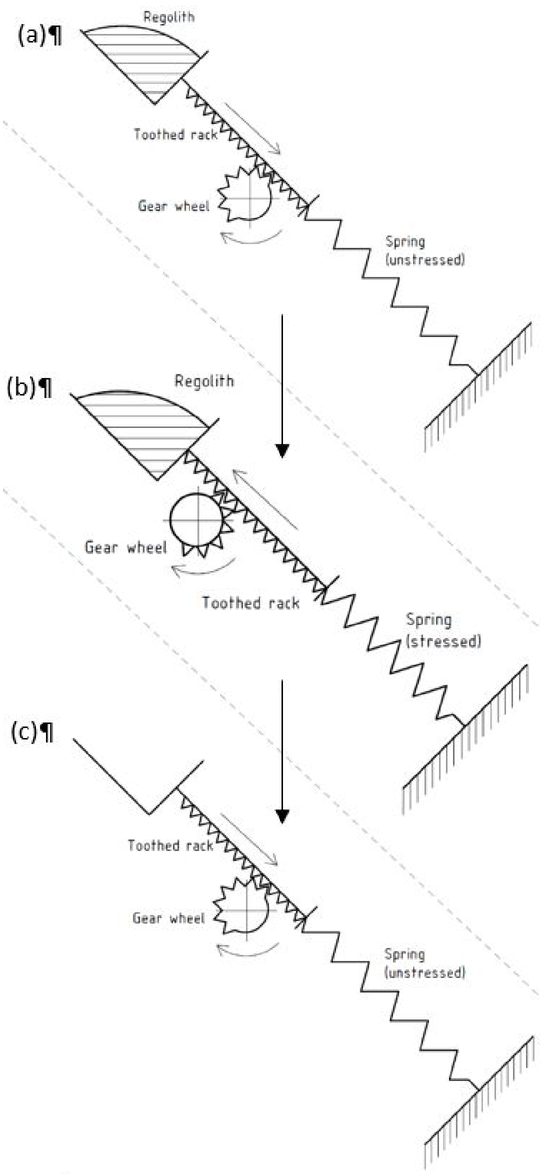


Figure 9.9: Spring drive with toothed rack

9.1.9 Spring drive with a linear cylinder

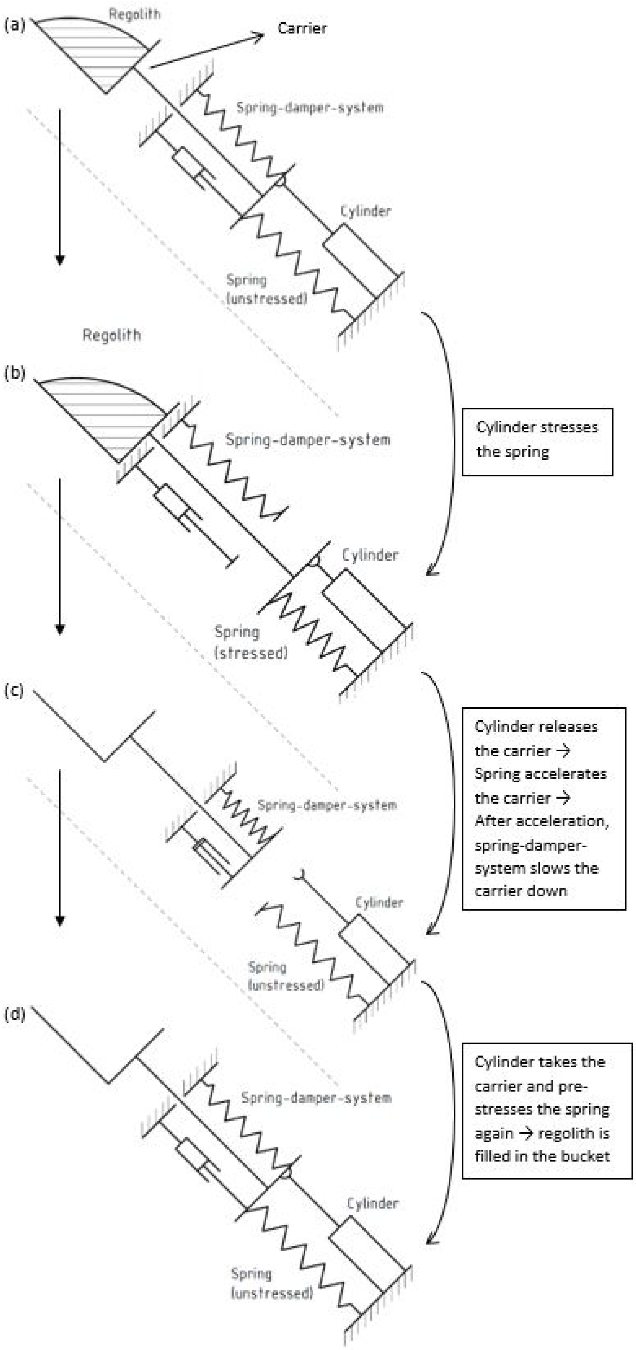
The basic structure of this concept is similar to the spring drive with a toothed rack. However, the spring drive is pre-tensioned by a linear cylinder. In addition, a spring-damper system is implemented to decelerate the throwing assembly. The operating principle is illustrated in Figure 9.10. In the initial step, regolith is deposited in the bucket (Figure 9.10 (a)). Second, the linear cylinder stresses the spring drive via a plate (Figure 9.10 (b)). Third, the linear cylinder release the throwing assembly, and the stored potential energy of the springs accelerates the throwing assembly instantly (Figure 9.10 (c)). After a certain distance, the throwing assembly is slowed down by the spring-damper system (Figure 9.10 (d)). Lastly, when the throwing assembly is decelerated, the linear cylinder connects to the pre-tensioning plate again and regolith is filled in the bucket.

Advantages

- Constant working cycle
- Barely relative velocity between conveyor and material
- Low dust generation
- Large accelerations are feasible compared to other drive concepts

Disadvantages

- Special spring material, which fits the requirements of the lunar environment, is necessary
- Gear and rack must be protected, otherwise, they will wear out under the abrasive regolith



Cylinder stresses the spring

Cylinder releases the carrier → Spring accelerates the carrier → After acceleration, spring-damper-system slows the carrier down

Cylinder takes the carrier and pre-stresses the spring again → regolith is filled in the bucket

Figure 9.10: Spring drive with a linear cylinder

9.1.10 Discussion

In this subsection, the advantages, and disadvantages of the concepts are discussed as well as they are compared with each other.

To start with, regolith is an abrasive material with a sharp morphology resulting in friction and wear when the material has contact with mechanical parts. Especially, when there is a relative velocity between the conveyor surfaces that transports or accelerates the material and the material itself, the level of friction and wear increases sharply. Therefore, concepts, where this problem occurs, are not suitable due to maintenance demand after a short operation time. The blast wheel and the cylinder-piston system have a substantial relative velocity between the conveyor and conveyed material. Conversely, all other concepts do not have this problem in general because regolith is filled in the buckets when the conveyor is not in motion, and regolith is accelerated by the gravitational force leading to low velocities. So, the relative velocity is slow compared to the blast wheel. As a consequence, the blast wheel and the cylinder-piston concept are not suitable for the mentioned requirements, and they are not considered further.

Furthermore, it can be distinguished between two basic working principles from the ancients: the ballista (Figure 9.11 (a)), and the catapult (Figure 9.11 (b)). Originally, they were used to shoot projectiles, such as stones or arrows, at enemies during war. The catapult accelerates rotational, whereas the ballista accelerates linearly. Due to the rotational acceleration in the case of the catapult, the particles have different velocities depending on their position in the bucket. In addition, the launch angle and direction are simpler to set with the ballista than with the catapult. Therefore, compared to the catapult, it is less complicated to predict the trajectory as well as to change between different targets. Consequently, concepts based on the ballista principle are preferred. The rotational slingshot with and without cylinder, the bucket wheel, the acceleration wheel with pre-tensioned spring, and the four-bar linkage system are based on the catapult working principle. As a result, these concepts are no longer considered.

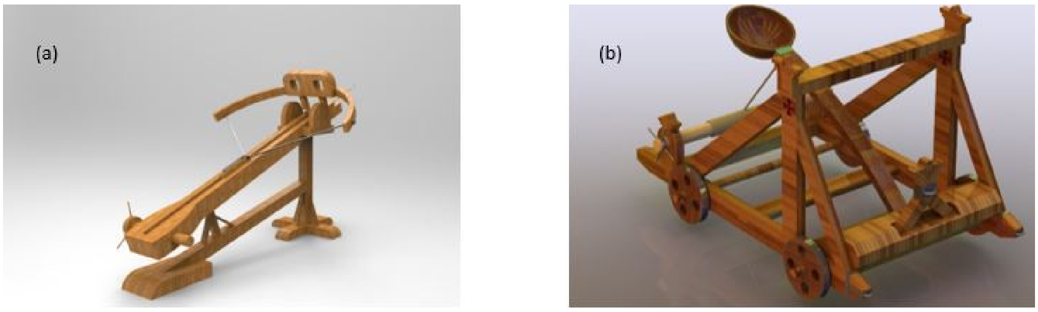


Figure 9.11: (a) Ballista [6], (b) Catapult [9]

Two proposals are remaining: spring drive with a toothed rack and spring drive with a linear cylinder. They are similar concepts with minor differences. Nevertheless, the toothed rack and the gear wheel are more difficult to protect against lunar dust than the linear cylinder. Moreover, the force that pre-tensions the spring drive is adaptable in the case of the linear cylinder, whereas the pre-tension force is defined by the diameter and the number of teeth of the gear wheel leading to a non-customizable force at the other concept. The adaptable force is a significant benefit to adjust the throwing distance. For example, when the system operates closer to the deposition target, the pre-tensioning force can be simply reduced or vice versa by the linear cylinder. As a result, the spring drive with a linear cylinder is the concept that is considered for further development.

9.2 Swivel mechanism

This subchapter first describes how the conveyor machine aims and must therefore swivel. Then, principles for the swivel mechanism of the conveyor are described with advantages and disadvantages, followed by a discussion of which principle fits the requirements best.

The target of the conveyed material, where the material arrives after the ballistic acceleration, is static, therefore, the shooting direction of the drive must be necessarily adaptable. For clarification, drive means the ballistic acceleration system. Besides, the excavation unit is constantly moving during excavation and the conveying unit has to work simultaneously. That is another reason for the adaptability of the alignment of the conveying machine. Initially, the conveying unit does not have its own chassis, though, it is mounted directly on the excavation unit. Consequently, the conveyor drive must be realigned for each shot, even if the changes are marginal. Importantly, the control and automatization of the realignment of the conveyor machine is not part of this thesis but is feasible. The proof that it is feasible is the control of the firing system of a tank. Tanks can accurately aim and hit their targets even when moving at high speed.

Regarding the excavation unit, the conveyor is attached to the part of the excavation unit oriented to the target of the ballistic conveyor. This means that the conveyor does not have to shoot over the excavator. In addition, the maximum throw distance is achieved at an angle of 45° to the ground. However, the angle to the ground must be adjustable (rotation around the x-axis) in order to realign, since the excavator does not stand level every time due to the unevenness of the lunar surface. Consequently, the following angular ranges are determined where the drive must be able to swivel: from 30° to 60° rotatable around the x-axis and from -90° to 90° degrees swivelable around the z-axis. The angular ranges are illustrated in Figure 9.12.

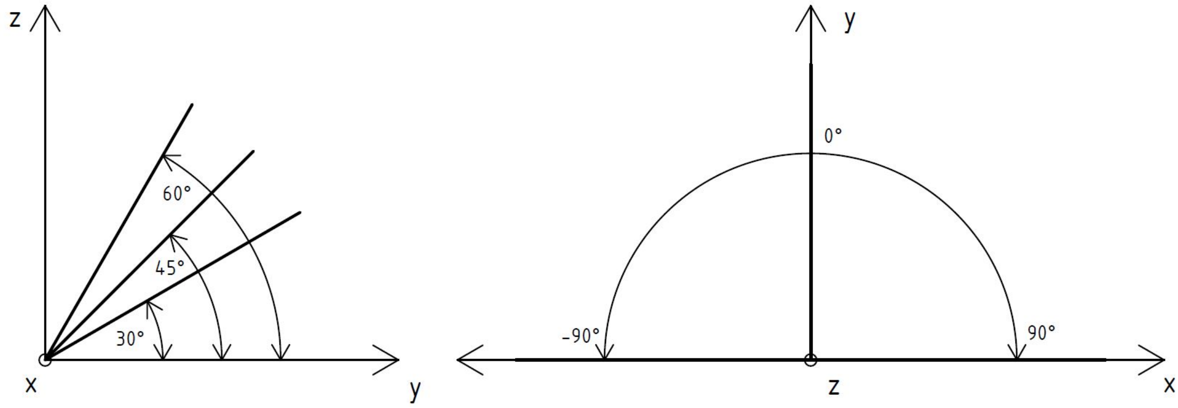


Figure 9.12: Angular ranges

9.2.1 Rope or cylinder

The swivel mechanism can be realized with a rope or a linear cylinder. Figure 9.13 shows the rope approach and Figure 9.14 shows the principle with the linear cylinder. Both concepts are responsible for the rotation around the x-axis. According to the rope principle, the rope is wounded on a rope drum and the other end of the rope is mounted on the drive assembly of the conveyor. The drive assembly is installed on a rotational joint, so it can fulfill the adaptations of the launch angle. If the drive has to adjust the shooting direction, in other words, change the launch angle, the rope drum must either release the rope or wind it up, depending on whether the weft angle has to increase or decrease.

In the case of the linear cylinder approach, the swivel mechanism is similar. Instead of the rope, the linear cylinder regulates the launch angle, but the drive assembly is also mounted on a rotational joint. Rather than the rope being wound up or released, the cylinder extends or retracts.

Advantages

- Simple working principle
- Few moving parts

Disadvantages

- No fixation in the case of the rope concept (rope can only absorb tensile forces)
- Large space required
- Complex attachment of the rope drum or the fixed point of the cylinder is necessary, because of the rotation of the drive around the z-axis. If the drive must be swiveled around the z-axis, these fixed points must also move, or the rope must be redirected (otherwise collision with drive)

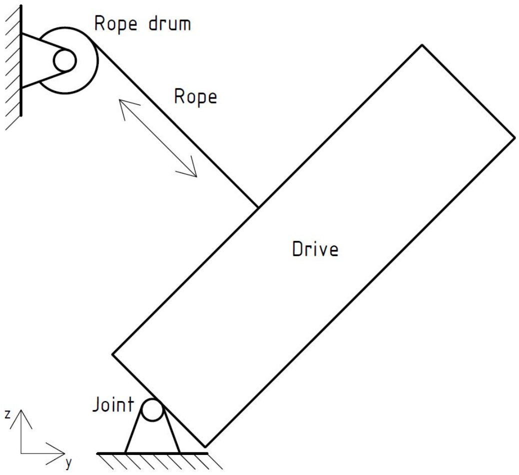


Figure 9.13: Rope

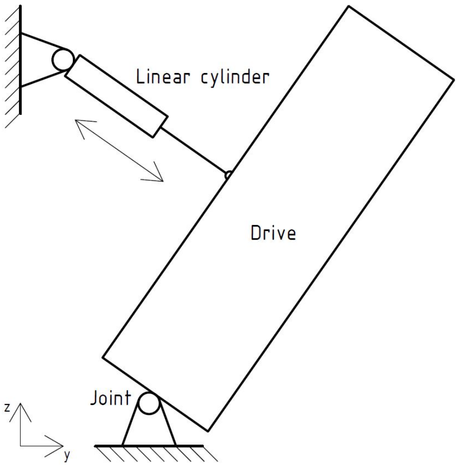


Figure 9.14: Cylinder

9.2.2 Worm gear

The worm gear concept (Figure 9.15) is another approach for swiveling around the x-axis. Through the rotation of the worm shaft the worm wheel, which is installed on the drive assembly, rotates and as a result, the drive assembly changes the launch angle. The worm shaft can be driven by an electric motor.

Advantages

- Precise adjustability of the launch angle
- Small space required
- Compatibility with swivel system around z-axis realizable

Disadvantages

- Sensitive to dirt and dust; must be protected against dust
- Center of gravity of the drive assembly far from the rotation pint

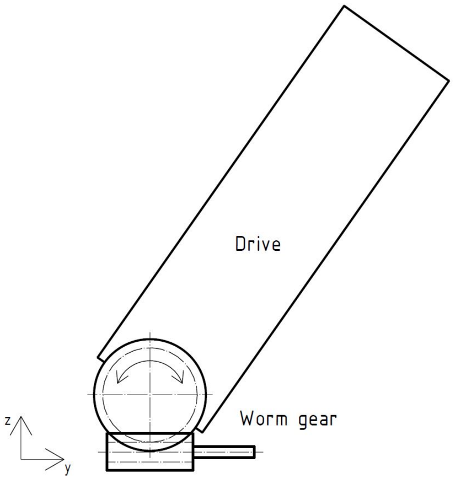


Figure 9.15: Worm gear

9.2.3 Curved telescopic cylinder

This concept is based on a curved cylinder. The curved cylinder is also an approach for swiveling around the x-axis. Figure 9.16 illustrates the principle. The working operation is similar to the concept with the linear cylinder, but with the crucial difference of the cylinder itself. The cylinder is curved and not linear. Extending or retracting the piston changes the launch angle of the drive assembly.

Advantages

- Simple working principle
- Few moving parts

Disadvantages

- Large space required

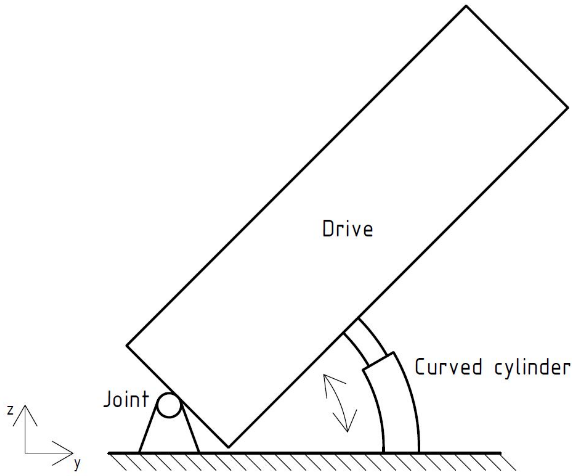


Figure 9.16: Curved cylinder

9.2.4 Linear cylinder

The linear cylinder concept, shown in Figure 9.17, is a concept for swiveling around the z-axis. The drive assembly is placed on a disk. This wheel is connected with the linear cylinder and this linear cylinder is responsible for swiveling the drive assembly or the disk around the z-axis.

Advantages

- Simple working principle
- Few moving parts

Disadvantages

- Difficult to realize for a degree range from 0° to 180°

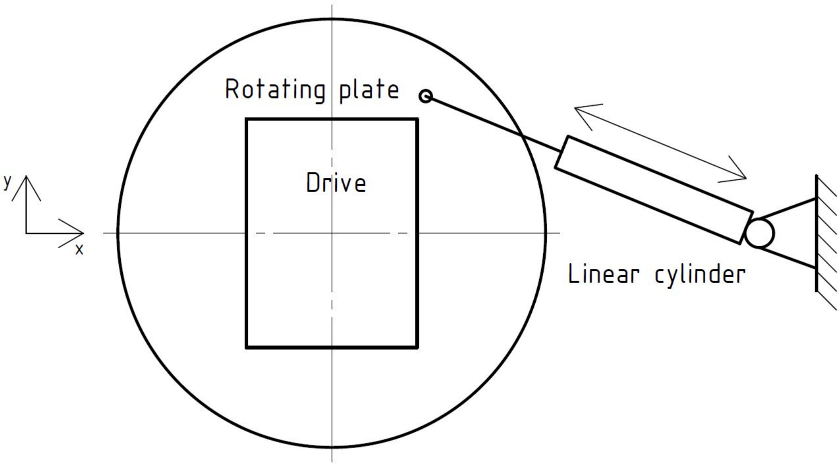


Figure 9.17: Linear cylinder

9.2.5 Eccentric mechanism

The eccentric mechanism (Figure 9.18) is another concept for swiveling around the z-axis. The working principle of the eccentric mechanism is comparable with the linear cylinder working principle. The drive assembly is also positioned on a rotating plate, which is connected with a smaller disk, namely the swivel drive, via a connecting rod. If the swivel mechanism rotates, the connecting rod delivers the motion to the rotating plate and the drive assembly changes the launch angle around the z-axis. The swivel mechanism can be driven by an electric motor.

Advantages

- Simple adjustability of the launch angle with an electric motor for the swivel drive

Disadvantages

- Bearing points must be protected from dust and dirt
- Many moving parts compared with other concepts
- Large space required

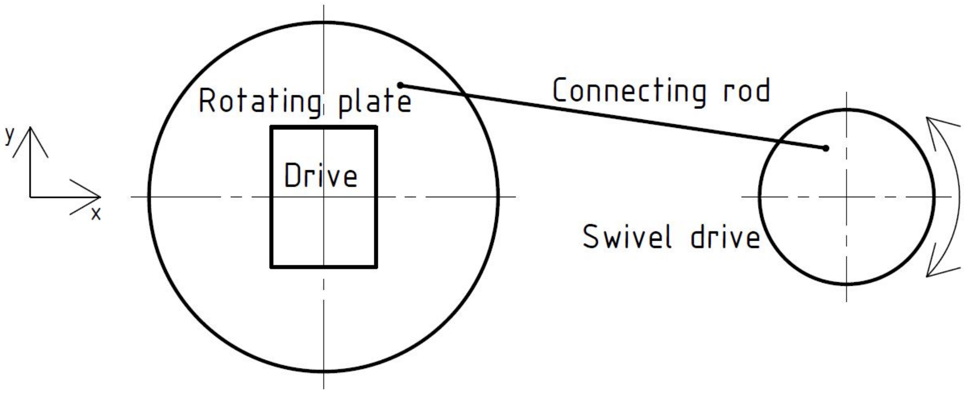


Figure 9.18: Eccentric mechanism

9.2.6 Direct mechanism

The direct mechanism ensures the swivel motion of the drive assembly around the z-axis and is directly connected to the rotation plate on which the drive assembly is mounted. Figure 9.19 illustrates this principle.

Advantages

- Small space required
- Few moving parts

Disadvantages

- Low rotation speed of the swivel mechanism is necessary
- Accurate rotation speed and angle control required

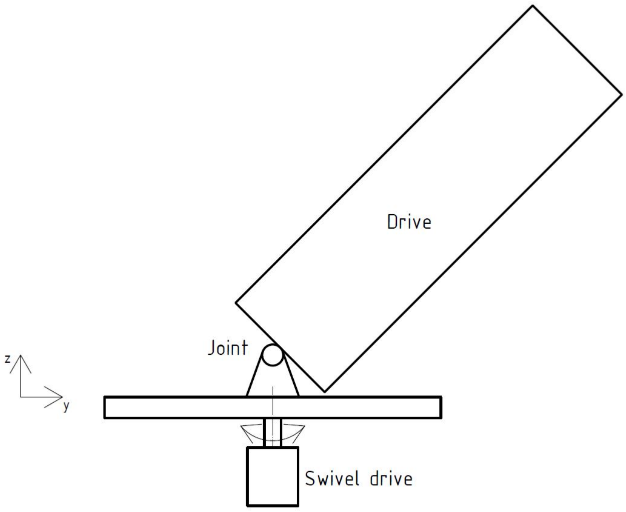


Figure 9.19: Direct mechanism

9.2.7 Gear wheel

The gear wheel concept also executes the swivel motion around the z-axis. Figure 9.20 shows the principle. The drive assembly is mounted on a rotational plate. This plate has a toothed surface on the bottom with which the small gear wheel is connected. The small gear wheel is driven by an electric motor. If the small gear wheel rotates, the motion is delivered to the rotational plate through the tooth connection and finally, the drive assembly changes its launch angle. The toothing can also be designed as pinion toothing.

Advantages

- Small space required
- Precise adjustability of the launch angle feasible

Disadvantages

- Tooth connection must be protected from dust and dirt
- Precise assembly of the toothed parts is necessary in order to avoid errors

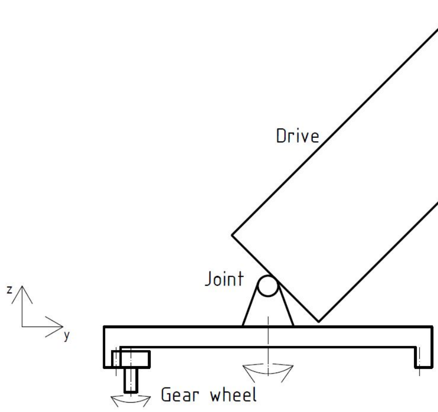


Figure 9.20: Gear wheel

9.2.8 Tiltable plate

Figure 9.21 shows the concept. This concept is useable for both, an adaption of the launch angle around the x-axis and the y-axis. However, this system cannot adapt the launch angle of the drive assembly around the z-axis, but all required launch angles are still reachable with such a system. The basic structure of the principle is as follows: the main parts responsible for the movement are four linear cylinders. They are mounted on a fixed plate at the bottom. Further, the other end is connected to another plate, which is flexible, and which is the base or the plate where the drive assembly of the shooting system is mounted. So if the cylinders extend or retract their pistons the upper plate moves in the desired position. However, four linear cylinders result in four degrees of freedom, but two degrees of freedom are necessary (rotation around the x-axis and y-axis). Therefore, two cylinders are enough and the upper plate is connected to a Cardan joint (shown in Figure 9.22 (a)).

Advantages

- Small space required
- Time-saving adjustment of the launch angle feasible
- Both rotation directions combined in one assembly

Disadvantages

- The Center of gravity of the drive assembly is far, so both cylinders have to be strong if realizable, due to the small distance to the rotation point (Cardan joint). This problem is shown in Figure 9.22(b).

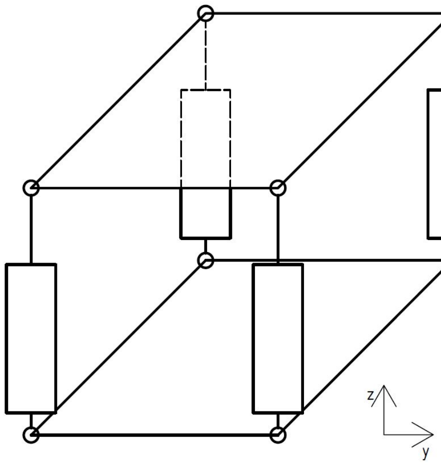


Figure 9.21: Tiltable plate

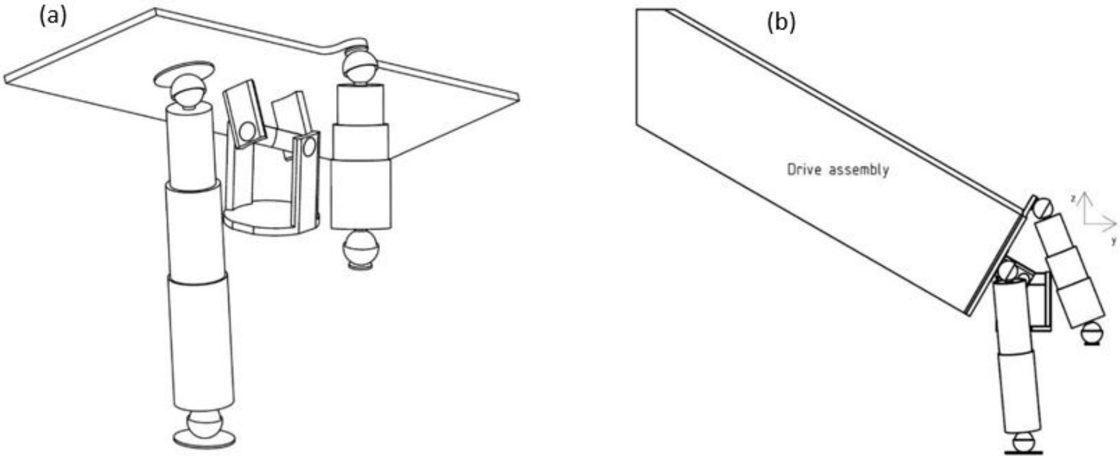


Figure 9.22: (a) tiltable plate with Cardan joint; (b) tiltable plate with the mounted drive assembly

9.2.9 Fork system

The fork system (Figure 9.23) concept is another approach that fulfills both rotations with one assembly. Similar to the tiltable plate, this concept applies the rotation around the x-axis and y-axis. The fork is the main part of this principle. The drive assembly is connected to the fork via a shaft and the associated bearing at rotation point two. On the other end of that shaft, there is a rotary actuator that is responsible for the rotation of the drive assembly around the y-axis. Furthermore, the fork is also mounted in rotation point one. If the linear cylinder, which is also connected to the fork, extends or retracts its piston, the fork rotates around the x-axis at rotation point one, which in turn means that the drive assembly also rotates around the rotation point one, since the drive assembly is connected to the fork.

Advantages

- Time-saving adjustment of the launch angle feasible
- Both rotation directions combined in one assembly
- Both rotation points are close to the center of gravity, so less energy is needed to adapt the launch angle

Disadvantages

- The rotary actuator must be able to provide an accurate adjustment of the launch angle

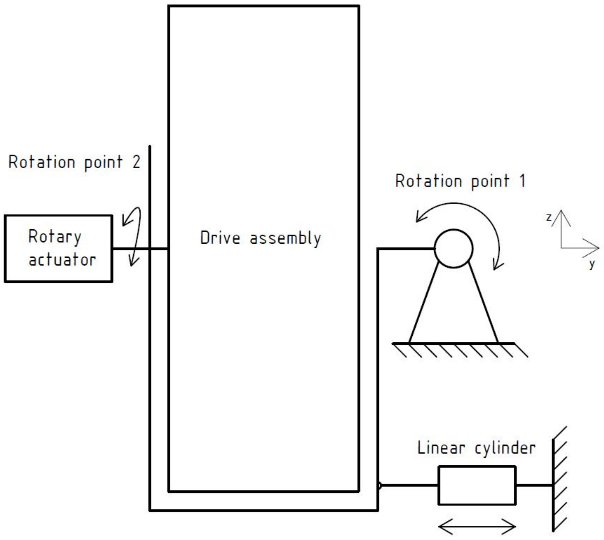


Figure 9.23: Fork system

9.2.10 Discussion

In this subsection, advantages and disadvantages of the concepts are discussed as well as compared with each other. In the end, the concept with the highest potential is chosen.

Problems can occur at systems, that fulfill rotation around one axis. These systems must be combined with other systems to realize the rotation around two axes, but this combination can be difficult. For example, combining the rope concept with the eccentric drive concept lead to challenges. If the eccentric drive rotates the shooting assembly, the rope must be redirected or the rope drum must not be fixed in its position, otherwise, the rope collides with the shooting assembly. As a result, the combined systems have a benefit, due to the combination of both rotations around different axes in one assembly.

Furthermore, concepts with sensitive mechanical connections, such as gear wheels and many bearings, are not suitable or must be protected well from dust and dirt.

Nevertheless, the protection is a major challenge, since the lunar dust particles are very small. Moreover, lunar dust is during the entire excavation and conveying process present.

Another challenge is to find the right combination of the connection point of the swivel concept close to the center of gravity of the shooting assembly and short extending or retracting distances of the rope or the cylinders. This challenge occurs for swiveling around the x-axis. To illustrate the trade-off: the rope or cylinder concept is connected to the shooting assembly close to the center of gravity, but must take long distances to adapt the launch angle. Conversely, the cylinders of the tiltable plate have to move minor to adjust the launch angle, but the cylinders must be strong (if at all possible) to cover large forces, due to the large distance between the rotation point and center of gravity of the shooting assembly.

Finally, the chosen concept is the fork system. This system combines both rotations in one assembly, therefore there is no need to adjust the different systems so that they can work simultaneously. Further, the fork system uses no sensitive mechanical parts or connections, such as gear wheels. Moreover, the rotation points are close to the center of gravity of the shooting assembly, so low forces are necessary to adapt the launch angle. Consequently, the tiltable plate is not the chosen concept, because of the large distance between the rotation point and the center of gravity.

9.3 Machine loading system

This subchapter first describes the purpose of the loading system and how it works. Then, principles for the machine loading system are described with advantages and disadvantages, followed by a discussion of which principle fits the requirements best.

Initially, the machine loading system is an important assembly within the entire conveying machine. The purpose of this assembly is to transfer the excavated material from the excavator to the shooting operation of the conveyor. Basically, the excavated material is dumped into a transfer chute by the excavator. The transfer chute guides the material into buckets and not directly to the shooting assembly. The reason is that lunar regolith is abrasive and has a sharp grain shape which leads to high friction and wear. The main task of the machine loading system is to transfer the filled buckets from the transfer chute to the drive and transport the empty buckets after the shooting operation from the drive to the transfer chute, where the buckets are refilled again. For clarification, drive means the ballistic acceleration system.

The machine loading system is, obviously, the interface between the excavation operation and the conveying operation. However, some challenges occur here. Generally, the excavator is realized as a bucket scraper that works continuously, but the ballistic conveyor system works discontinuously. As a result, the ballistic conveyor must be able to handle the material flow of the excavator and adapt its material flow to the other. Since the excavator mines continuously for several hours without a break, the material flows of the two machines must be at least similar, otherwise, a large buffer is required, which is not feasible. Furthermore, the goal is to attach the ballistic conveyor to the bucket scraper. However, the ballistic system has to realign its target at each operation cycle, so the machine loadings system must be flexible or the swivel mechanism must move the drive in a certain position at each operation cycle.

9.3.1 Intermediate storage with rotary feeder

The main part of this concept is the temporary storage. The excavator dumps the material into the storage. The shooting assembly repositions after each shoot in order to locate the bucket, which is connected with a mechanical gripper to the drive, under the opening of the storage. After that, the rotary feeder releases material into the bucket. The concept is shown in Figure 9.24.

Advantages

- Simple operation
- Few moving parts
- Small space required
- The working cycles of the excavator and the conveyor are separate and independent from each other

Disadvantages

- Risk that clogging occurs due to the cohesiveness of lunar regolith
- High friction and wear

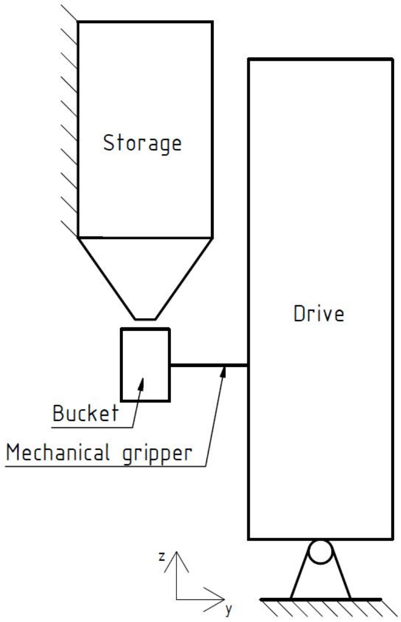


Figure 9.24: Intermediate storage

9.3.2 Drum type bucket storage

The drum type bucket storage concept (Figure 9.25) consists mainly of the rotating plate, where the buckets are located at the circumference. The excavator dumps the material into the transfer chute and the material is guided into the buckets. On the opposite side, the drive picks a filled bucket via a mechanical gripper and accelerates it, to convey the material to the target location. In the next step, the drive returns the bucket to the plate and the plate rotates that the next filled bucket is located in front of the drive and an empty bucket is located under the transfer chute. Finally, the working cycle starts again.

Advantages

- No storage where the material can clog essential parts
- Simple operation

Disadvantages

- The working cycles of the excavator and the conveyor are not separate and not independent from each other
- The working cycles of the excavator and the conveyor must be coordinated so that there is no material overflow. The filling of a bucket must take at least the same time or longer than the acceleration of a bucket by the conveyor
- Large space required
- Low flexibility

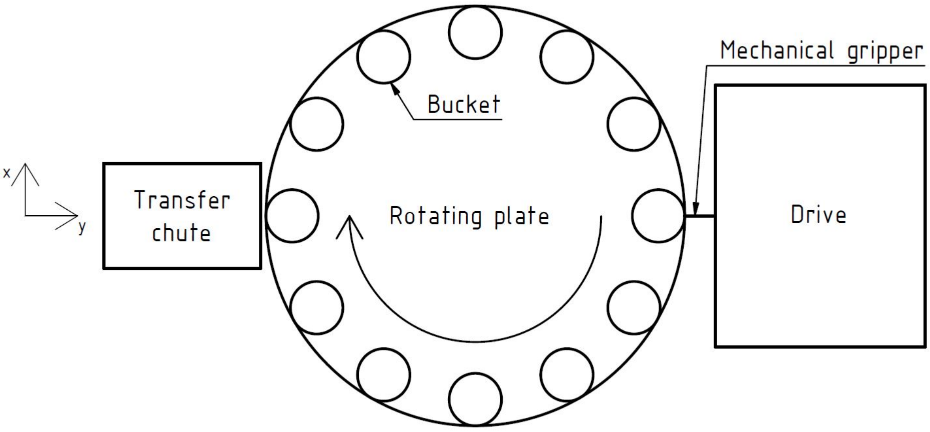


Figure 9.25: Drum storage

9.3.3 Circular type bucket storage with pusher

This concept is illustrated in Figure 9.26 and is similar to the drum type bucket storage concept. A link belt conveyor transfers the buckets from the transfer chute to the drive and is at the same time a bucket storage. When the bucket is filled at the transfer chute, it is transported to the drive by the link belt conveyor and a pusher delivers the bucket to the drive. After the acceleration when the bucket is empty, the pusher takes the bucket again and puts the bucket back to the link belt conveyor. Finally, the bucket is transported to the transfer chute where it gets refilled.

Advantages

- More flexible compared to the drum type bucket storage
- No storage where the material can clog essential parts

Disadvantages

- Many moving parts
- Large space required
- The working cycles of the excavator and the conveyor are not separate and not independent from each other
- The working cycles of the excavator and the conveyor must be coordinated so that there is no material overflow. The filling of a bucket must take at least the same time or longer than the acceleration of a bucket by the conveyor

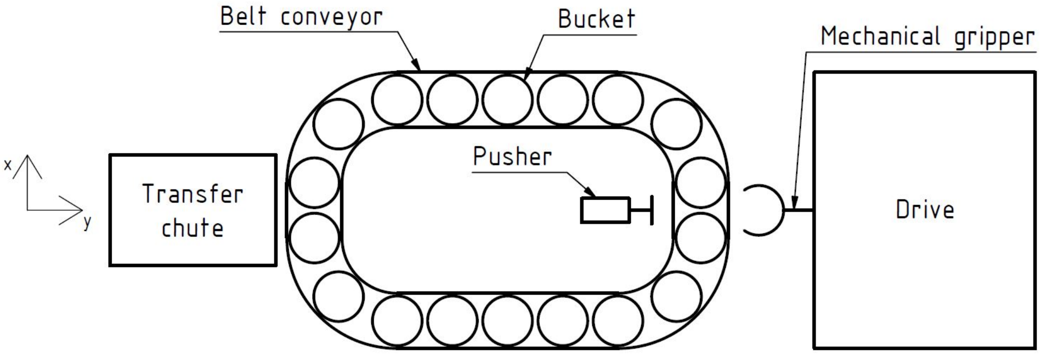


Figure 9.26: Circular storage

9.3.4 Rotary system on 2 levels

This concept (Figure 9.27) consists of a tree-like assembly. The rotating support in the center is comparable to the trunk and the mechanical grippers to the branches of a tree. Initially, the bucket is filled on the second level under the transfer chute and is held by a mechanical gripper. In the following step, the second level rotates and provides a filled bucket to the drive to convey the material. After that, the empty bucket is transferred to the first level by a puller and the second level, where the filled buckets are located, rotates to provide a filled bucket to the drive again. The first level held the empty buckets and through rotation of the first level, the empty buckets are positioned under the transfer chute. A pusher moves the bucket upwards to refill the bucket and transfers the filled bucket to the second level. Finally, the working cycle starts again.

Advantages

- Fast changing mechanism of the buckets at the drive
- No storage where the material can clog essential parts

Disadvantages

- Complex system

- Many moving parts
- Large space required
- Low flexibility
- The working cycles of the excavator and the conveyor are not separate and not independent from each other
- The working cycles of the excavator and the conveyor must be coordinated so that there is no material overflow. The filling of a bucket must take at least the same time or longer than the acceleration of a bucket by the conveyor

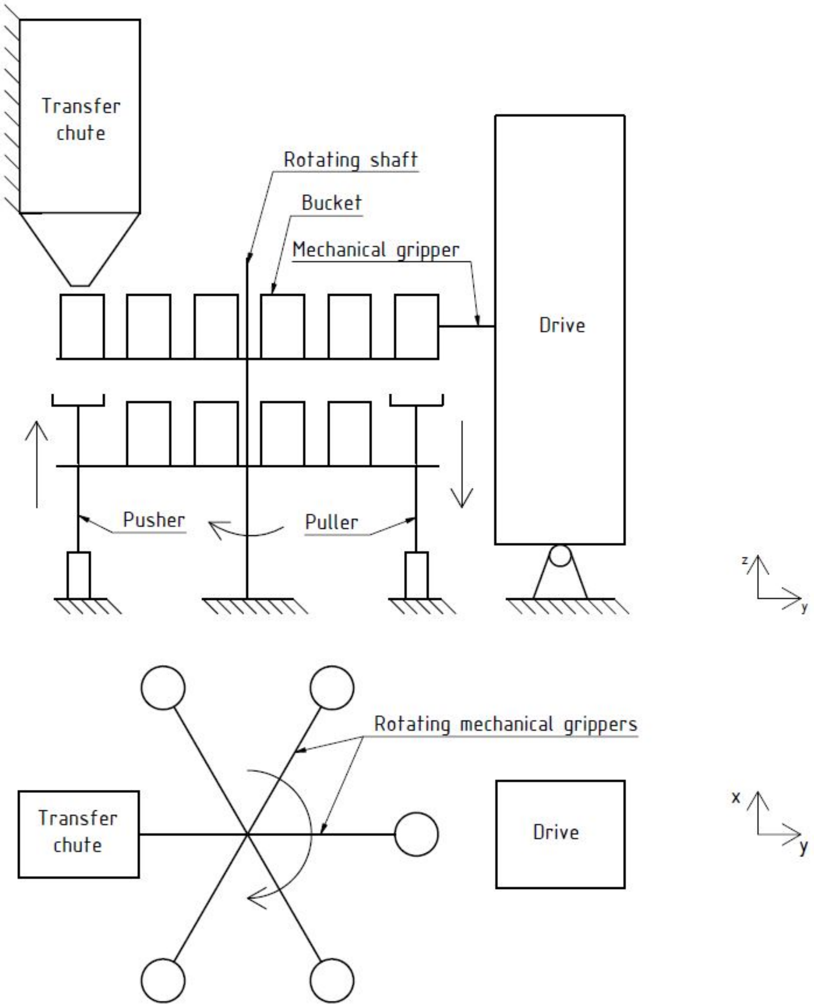


Figure 9.27: Rotary storage

9.3.5 Vertical loading system

The vertical loading system (Figure 9.28) transfers the buckets from the ground level to an upper level, where the shooting assembly is located. The vertical conveyor is the main point in this principle: it conveys the filled buckets from the transfer chute to the shooting assembly as well as in the bucket storage and conveys the empty buckets to the transfer chute. The shooting assembly is mounted on a higher floor, therefore the shooting assembly has more freedom to swivel and move. This means that the firing unit is less likely to be obstructed and other firing angles are possible.

Advantages

- High flexibility
- No storage where the material can clog essential parts
- Large swivels and movements are possible
- The working cycles of the excavator and the conveyor are separate basically, due to the arranged bucket storage

Disadvantages

- Complex system
- Many moving parts
- Slow changing mechanism of the buckets in general

9.3.6 Robot system with intermediate bucket storage

The basic principle of this concept (Figure 9.29) is based on an industrial robot with a mechanical gripper at the end to transfer the buckets. The industrial robot is placed in the middle of a bucket storage, which has a rectangular base. The task of the industrial robot is to transfer the buckets between the various devices (transfer chute, bucket

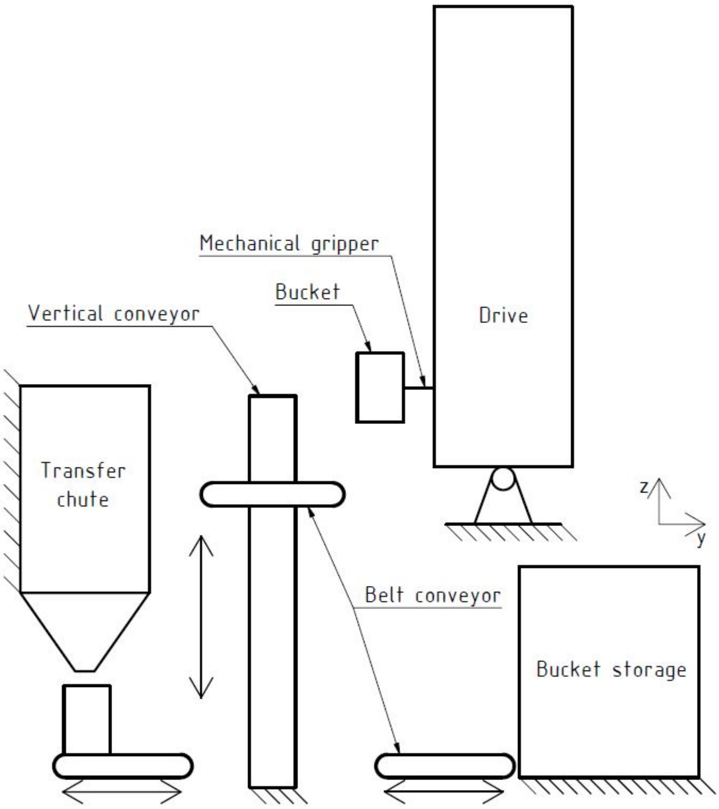


Figure 9.28: Vertical loading system

storage, shooting assembly). After filling a bucket at the transfer chute, the bucket is placed in the bucket storage. When the shooting assembly has emptied a bucket, it is also placed in the bucket storage and a filled bucket is transferred from the storage to the shooting assembly.

Advantages

- High flexibility due to the industrial robot
- Few moving parts (only the industrial robot)
- No storage where the material can clog essential parts
- The working cycles of the excavator and the conveyor are separate basically, due to the arranged bucket storage

Disadvantages

- Complex automation of the industrial robot is necessary
- Slow changing mechanism of the buckets in general
- Large space is required because of the storage

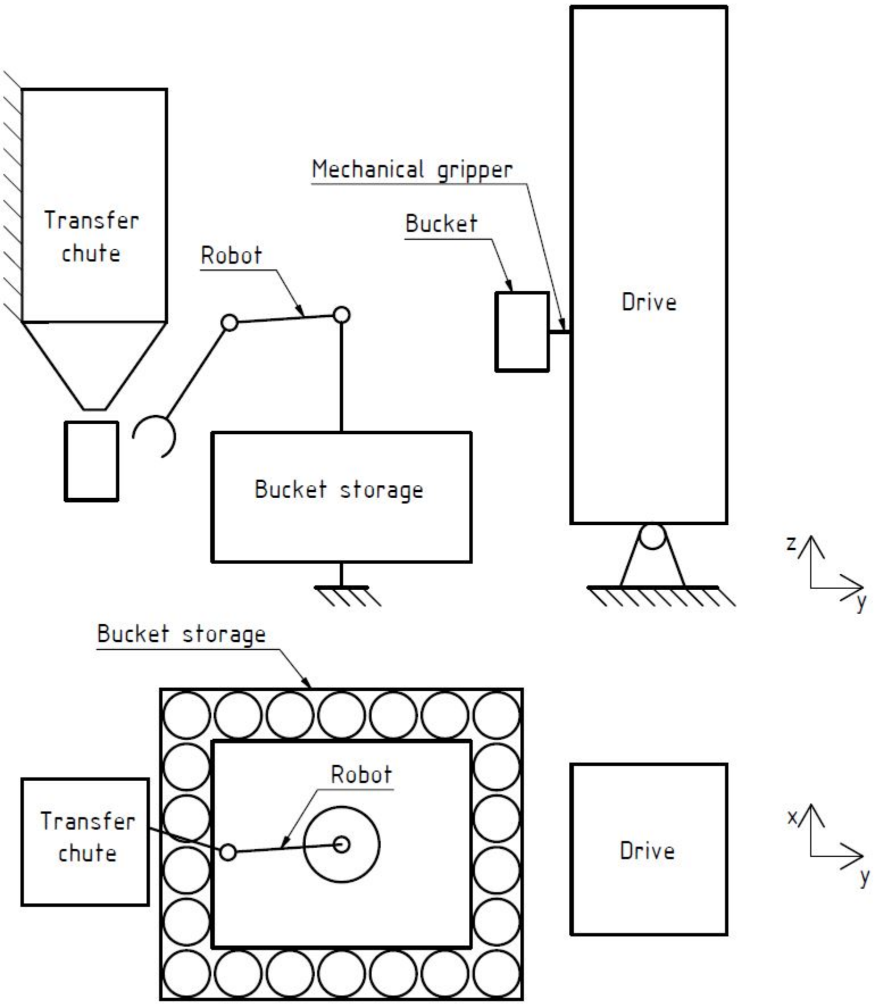


Figure 9.29: Robot system with intermediate bucket storage

9.3.7 Loading system with linear cylinders

The loading system with linear cylinders is shown in Figure 9.30. Four linear cylinders with a mechanical gripper are arranged in a circle on a rotating shaft. These four linear cylinders transfer the buckets between the transfer chute and the shooting assembly.

When the shooting assembly has conveyed the material of a bucket, the empty bucket is picked up by a linear cylinder. The shaft then continues to rotate and transfers a full bucket to the shooting assembly. During the acceleration process of the shooting assembly, an empty bucket is filled at the transfer chute.

Advantages

- Simple operation and system
- Low space required

Disadvantages

- Low flexibility of the linear cylinders compared to an industrial robot
- The working cycles of the excavator and the conveyor are not separate and not independent from each other

9.3.8 Rotating plate with gates

The rotating plate is located between the transfer chute and the drive. The purpose of the rotating plate is that the plate works as a bucket storage. During the filling process of a bucket, the gate in front of the transfer chute is closed, so that the empty buckets do not go further and can be also refilled. When the bucket is completely filled, the gate opens and releases the filled bucket to the shooting assembly. Similarly, the gate in front of the drive is closed during the acceleration process in order to stop the full buckets and that they do not go further to the transfer chute. When the bucket gets back from the acceleration process, the bucket is placed on the rotating plate to get back to the transfer chute. This concept is illustrated in Figure 9.31.

Advantages

- Few moving parts

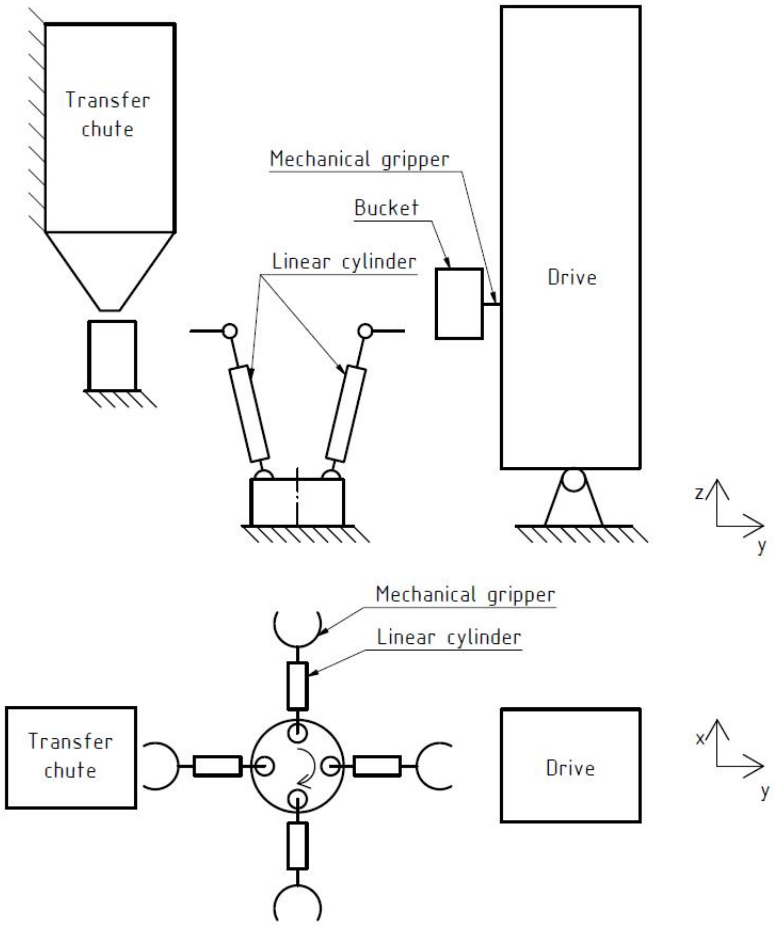


Figure 9.30: Loading system with linear cylinders

- Simple working principle
- No storage where the material can clog essential parts
- The working cycles of the excavator and the conveyor are separate basically, due to the arranged bucket storage

Disadvantages

- Large space required
- Low flexibility
- Friction and wear at the bottom of the buckets and the plate due to the gates which stops the buckets but the plate keeps rotating

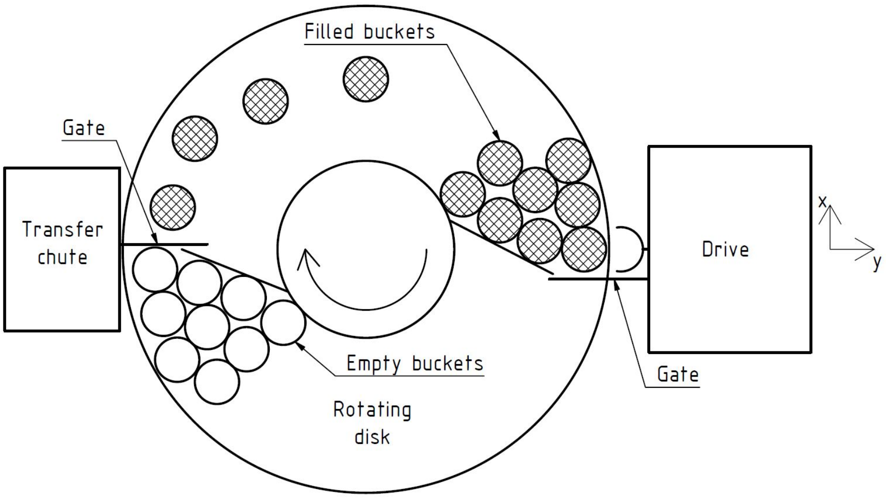


Figure 9.31: Rotating plate with gates

9.3.9 Loading system with 3 robots

The loading system with three robots (Figure 9.32) is similar to the loading system with linear cylinders, but instead of the linear cylinders, there are three industrial robots with mechanical grippers to handle the buckets. This system works with three buckets in total. The industrial robots are responsible for the transfer of the buckets between the transfer chute and the drive. They are placed on a rotational disk. The working cycle is similar to the working cycle of the loading system with linear cylinders.

Advantages

- Higher flexibility compared to the loading system with linear cylinders
- Low space required
- Fast changing mechanism of the buckets

Disadvantages

- The working cycles of the excavator and the conveyor are not separate and not independent from each other
- Complex automation of the industrial robots is necessary

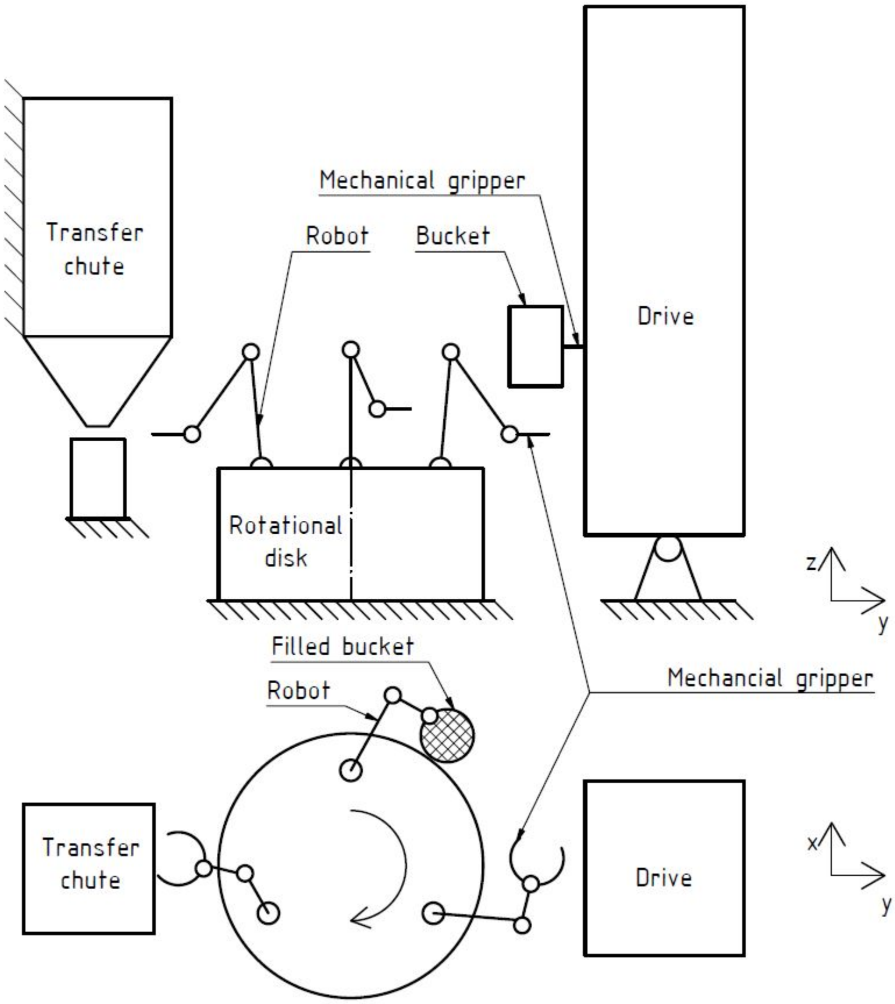


Figure 9.32: Loading system with 3 robots

9.3.10 Loading system with 2 robots

This concept, shown in Figure 9.33, is mainly based on two industrial robots. The robots have a mechanical gripper that can handle two buckets at the same time for an efficient bucket transfer operation. They are mounted on a box that is fixed and provides storage for energy supply and control systems. This system also works with three buckets. Immediately after the shooting assembly releases an empty bucket, it is taken over by a robot, which then instantly transfers a full bucket to the shooting assembly. After the transfer process, this robot moves with the empty bucket to the transfer chute. In the meantime, the other robot moves with the filled bucket in the direction of the shooting assembly and waits until it can take over the empty bucket from the shooting assembly before immediately transferring the full bucket again.

Advantages

- High flexibility
- Low space required
- Fast changing mechanism of the buckets

Disadvantages

- The working cycles of the excavator and the conveyor are not separate and not independent from each other
- Complex automation of the industrial robots is necessary

9.3.11 Discussion

In this subsection, advantages and disadvantages of the concepts are discussed as well as compared with each other. In the end, the concept with the highest potential is chosen.

Initially, lunar regolith is a material with a high cohesiveness and high friction and wear. Therefore, static large storages, such as a silo, are not preferable for storing lunar regolith. Regolith clogs the opening of the silo, so no material can be released through the opening. This is a worst-case scenario for the conveying machine because it cannot convey any regolith anymore. Consequently, the intermediate storage with rotary feeder concept is not appropriate. The material could build a bridge-type obstacle over the rotary feeder for the upcoming material, so the feeder will rotate but no material exceeds the storage. This is why a bucket storage system, where the material is filled

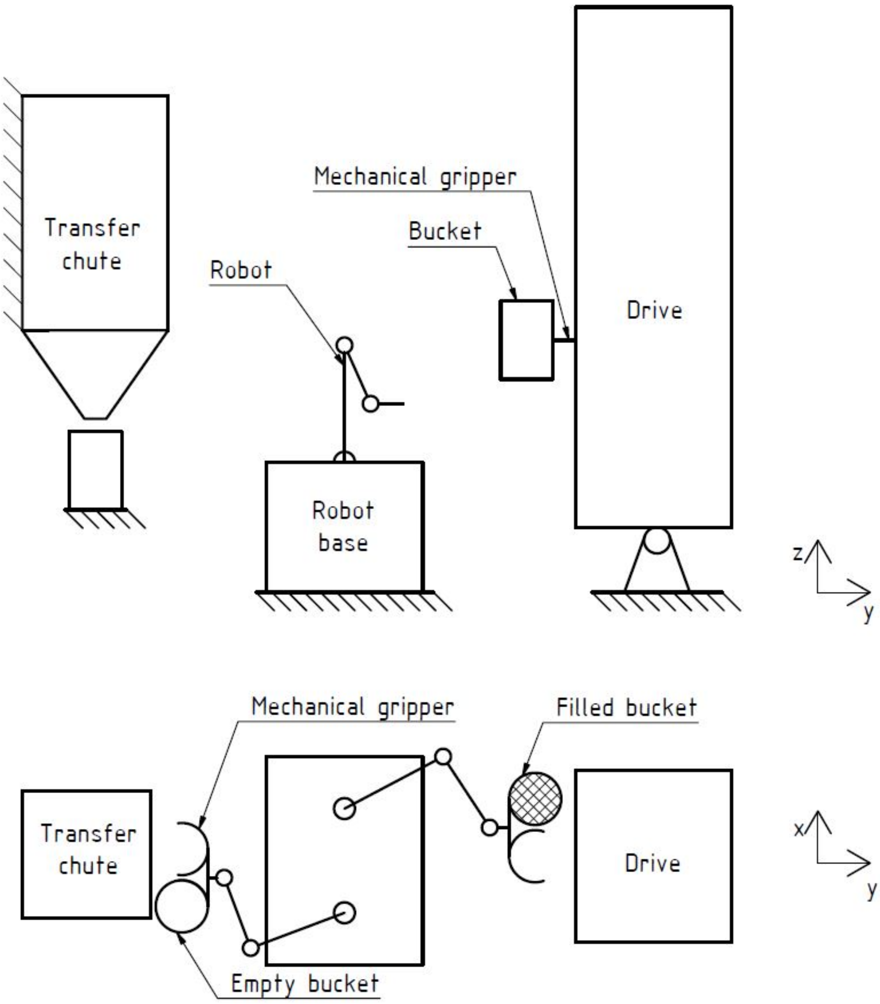


Figure 9.33: Loading system with 2 robots

into buckets that are accelerated by the drive of the machine and let the material fly to the desired location, is preferable to, for example, a silo.

Furthermore, it would also be beneficial if the excavator and conveyor could operate independently of each other so that they do not have to be coordinated. It is problematic if the excavator excavates more material than the conveyor machine can transport away, conversely, no problems occur. One solution is the bucket storage, the full buckets are temporarily stored in the storage and are transferred to the conveyor when required. But the excavator works continuously for a longer period of time without pause. This means that if there is an excess of material, the bucket storage must be very large to accommodate the excess material. However, the entire conveyor unit is attached to the excavator, and therefore space is limited and consequently, the machine loading system must also be space-saving. The result is that a bucket storage is not feasible for the reasons mentioned above and all concepts with a bucket storage are not considered further.

In addition, the machine loading system should have a certain flexibility, since the drive that accelerates the buckets must be swiveled around two axes over a certain angular range in order to always aim at the same target while constantly changing position. In machine loading systems with low flexibility, the drive can move to the same starting position after each work cycle, so that these machine loading systems still function and the bucket can be transferred. However, it is time-consuming if the drive has to return to the starting position after each work cycle and then refocus the target again, so it is better if the drive constantly focuses on its target and the machine loading system transfers the bucket to the drive in the respective position. Additionally, more energy is needed to always move the drive to the starting position than the machine loading system transfers the bucket in the respective position. Further, the bucket changing operation must be fast to keep the time low which is necessary to change the buckets. Short changing time leads to an increased material flow and since the conveyor and the excavator cannot work independently because a bucket storage is not feasible, the excavator can excavate more material at the same time. Due to the harsh environment, the machine loading system should consist of a few moving parts.

Finally, the loading system with two robots is the chosen concept for the conveying machine. This concept combines the different requirements best compared to the other concepts. The two robots ensure the required flexibility, but at the same time are space-saving and consist of few moving parts. They also ensure a fast bucket exchange. The control of the robots is complex, but since the working cycle is always the same, the control of the robots is feasible.

10 Estimated calculation

In this chapter, basic rough calculations are performed. In particular, the energy and velocity requirements during launch for different conveying distances are of interest for the development of the acceleration drive of the conveyor system.

The basis for the calculation is the approach of the oblique throw. The vertical axis is assumed to be the y-axis and the horizontal axis is assumed to be the x-axis. The launch angle is referred to as α and is 45°, since the maximum range is achieved at this angle. For a constant gravitational acceleration (on the Moon g_M=$1.62\frac{m}{s^2}$ and on the Earth g_E=$9.81\frac{m}{s^2}$) in the direction of the y-axis, the following equations for the path x are calculated:

$$x_x = v_0 * cos(\alpha) * t \tag{10.1}$$

$$x_y = -g * \frac{t^2}{2} + v_0 * sin(\alpha) * t \tag{10.2}$$

Equation 10.2 is set equal to 0, since the conveyed material then arrives at the surface. Solving the system of equations results in the required initial velocity as a function of the horizontal conveying distance:

$$v_0 = \sqrt{\frac{x_x * g}{2 * sin(\alpha) * cos(\alpha)}} \tag{10.3}$$

Figure 10.1 shows the required initial velocity at the Moon and on Earth as a function of the horizontal conveying distance.

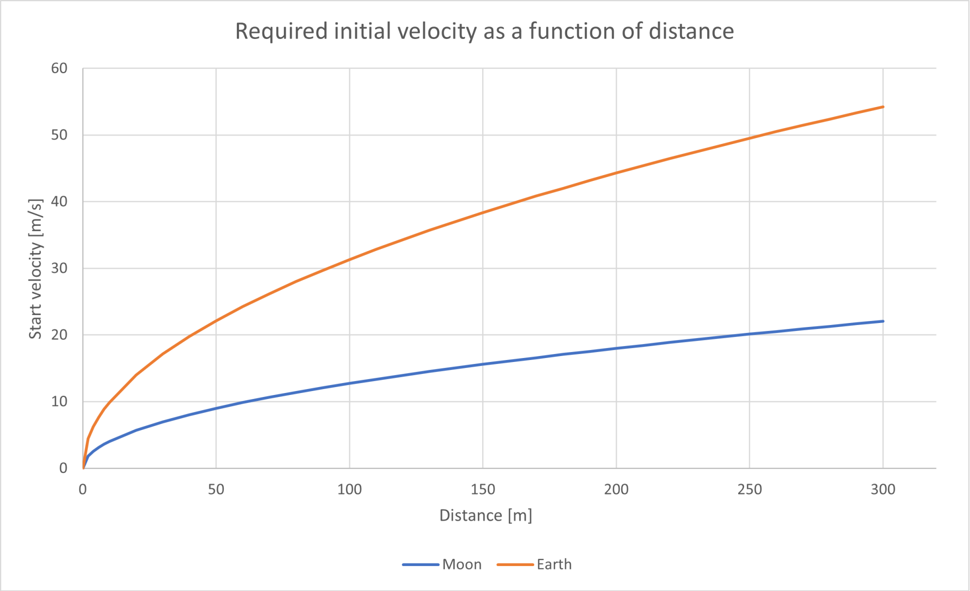


Figure 10.1: Required initial velocity as a function of distance

Using the calculated initial velocity, the kinetic energy can be calculated for a given mass ($m{=}10kg$):

$$E_k{=}\frac{m*v_0^2}{2} \tag{10.4}$$

Figure 10.2 shows the required energy at the Moon and on Earth as a function of the horizontal conveying distance. In the figures 10.1 and 10.2 the advantage of the ballistic conveying system on the Moon compared to the Earth can be seen very well: the required initial velocity as well as the required energy on the Moon for a given conveying distance is significantly lower than the initial velocity and energy on Earth.

The required kinetic energy must be provided by the springs as potential energy. The springs are pre-tensioned by an electric linear cylinder to obtain the required potential energy. Further, the electric linear cylinder is supplied from the energy system of the conveying system, which is not developed in this thesis, but approaches for further

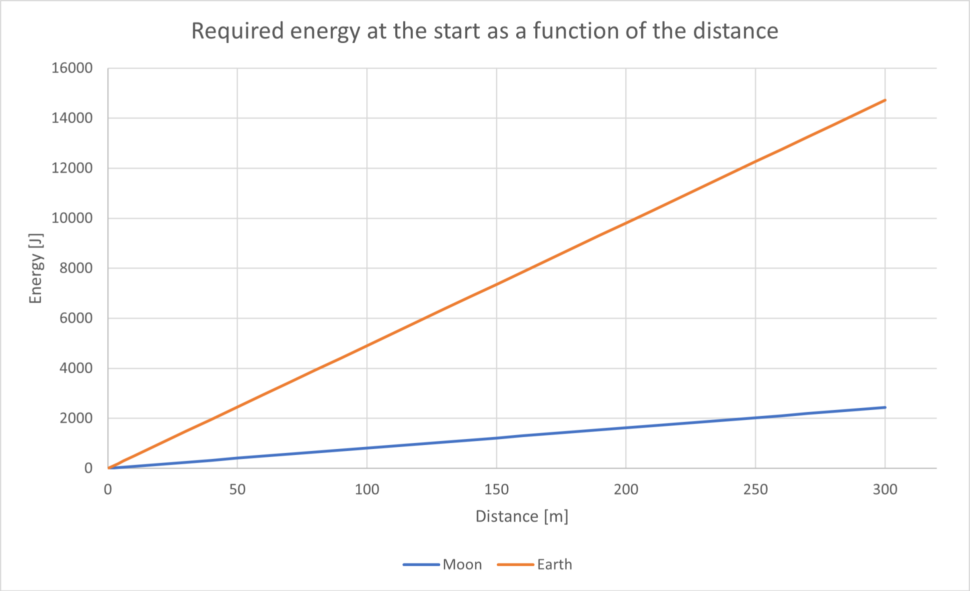


Figure 10.2: Required energy at the start as a function of distance

development are made in the chapter 13.8. The spring energy is calculated as follows, where k is the spring constant and Δ x is the deflection of the spring:

$$E_p = \frac{1}{2} * k * \Delta x^2 \tag{10.5}$$

Initial research has identified a suitable spring material that can operate in the temperature range at the Moon, namely $1.4568RS$ from Hennlich GmbH & Co KG. It is also clear that more precise load calculations, especially in the high-cycle fatigue area, must be carried out before realization.

For a maximum conveying distance of 300 m ($r_{max}=300m$), energy of 2430 J is required. This energy can be applied by springs that are pre-tensioned by a linear cylinder. If it is taken into account that no excavation is allowed within a radius of 100 m ($r_{min}=100m$) around the lunar base, the result is a circular ring area of:

$$A = \pi * (r_{max}^2 - r_{min}^2) = 251327 m^2 \tag{10.6}$$

If it is further assumed that the uppermost 15 cm (h=$0.15m$) of the entire surface (i.e. the entire area of the circular ring can be mined without restrictions, for example, due to steep terrain) can be excavated, this results in an excavatable volume of:

$$V = A * h = 37699 m^3 \tag{10.7}$$

Furthermore, the excavator and therefore the conveyor system (because otherwise there will be an overflow of material) has a volume flow of $\dot{V}=0.4\frac{dm^3}{s}$. In addition, it is assumed that the excavator as well as the conveyor can operate 12 hours within one Earth day. From this, the required time t is calculated, how long it takes until the complete excavatable volume has been excavated:

$$t = \frac{V}{\dot{V}} = 5.98 years \tag{10.8}$$

So, theoretically, it takes almost 6 whole Earth years to excavate the entire area within the reachable range of the conveyor system if the systems operate 12 hours a day.

11 Final design

In this chapter, the final design of the conveying unit is presented. Initially, an overview of the system is illustrated and described. Further, the design of the major assemblies is presented. The main assemblies (drive, swivel mechanism, and loading system) are based on the chosen concepts of chapter 9.

11.1 Overview of the system

Figure 11.1 illustrates the overview of the final design of the conveying unit. The conveying unit is directly attached to the excavator. The excavator was developed by Dominik Höber in the context of a master's thesis and is illustrated in green in Figure 11.1 and Figure 11.2. The drive of the conveyor unit is mounted on the main part of the swivel mechanism, the fork (shown in cyan). This fork is in turn connected to the excavator with 2 bolts, shown in red. In addition, two linear cylinders are mounted on the excavator and on the fork to perform the slewing around an axis. The machine loading system is mounted on the platform of the excavator and transfers the buckets between the transfer chute and the drive.

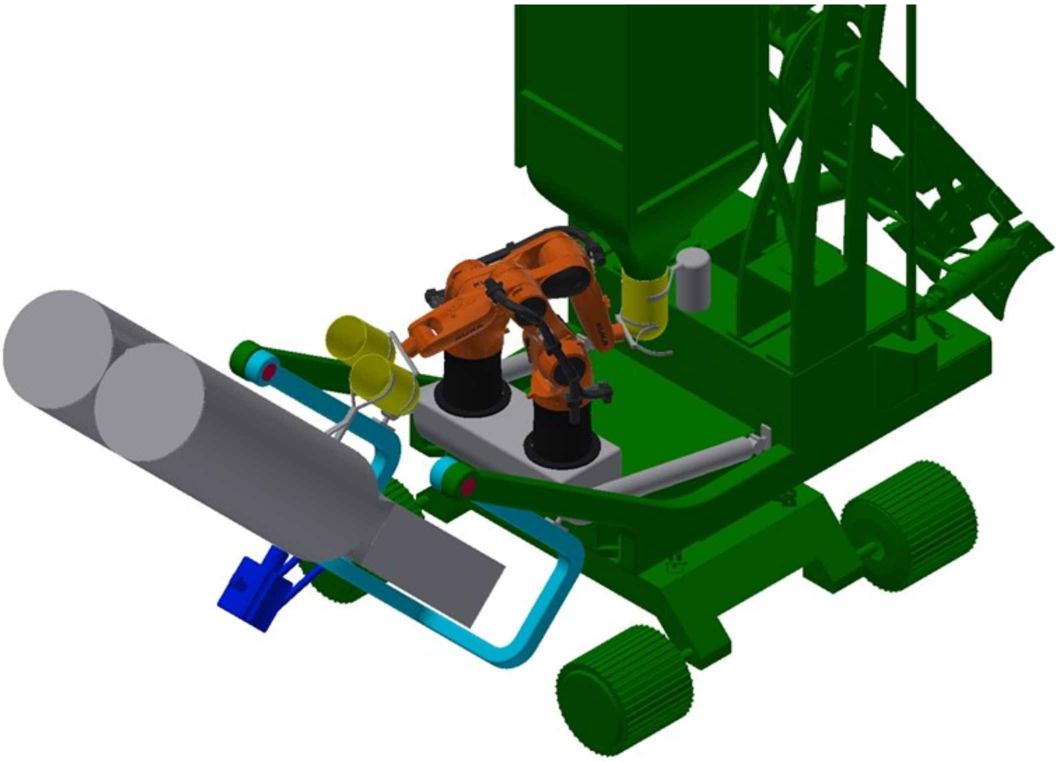


Figure 11.1: Overview of the conveying unit

11.2 Major Subsystems

In this subchapter, the major subsystems of the conveying unit are shown and explained. The ballistic acceleration system, the swivel mechanism, the machine loading system, and the bucket are presented.

11.2.1 Ballistic acceleration system

In this subsection, two development stages are presented. The first development step (Figure 11.3-11.5) shows the drive with one cannon. Figure 11.6 shows the final development step, in which 2 cannons are connected in parallel and the bucket volume is doubled.

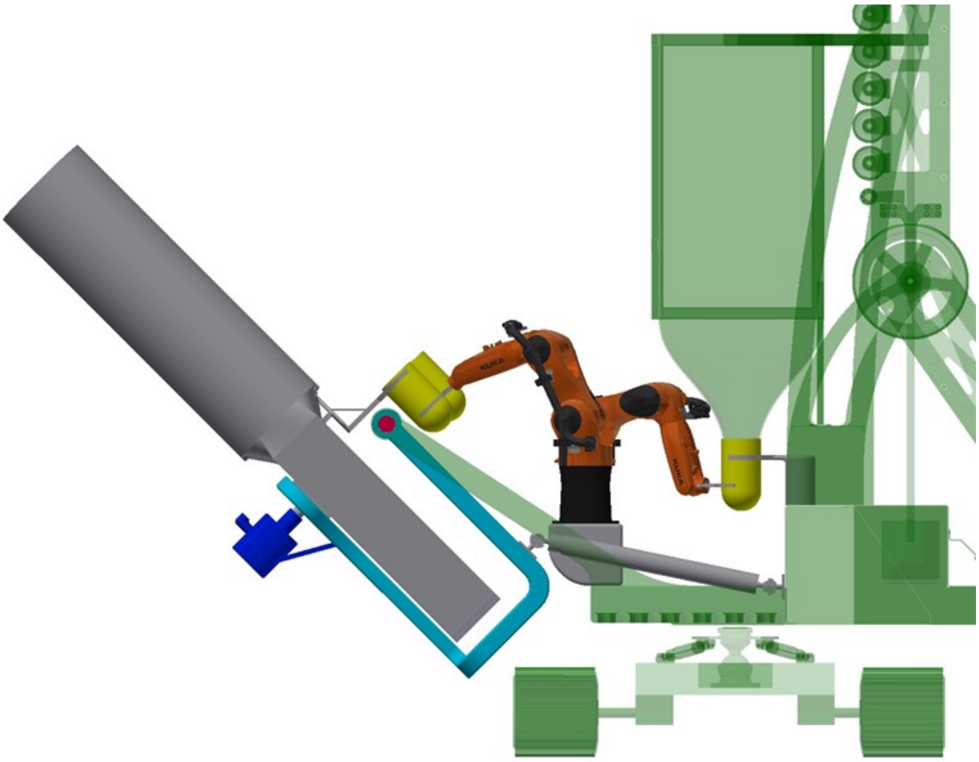


Figure 11.2: Side view of the conveying unit

The design of the drive is shown in Figure 11.3 in a pre-tensioned state (a) and an unstressed state (b) of the spring drive. The main parts are protected by the different coverings. Furthermore, regolith is placed in the bucket, illustrated in yellow in Figure 11.3, and it is connected to the drive via a mechanical gripper. The mechanical gripper is the connection part between drive and bucket. In Figure 11.3 (c) the essential parts of the drive are shown. Eight springs, illustrated in red, are allocated in a certain arrangement. The green plate preloads the springs and is moved by the electric linear cylinder. In addition, the electrical linear cylinder is a commercial part of the company Bosch Rexroth AG and it is clear that this part has to be adapted for non-terrestrial applications. Further, the part that is illustrated in blue in Figure 11.3 (c) is the spring-damper system. It is a friction spring that slows the green part down after the complete acceleration.

Figure 11.4 depicts the cross-section of the drive in an (a) unstressed and in a (b)

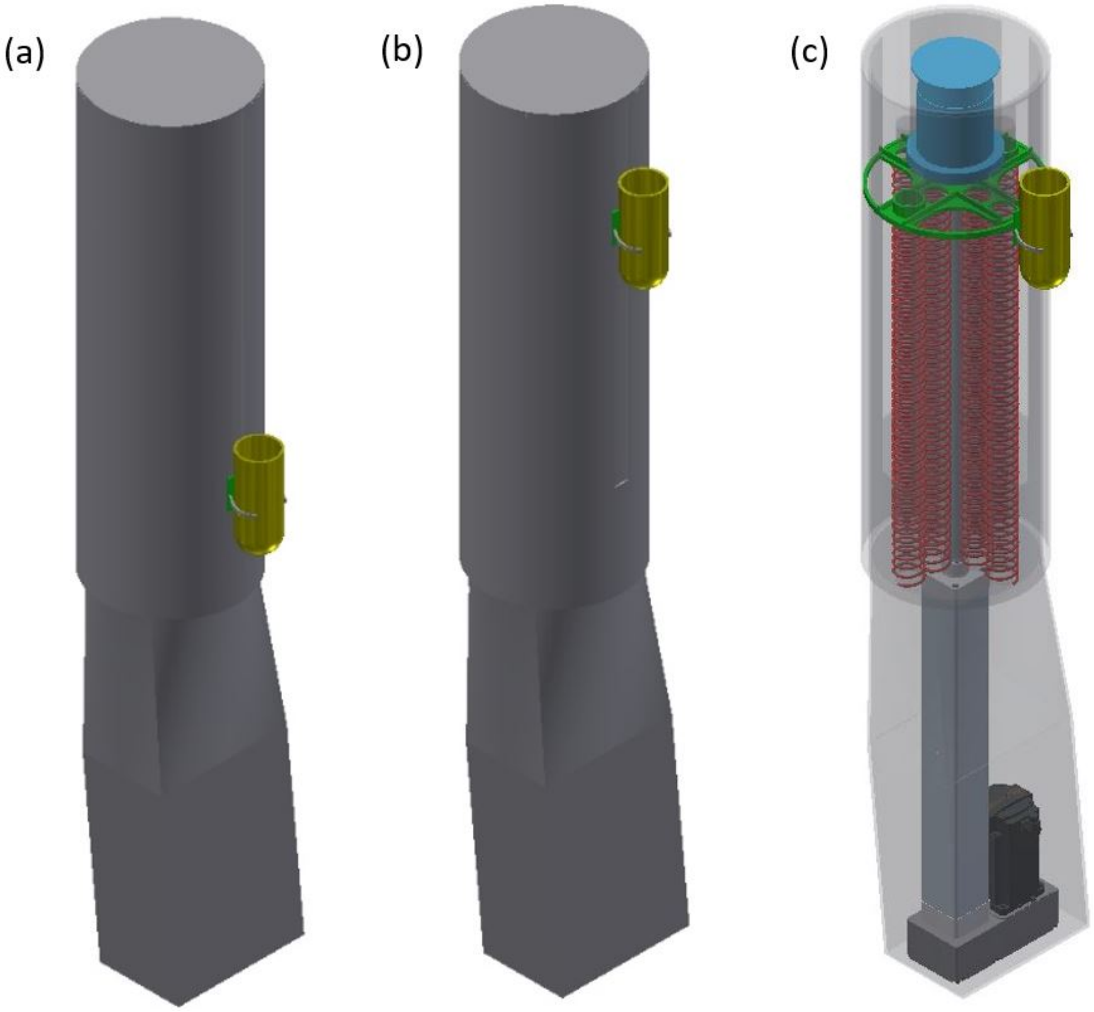


Figure 11.3: Drive (a) stressed, (b) unstressed, (c) transparent

stressed condition. The operation cycle works as follows: initially, the application is in an unstressed state (Figure 11.4 (a)). The linear cylinder moves upwards to connect with the pre-tensioning plate. Afterward, the linear cylinder moves the green plate downwards and the springs are pre-tensioned simultaneously. When a predefined level of tension is reached (Figure 11.4 (b)), the cylinder stops, and regolith can be placed in the bucket or the whole bucket is exchanged for a bucket full of lunar regolith. Next, the cylinder releases the pre-tensioning plate leading to an instant acceleration of the plate and the bucket caused by the stressed springs. When the springs are completely relieved, the plate and the bucket reach the maximum velocity. After a certain distance with high velocity, the plate hits the spring-damper system (illustrated in blue) and it is slowed down abruptly. Finally, the operation cycle starts again.

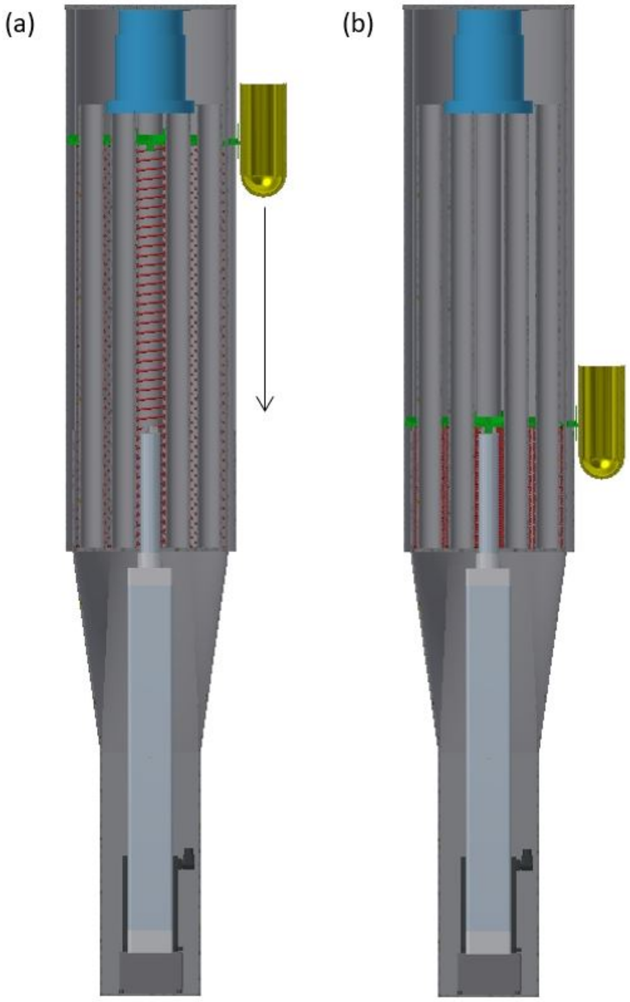


Figure 11.4: Cross-section of the drive (a) unstressed, (b) stressed

Figure 11.5 (a) shows a detail of the cross-section and (b) a top view cross-section. The spring-damper system for slowing down the accelerated pre-tensioning plate is realized by a friction spring. Such a type of spring-damper solution is already utilized in the Mars rover Curiosity, so it is a proven application for non-terrestrial operations. In addition, the preloading plate is guided by the pins positioned in the inner diameter of the springs. The electrical linear cylinder connects to the pre-tensioning plate via a mechanical gripper. In detail, the gripper opens to release the plate and closes to grab the plate. Figure 11.5 (b) illustrates the system behind the different coverings to protect the essential parts against lunar dust and regolith. In general, the two protections are realized as cylindrical shells. Within the inner shell, there are the crucial parts located, such as the springs and the linear cylinder. Besides, the pre-tensioning plate consists of the main plate which pre-tensions the springs, and an outer ring that connects the pre-tensioning part with the mechanical gripper and further with the bucket. There are three transition points where the inner plate and ring are connected, and the inner shell has three slots to allow these transition points to move up and down during the duty cycle. Thus, the outer ring is located between the inner and outer cylindrical shells. In addition, the outer shell also has a slot where the outer ring of the plate is connected to the mechanical gripper that holds the bucket filled with lunar regolith. As a result, the lunar dust must pass through at least two slots, arranged at different angles, to reach the critical mechanical parts of the drive. This protection system ensures that the drive is adequately protected from lunar dust.

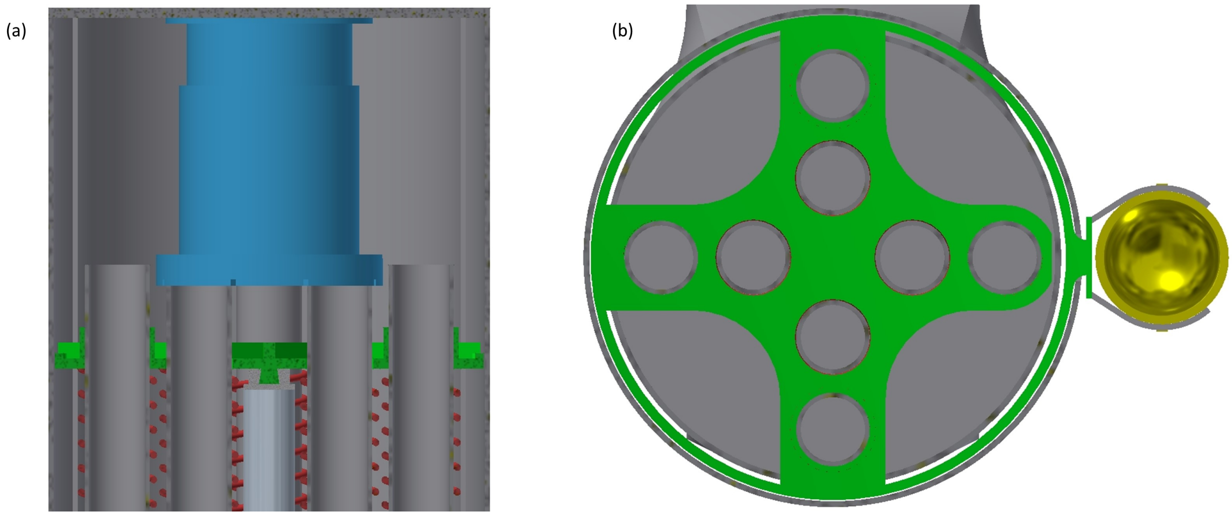


Figure 11.5: (a) detail of cross-section, (b) top view cross-section

As at the beginning of this chapter mentioned, Figure 11.6 shows the final design of the drive. Two cannons are connected in parallel, resulting in twice the acceleration force, and the volume of the bucket is doubled.

Figure 11.6: Final design of the drive

11.2.2 Swivel mechanism

In this subsection, the swivel mechanism of the conveying unit is described. Figure 11.7 shows the swivel mechanism implemented in the whole system. The main parts are the fork (cyan), the direct drive (blue), and two linear cylinders which are mounted on the excavator and the fork. Furthermore, the fork is connected to the excavator via two bolts (red). As previously mentioned in chapter 9.2, it is required that the swivel mechanism is able to fulfill swivel motions around two axes in a certain angle range. Swiveling about one axis is realized by retracting or extending the cylinders. Swiveling about the other axis is performed by the direct motor (blue). The direct motor is directly connected to the drive unit and by performing a rotary movement it swivels the entire drive unit. The drive is rotatably beared at the fork and the direct motor itself is mounted at the fork with two supports. Figure 11.8 shows one of many possible positions of the drive.

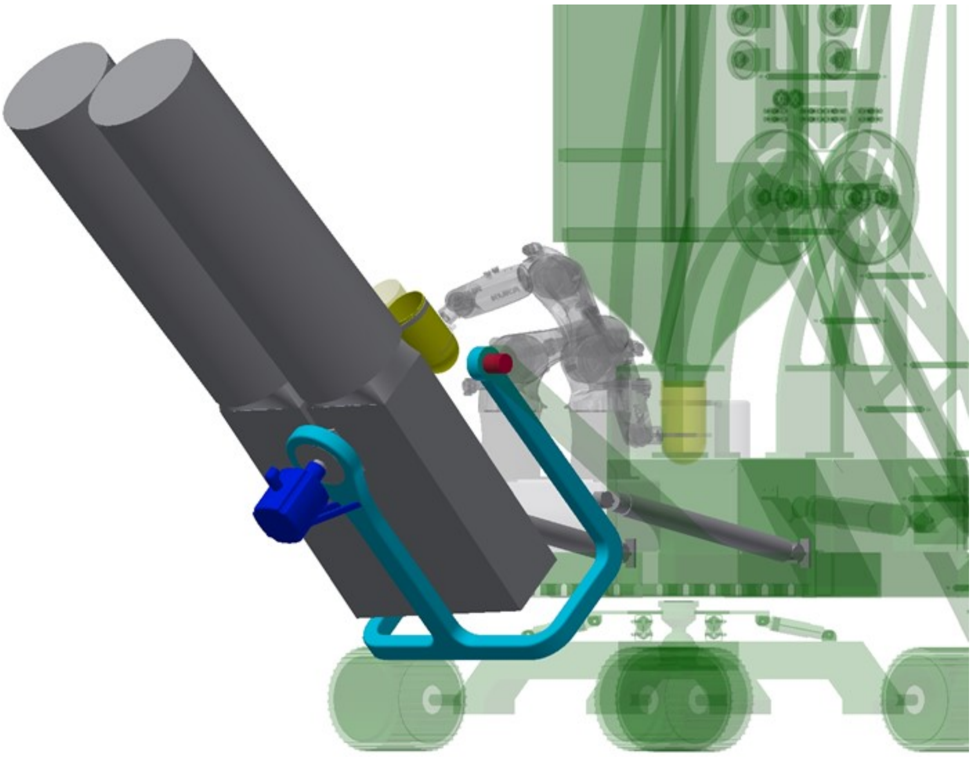


Figure 11.7: Overview of the swivel mechanism

11.2.3 Machine loading system

The machine loading system, illustrated in Figure 11.9 and 11.10, consists basically of two industrial robots from the company KUKA AG with mechanical grippers (orange/black), three buckets where regolith is transported (yellow), a mechanical gripper at the transfer chute, and a box where the robots are mounted and where is a place for control systems and energy supply. The mechanical gripper at the transfer chute is there so that the robot can release its gripper to pick up the bucket again at another position. It also enables the robot to release its grip during filling and, if necessary, to perform other activities while the bucket is being filled. The robot's mechanical grippers are concepted for delivering two buckets at the same time, this leads to a fast changing time of the buckets. After the drive has accelerated the bucket, the robot picks up the empty bucket with one part of the gripper, and with the other part of the gripper, it places the filled bucket in the drive. In the meantime, the third

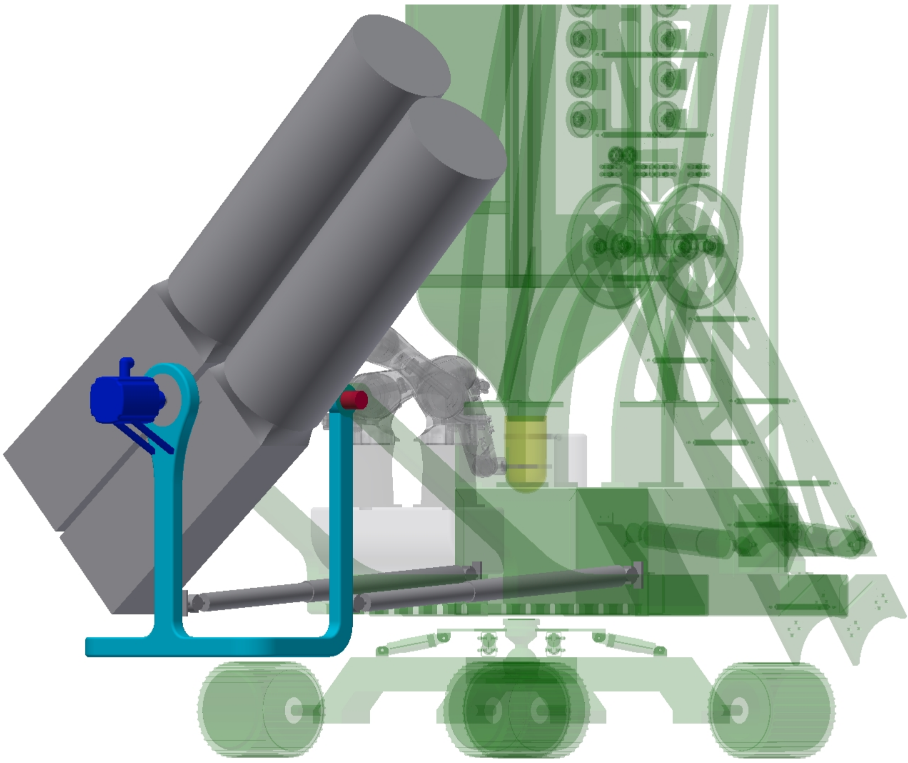


Figure 11.8: One of many possible positions of the drive

bucket is held by the other robot and refilled at the transfer chute. Afterward, the robot with the empty bucket moves to the transfer chute, and the robot with the refilled bucket moves to the drive and waits to change the empty with the full bucket. The entire operating cycle of the conveyor unit is described in detail in Chapter 12.

11.2.4 Bucket

Overall, three buckets are in use in the final design approach. Figure 11.11 shows a section view of the bucket. The bucket can hold a maximum volume of 4 dm^3 of lunar regolith. Furthermore, the bucket has a truncated cone shape combined with a spherical shape because of the conditions of lunar regolith. Specifically, the cohesiveness of lunar regolith is high, so the forces holding the particles together are high. Therefore, lunar regolith usually still sticks together after the acceleration process. However, relative

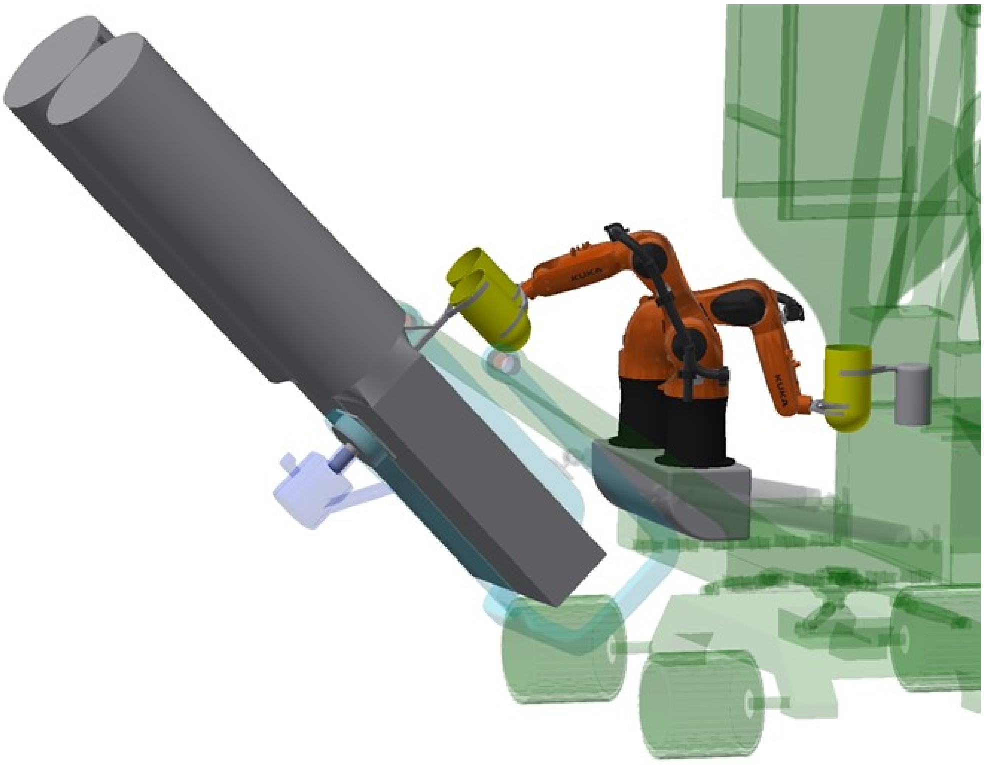


Figure 11.9: Overview of the machine loading system

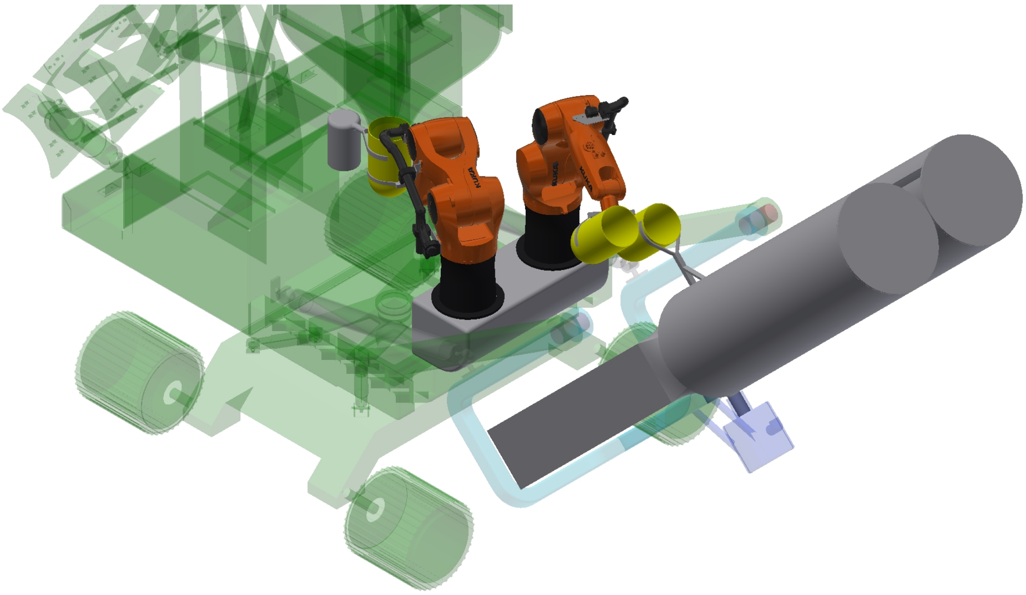


Figure 11.10: Another view of the machine loading system

velocity between lunar regolith and a mechanical part, such as the bucket, leads to high friction and wear. Thus, high friction and wear occur during the acceleration process when the bucket has a cylindrical shape and regolith slides over it. Additionally, the cohesion within the material to be conveyed is partially destroyed by friction, resulting in higher dust formation during the conveying process. Consequently, the bucket is realized with a conical shape leading to less friction and wear. The hemispherical shape at the end of the bucket results in a hemispherical shape of the accelerated material on one side, which has a beneficial effect on the flight characteristics.

Figure 11.11: Bucket

12 Operation cycle

In this chapter, several topics about the operation cycle are explained. First, two possible excavation areas are presented. Afterward, the material flow through the transfer chute is described. Finally, each step of the working cycle is explained.

12.1 Excavation area

Since the conveying system cannot swivel between 0 and 360 degrees, not every shooting angle is possible. For example, the conveying system is not able to shoot over the excavation robot. Instead, the conveyor always shoots away from the excavator. As a result, not every possible shot direction can be realized. In this subsection, two possible excavation areas are presented.

Figure 12.1 shows the spiral excavation method. The excavator and the conveyor are shown in simplified form, the exact design and operation of the excavator are described in detail in Dominik Höber's master's thesis 'Development of an Excavation Concept for Lunar Regolith'.

Generally, the excavator is a bucket scraper that drives with two robots and in the middle is the bridge where the buckets go around. One of the two robots drives on the already excavated surface, so this robot has no obstacles to overcome. The conveyor is attached to this robot, so the conveyor does not have to realign its direction due to the unevenness of the lunar surface.

The cross in the center of the spiral visualizes the target of the conveyor, where the conveying material has to land in order to be available for further processing. The excavator starts its operation approximately 100 m away from the lunar base due to dust generation during the operation. The excavator follows a spiral during excavation, thus it continuously moves away from the lunar base. The robot, to which the conveyor is attached, is always facing the target, so the conveyor never has to shoot over the excavator. Due to the distance between the mining position and the conveyor's target, the angle α and β must be minimally adjusted after each shot. When this excavation method is used, the material can be continuously excavated and conveyed without losing time for, for example, rearranging the excavator. In addition, the entire area is excavated without leaving any gaps.

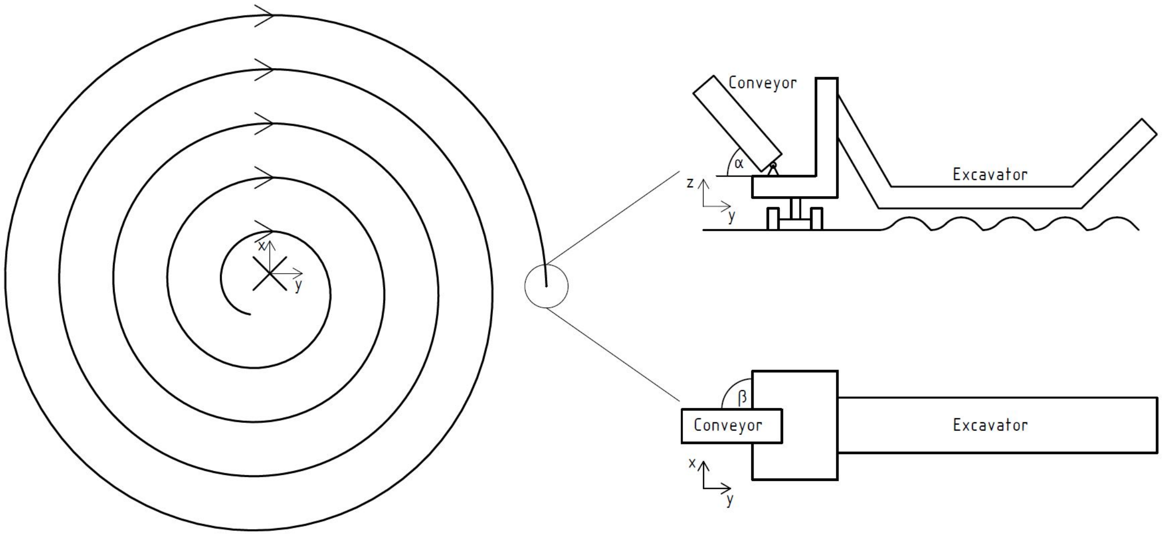


Figure 12.1: Spiral excavation method

Figure 12.2 shows another possible excavation method, the line excavation method. In this approach, the excavator follows are a certain route to excavate lunar regolith. In this case, the robot, to which the conveyor is attached, also always faces the lunar base. In Figure 12.2, the lunar base is also visualized with a cross. If this excavation method is used, then repositioning of the excavator is necessary so that the conveyor always faces the base. In addition, when the maximum conveying distance is reached, the excavator must change the base direction, which again takes time. The maximum conveying distance can be used as the radius of a circle to illustrate the maximum excavation area, which is limited by the maximum conveying distance. Thus, it can be seen that a circular excavation method, like the spiral excavation method, is preferable if the time required to excavate a certain area is to be kept to a minimum.

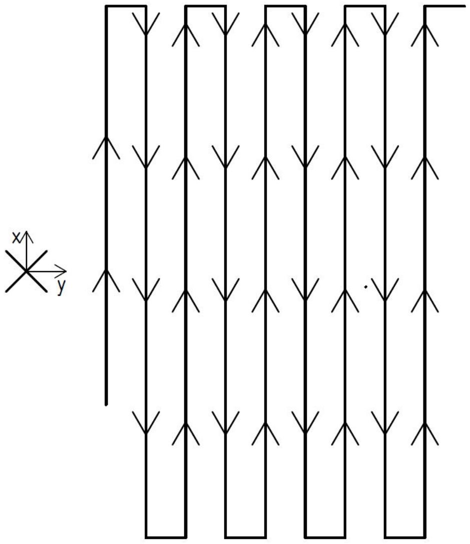


Figure 12.2: Line excavation method

12.2 Material flow

The material flow is a critical parameter for both systems, as there is no intermediate storage at the transition from the excavator to the conveyor. Therefore, the material flow of both machines must be coordinated to avoid material overflow and to ensure trouble-free operation.

The transition point is the transfer chute, which is circled in red in Figure 12.3. Basically, the buckets of the excavator dump lunar regolith in the transfer chute. Afterward, regolith goes through the chute. Finally, regolith leaves the transfer chute and flows in the conveyor buckets. Figure 12.4 illustrates the volume flow within the transfer chute as a function of time. One bucket of the excavator delivers 2 dm^3 and it takes 5 seconds for the next bucket to deliver 2 dm^3 again. It takes roughly 2 seconds that the material volume of one bucket goes through the chute. The conveyor buckets have a volume of 4 dm^3, so, 2 buckets of the excavator fill 1 bucket of the conveyor. According to Figure 12.4, the filling process of one bucket of the conveyor takes 7 seconds. However, this also means that the complete acceleration process for the volume of one bucket of the conveyor must not take longer than 7 seconds. The loading system of the conveyor can use the remaining 3 seconds to change the buckets at the transfer chute before new material arrives from the excavator. Conveying 4 dm^3 every 10 seconds leads to a volume flow of 0.4 $\frac{dm^3}{s}$.

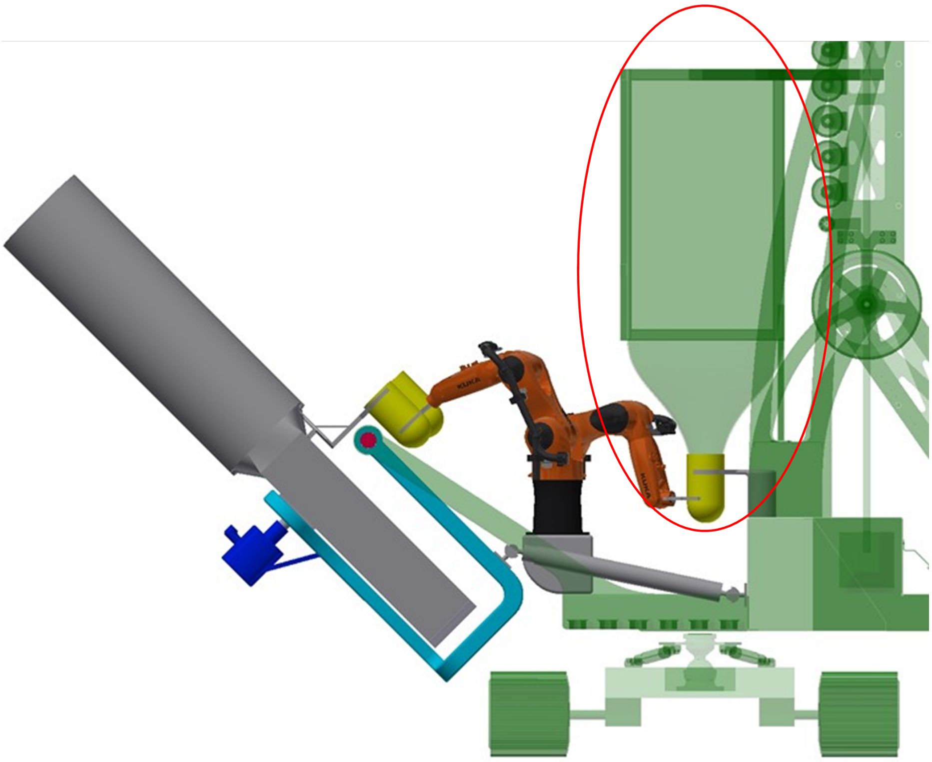


Figure 12.3: Transfer chute

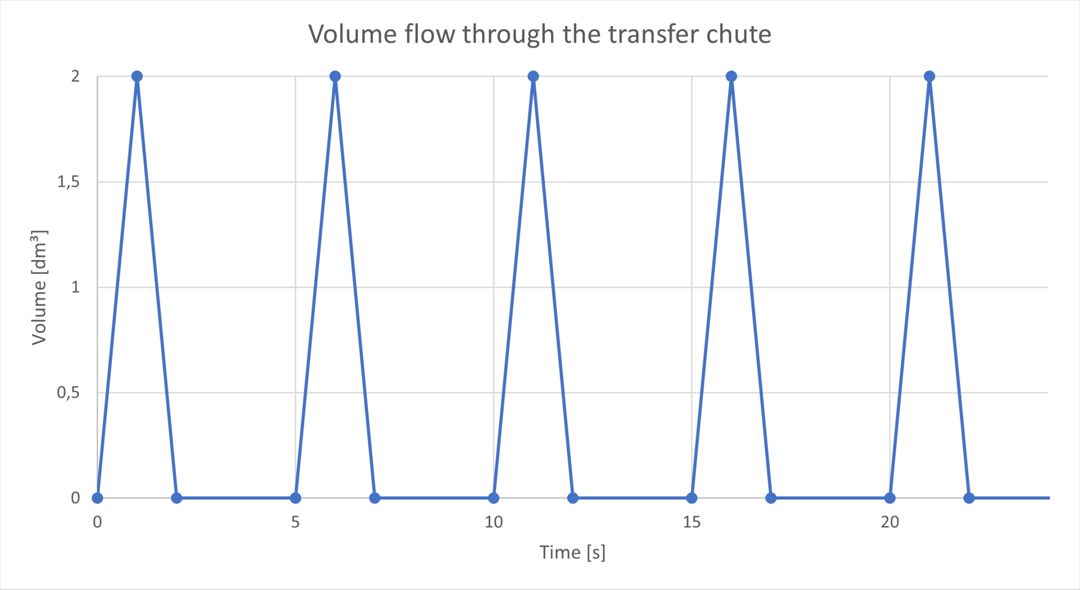


Figure 12.4: Volume flow through the transfer chute

12.3 Working cycle

In this subsection, the working cycle of the conveying system is structured in 4 main steps. These steps are illustrated in Figure 12.5. All four steps involve the same assemblies which are shown in simplified form in Figure 12.5, namely: the drive, which is responsible for accelerating the buckets, the two industrial robots which transfer the buckets between the transfer chute and the drive, the transfer chute where the buckets are filled, and 3 buckets into which the material is filled and accelerated by the drive. The consecutive steps are arranged clockwise in Figure 12.5, starting with the first step in the upper left corner.

Starting with the 1. step, robot 1 holds a filled bucket and is waiting for the empty bucket which comes back from the acceleration process of the drive. In the meantime, robot 2 locates the remaining bucket directly under the transfer chute in order to refill the bucket.

In the 2. step, robot 1 exchanges the empty bucket for the full bucket at the drive, this allows the drive to accelerate a full bucket again and convey the material to the target. Robot 2 is still holding the remaining bucket under the transfer chute to refill this bucket completely.

Moving on to the 3. step: robot 1 rotates to face the transfer chute and locates the empty bucket under the transfer chute to refill the bucket. Meanwhile, robot 2 rotates to the drive with the filled bucket and waits until the drive releases the empty bucket from the acceleration process.

In the 4. step, robot 1 is still holding the bucket under the transfer chute to refill this bucket completely. Robot 2 exchanges the empty bucket with the full bucket at the drive. Finally, the entire working cycle begins at the 1. step again.

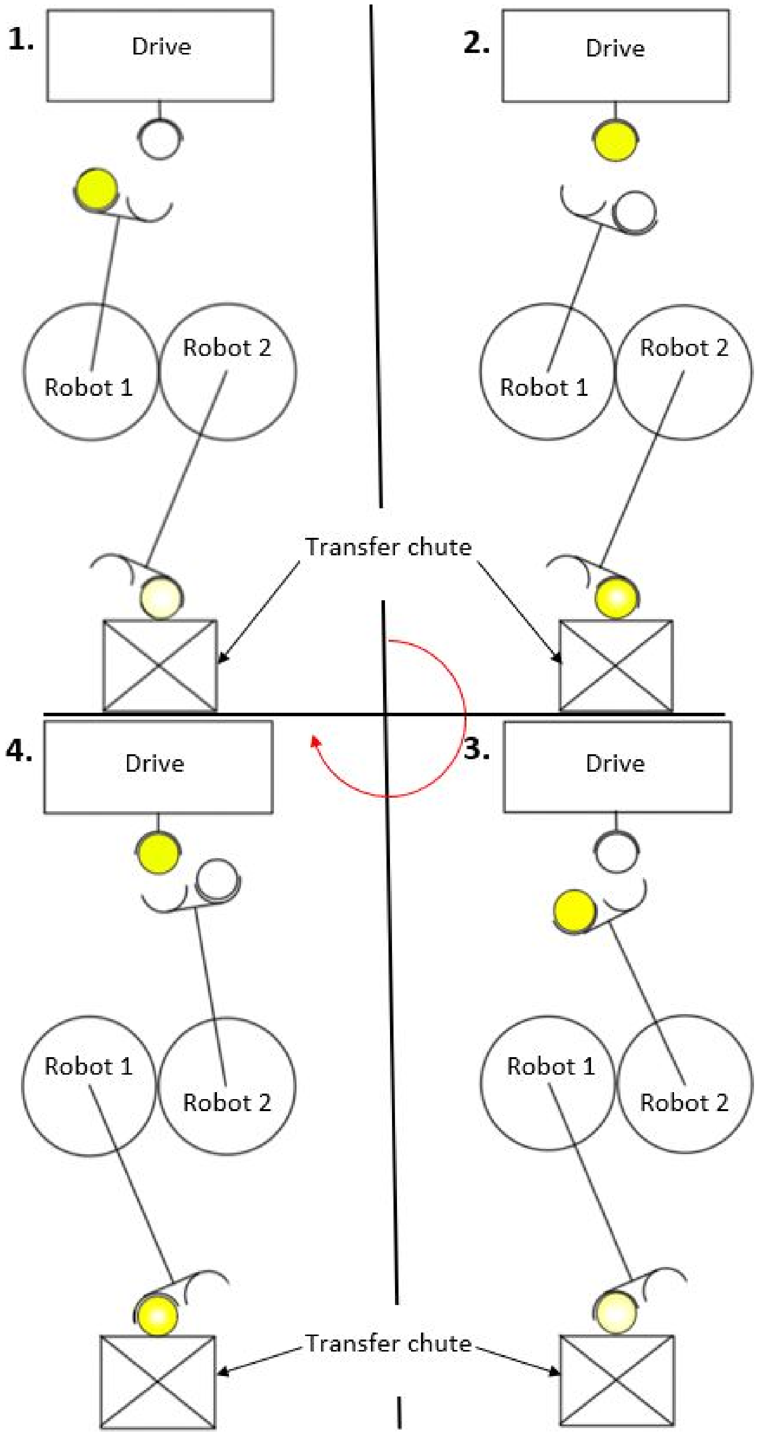


Figure 12.5: Working cycle structured in 4 steps

12.4 Material collection

After the conveying material has been accelerated by the conveyor, it must also be caught or collected at the conveyor's target. Generally, the intent of the basic principle is that the conveyor accelerates lunar regolith so that it has sufficient velocity to fly from the mining site to the lunar base or other location where lunar regolith will be further processed. The detailed layout and design of the landing site is not part of this thesis and needs to be further developed. The following approaches illustrate ideas on how the material collection can be implemented with advantages and disadvantages, followed by a discussion of which approach has the highest potential. Certainly, there are other approaches for the landing site that need to be taken into account, but which have not been considered in this thesis.

Bunker

This concept, shown in Figure 12.6, uses a bunker to collect the thrown material. Either a collection bin or a dug hole in the lunar surface can be used as a bunker. The material arrives generally at an angle of 45° to the lunar surface and is collected in the bunker. Another mechanical conveyor can be used for discharging the bunker to transport the collected material to the further processing stages. The benefits of this concept are the simple system, only a few parts necessary, and simple to install/many locations are appropriate for this solution. Disadvantages are that the hopper is static, dust generation occurs directly on the lunar surface which is a problem because such bunkers are usually placed near further processing steps or a lunar base, and a mechanical conveyor must actively move the material on to transport it to another position, such as the separation step. Another risk is that the processing plant, normally located close to the bunker, is at risk if the ballistic conveyor fails to hit its target.

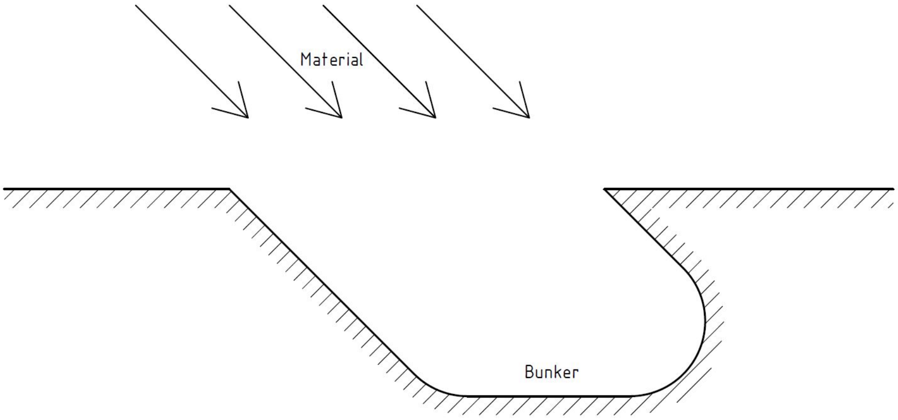


Figure 12.6: Bunker

Collection rover

The collection rover, illustrated in Figure 12.7, is another concept to collect lunar regolith after the acceleration through the conveying system. This concept can be realized as a mobile rover that has a collection bin mounted on the chassis. It can thus change its position which leads to advantages in terms of range and flexibility of the conveyor. However, more than one rover is needed, because when the rover is completely filled, it must return to the base and empty its collection bin. In the meantime, it cannot collect material and the conveyor cannot convey, which in turn leads to an overflow of material at the interface between the excavator and the conveyor. Another drawback is that the wheels or chains of a rover suffer from the challenging properties of lunar regolith which cause high friction and wear.

Collection container

This concept uses a collection container mounted on a large mast. Figure 12.8 shows this concept. The conveyed material is collected in the collection container. The collection container is mounted at a great height, as can be seen in Figure 12.8. This has significant benefits: dust is generated at a great high and not directly at the lunar surface and the collected material has a high potential energy. The saved potential energy can be used for discharging the container. For illustration, the material can be discharged without

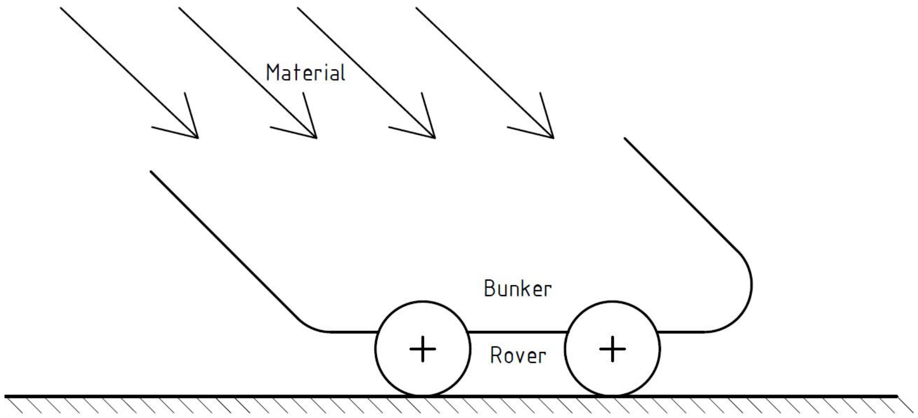


Figure 12.7: Collection rover

a mechanical conveyor, such as a screw conveyor. Instead, a drop chute can be used, which does not require a drive but can still guide the conveyed material to the desired location. The main drawback of this concept is the large mast that is necessary in order to locate the collection bin at such height.

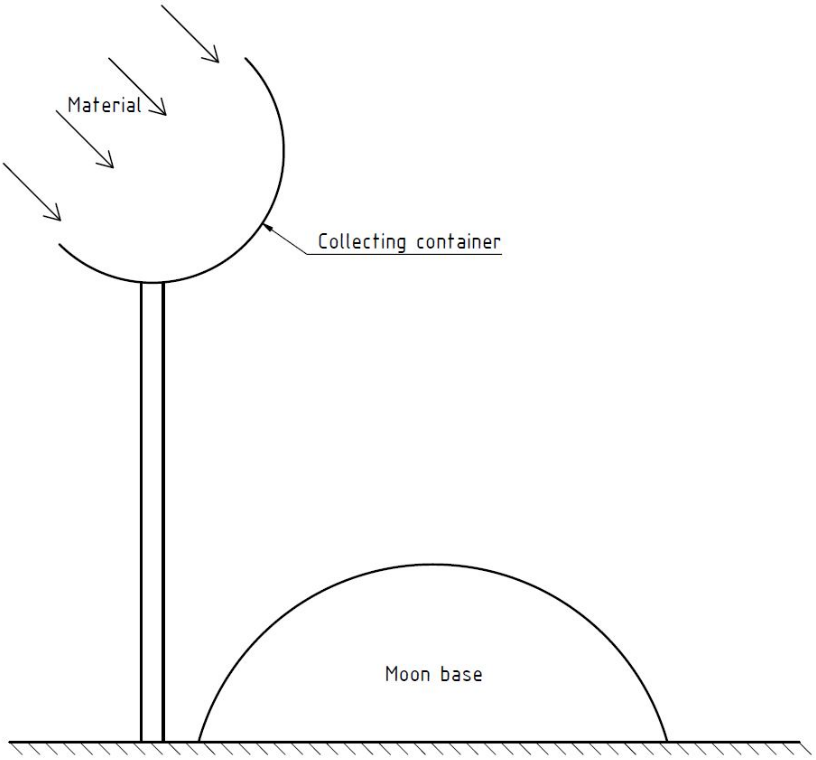


Figure 12.8: Collection container

Discussion

Each concept has its own advantages and disadvantages. The bunker is a simple system that can be used in many places without assembling, the excavator must dig the bunker, while the development of dust on the lunar surface and the required mechanical conveyor to discharge the bunker is a disadvantage. When flexibility are considered, the collection rover has valuable advantages compared to the bunker and collection container. The mobility of the rover can extend the range of the entire conveyor system to some extent. However, the collection rover also has significant disadvantages compared to the other two proposals: Several rovers are necessary to ensure the collection of the material, which results in an increased automation effort, and the moving parts, especially the wheels, are exposed to increased friction and wear, which has already been explained in chapter 8.1. Considering the collection container, the installation of the container and the large components is a disadvantage compared to the other concepts, but there are significant advantages: the stored potential energy in the material can be used to discharge the container, so no mechanical conveyor is needed for discharge, and the dust generation does not occur directly at the lunar surface.

The advantages and disadvantages of each concept compared with each other show that the collection container is the most suitable of these three concepts and brings the greatest advantages.

A misthrow of the conveyor poses a high risk to the nearby processing plant. Therefore, safety precautions must be taken to ensure that the processing plant is not damaged. To avoid false throws, the collection container should be as large as possible to compensate for possible conveyor aiming errors. In addition, collection nets should be installed in the area of the processing plant to slow down the material in case of a false throw and to separate the particles sticking together. For illustration, in Figure 12.8, the collection container should be large enough to protect the majority of the processing plant. For low misthrows that the collection container cannot catch, surrounding catch nets should prevent possible damage to the processing plant.

13 Further developments

In this chapter, further developments for the conveying system are considered and described. This thesis focuses on developing a basic principle for a conveyor system for the described application. The focus is on developing the mechanical principle of the conveyor to ensure the functionality for the certain requirements. Nevertheless, other topics have to be taken under consideration for a faultless operation of the conveyor. Redesigning subassemblies, automation of the operation, or topology optimization of the mechanical parts are some examples of such further developments. In the following subsections, several relevant topics are considered.

13.1 Range extension

The conveying system has a limited conveying distance. So, after a certain time (regarding to chapter 10 after several years) the distance between the mining site and a lunar base is too large for the conveyor to cover. This can be solved by range extenders. It is a mobile system on wheels or chains, that catches the conveyed material. Afterward, the range extender accelerates the material again. As a result, the material can cover greater distances. Furthermore, flexibility is increased because the material can be redirected through the range extender. This principle is shown in Figure 13.1.

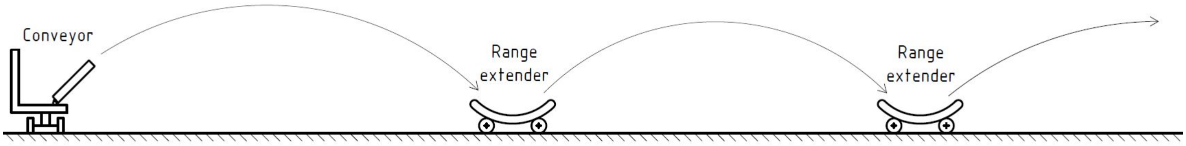


Figure 13.1: Range extenders

13.2 Pre-processing of conveying material

Due to the high and rapid acceleration of the conveyed material, some disintegration of the material, which is held together by cohesion, occurs. This in turn leads to increased dust formation in the area close to the conveyor. Furthermore, the complete material does not follow a trajectory, but scattering occurs. To overcome this challenge, there are several approaches. One of them is to pack the conveyor material into specific sizes, for example with a film or buckets. As the material flows through the transfer chute, it is tightly enclosed with a film after reaching a certain quantity. This prevents scattering during the subsequent acceleration and the packed material follows the trajectory.

Another approach is to press the material into a specific geometry, such as a sphere. Pressing the material leads to a significant increase in the forces that act between the particles and hold the material together. The spheres also have a specific size and would not disperse even in flight.

Finally, the conveying material can also be sintered before acceleration. The conveying material is held in a certain shape and then the surface is sintered so that there is no dispersion during acceleration and flight. Sintering can be performed with a laser, for example. This method is preferable compared to the other two mentioned because there is no waste or materials that have to be returned to the conveyor and still the hold of the material is ensured.

13.3 Automation

The automation of the complete conveying system is another essential point when it comes to developing a conveying system for the Moon. However, the automation is not part of this thesis, because it is very complex and would exceed the scope of this thesis. Nevertheless, automation is very important because it must ensure safe and error-free operation. Especially the cycle times of the loading system of the conveyor and the acceleration process of the drive have to be coordinated exactly. Furthermore, the system must also be remotely controllable so that, for example, in the event of problems or irregularities, a human can control the machine. The automation of the conveyor system can be realized surely, since the control and the automation from the basic principle functions similarly as the control of a tank. Modern tanks drive at high speeds over bumps and can still hit a target at a long distance with high precision.

13.4 Design materials

Basically, possible design materials are mentioned in chapter 6. However, it is also clear that further research is necessary to find the right material for the optimized components. The selection depends on several factors, such as the load on the component, whether the component is in direct contact with regolith, or the mass requirements. In conventional industry, the cost of the material is also a significant consideration. However, in this application, cost is secondary, as other points are more important, such as mass or functional safety. Materials for space applications are certainly available, as several rovers are already performing exploration missions on different planets.

Important components in this design proposal are the drive springs, which are preloaded by a linear cylinder and then accelerate the bucket. These components are subjected to large loads and are critical to the operation of the conveyor system. Therefore, the main attention must be paid to these components. The basic research has shown that the material 1.4568RS from Hennlich GmbH & Co KG meets the basic requirements of this special application. This material is high-strength, capable of withstanding dynamic fatigue loads, and is a reliable material for springs. However, this material was also developed for conventional industrial applications and not for space applications. Therefore, further research or cooperation with the manufacturer is necessary here as well.

13.5 Manufacturing and assembling

The manufacturing and assembling of the components to form the complete conveyor system is another important point. Various manufacturing processes can be used. However, this also depends on several factors such as the material used or the geometry of the components. For example, in the design proposal of this thesis, several components with complex geometry have been used, which can be manufactured with additive manufacturing. However, not every material can be processed with additive manufacturing. Similar to the design materials, cost is not the main factor since large quantities of the conveyor system are not produced. The manufacturing process must be determined separately for each individual component.

Furthermore, the design proposal uses purchased assemblies, such as the linear cylinders or the friction spring. These purchased assemblies, as shown in the figures in chapter 11, are not optimized for space applications. Instead, they have been developed for conventional industrial applications. However, linear cylinders are used on rovers that are on exploration missions on celestial bodies. The friction spring is also used in space applications. For example, a friction spring is used on-board the Mars rover Curiosity. So, both assemblies are used in space applications. However, they must also be adapted to the challenging environmental conditions and also optimized (for example, mass optimization).

13.6 Dust protection

Lunar dust is a major challenge when it comes to lunar exploration missions. Dust is generated in almost every motion on the lunar surface. On Earth, dust is also a problem but easier to handle. On the Moon, gravity is lower than on the Earth which causes that the dust is longer in the atmosphere and it takes more time for the dust to reach the lunar surface. Moreover, the lunar dust is electrostatically charged which leads to it adhering to the components of the conveyor. These particles are also a major problem for parts that execute motion, such as the linear cylinder or industrial robots.

There are two basic approaches to overcome the dust problem. First, to protect the important parts of the conveyor with multiple covers or to protect it with dust-preventing mechanisms. For example, an electromagnet that attracts the dust can be placed near the essential parts and ensure that the dust is not attracted to the components of the conveyor. Second, it is important to avoid dust development. To illustrate, each wheel that is moving on the lunar surface generates dust. So, it is critical that only necessary movements are done on the lunar surface in order to avoid dust. The design approach of this thesis has a major benefit compared to other conveyor concepts. The conveyor has not a chassis that is responsible for the movement of the system. Instead, the conveyor system is attached to the excavator directly. Therefore, dust development is reduced due to the use of the same chassis. Furthermore, the excavation area is about 100 m away from the lunar base where other processing steps are carried out. As a result, dust that is generated through the excavation and conveying operation affects the excavator and the conveyor but not other infrastructure such as the lunar base. Further studies have to be done to reduce dust development to a minimum.

13.7 Error handling and maintenance

Due to the absence of humans on the Moon, error handling and maintenance also takes on great importance. If a component or subassembly is no longer capable of performing its task without error, significant problems are the result. This leads with high probability to a total failure of the whole system. To avoid this, further analyses must be carried out on how to deal with and solve problems.

The industrial robots are not only suitable for the loading system of the machine, they also have significant advantages in maintenance and troubleshooting. Due to their high flexibility, they can repair or replace parts that are within their reach. For example, the industrial robots can solve problems and repair parts by changing from mechanical grippers to tools. This is a useful approach for performing simple maintenance tasks.

13.8 Energy

The energy supply of the system is another important point to consider. Since there is no existing infrastructure for energy supply as on Earth, the machine must have its own facilities that generate energy. For this design proposal, isotropic generators are suggested. Here it is important to avoid unnecessary energy consumption, such as from unnecessary movements. Rough estimations regarding energy consumption have been carried out. However, it has been found that the purchased subassemblies, which are not optimized for space applications, consume significantly more energy than subassemblies of the Mars rover. This is due to several factors, such as the degree of optimization, since cost is not important for space applications, but it is for conventional industrial applications.

Compared to terrestrial conveyors, the ballistic conveying approach has low energy consumption for the same conveying distance. According to the chapter 10, 2430J are necessary to throw the material 300m. Furthermore, it is possible to regain energy from the process. After the acceleration of the material, it follows a trajectory and reaches a collecting facility. When the material reaches the catching facility, it still has a certain velocity which means that the material has a certain kinetic energy. This kinetic energy can be transformed into electrical energy. For example, a material turbine can be used to convert kinetic energy into electrical energy. Such a concept is shown in Figure 13.2. The material turbine is mounted in the collecting bunker. The accelerated material hits the turbine blades and the turbine is rotated. Kinetic energy is converted into rotational energy. The material turbine is connected to a generator, which is driven by rotational energy and therefore generates electrical energy.

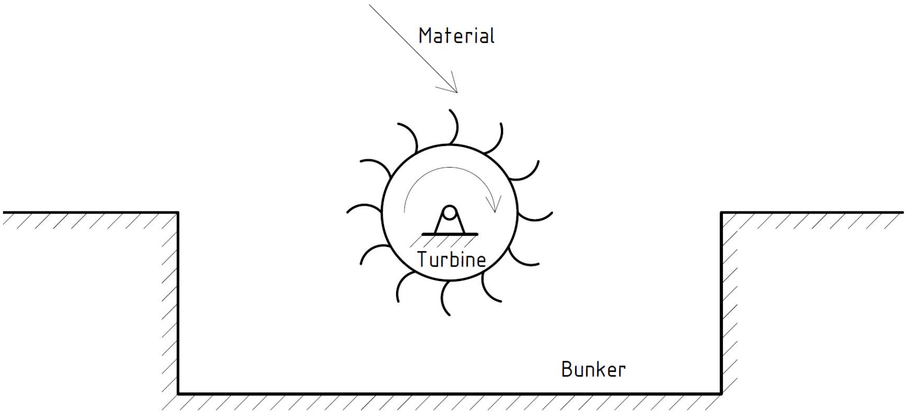


Figure 13.2: Material turbine

13.9 Interface between excavator and conveyor

The excavator and the conveyor must constantly cooperate when material is excavated, since there is no buffer in the design proposal of this thesis. Consequently, the interface must be planned very precisely to ensure smooth operation. Additionally, the interface must control both systems. For example, if the excavator excavates slower than planned, then the conveyor must also convey slower so that there are no misalignments in the cycle times and the filling of the buckets works properly. Conversely, the interface must also control the excavator if problems occur with the conveyor and, if necessary, slow down or stop the excavator.

14 Conclusion

After the end of the "Space Race" in 1969, space exploration received less attention in the years that followed. In recent years, however, space exploration has experienced a "renaissance". There are two main reasons for this. Private space companies, such as Blue Origin or SpaceX, have entered the space market. This creates new opportunities to conduct space missions. The other reason is that in addition to the U.S. and Russia, other countries, for instance, China and Saudi Arabia, are also conducting space missions, which in turn is leading to some competition between these countries. One of the most attractive celestial bodies at present is the Moon and Mars. The reason for this is that human life may be possible on these celestial bodies. A crucial aspect plays the Moon rock, which covers the surface of the Moon: This rock, namely lunar regolith, contains oxygen in oxide compounds. This oxygen can be extracted and is available for further use. At this stage, there are two major applications for this oxygen. On the one hand, to use it as rocket fuel. Rockets contain a considerable amount of oxygen as fuel at the start on the Earth. If the rockets can be refueled at the Moon, they can cover a larger traveling distance or can deliver a larger amount of payload due to the mass reduction at the takeoff on the Earth. Another approach is to refuel the rockets on the Moon so that they can then fly on to Mars. On the other hand, the extracted oxygen can enable longer human exploration missions on the Moon.

Lunar environment

The lunar environment is special and completely different from the terrestrial environment. Basically, a lunar day lasts 14 Earth days. The same applies to the lunar night. The temperature differences are greater compared to Earth, with -258°C as the lowest temperature and +127°C as the highest temperature. Furthermore, the gravity is 1/6 of the Earth's gravity and the atmosphere has a 14 times lower gas concentration compared to the Earth's atmosphere.

Regolith, the lunar rock to be extracted by the production system, covers the lunar surface with a layer thickness of several meters. The material lies loosely on the surface and does not have such a strong cohesion as the surface material of the Earth. This material has special properties and can hardly be compared with a material on Earth. The particle size varies greatly, has a sharp particle shape, and the cohesion is high. Furthermore, the fine particles of this material are easily stirred up when humans or machines are moving on the lunar surface, and dust is generated. This dust is a major problem for people and machines because the particles are small and also electrostatically charged, so they are attracted to various surfaces.

ISRU – In-Situ Resource Utilization

Normally, the oxygen needed for human space missions or as fuel is brought from Earth to the Moon. Instead of bringing oxygen from Earth, a future goal is to produce oxygen from lunar regolith via ISRU. The ISRU chain consists of 4 main links: excavation, conveying, beneficiation, and processing. The last 2 steps, beneficiation and processing, are part of several research projects but further research needs to be done in the first two stages, excavation and conveying. The link excavation is covered in Dominik Höber's master thesis "Development of an Excavation concept for Lunar Regolith". This thesis is concerned with the research of the conveying step.

Basic principles for conveying

The lunar environment and lunar regolith create special requirements for the conveyor system. First, lunar regolith has a sharp particle shape and has high cohesion. The sharp particle shape causes high friction and wear at relative speeds between the mechanical parts and this material. The cohesion results in a non-free-flowing material that easily clogs transfer points. Furthermore, the conveying system must be flexible, since the excavator only excavates the top layer of the surface and constantly changes its position. In addition, the conveyor system must transport the material over a longer distance (minimum 100m).

These special requirements make many terrestrial conveyor systems on the Moon unsuitable, such as the belt conveyor. Although the ballistic conveying system is rarely used on Earth, it has some distinct advantages for use on the Moon. First, gravity on the Moon is only 1/6 that of Earth, resulting in a greater range of accelerated material. Second, the thin atmosphere slows the accelerated material less than the atmosphere on Earth. Third, cohesion, which is normally a problem with conventional conveyor systems, is beneficial in this case because the material is held together and does not decompose during acceleration. Fourth, this conveyor system can be feasibly implemented with few moving parts and little contact with the material being conveyed. Furthermore, this approach can be implemented in a flexible/mobile way, such as directly mounted on the excavator.

Concept of a ballistic conveyor system

In general, the operation of the ballistic conveyor is based on that of a medieval ballista. Furthermore, the conveyor system is attached to the excavator, so the system does not need its own chassis. The system was further divided into 3 main assemblies: Drive, swivel mechanism, and machine loading system. For each main assembly, concepts were again collected, advantages and disadvantages were compared, and the concept with the highest potential was selected.

The machine loading system basically consists of 2 robots and 3 buckets and builds the interface between the excavator and the conveyor. The 2 robots transfer the buckets with mechanical grippers between the transfer chute, where the buckets are filled with regolith, and the drive of the conveyor system, where the material is accelerated. After the buckets are filled, they are transferred to the drive. This drive also holds the buckets with a mechanical gripper and the buckets are accelerated. After reaching the desired acceleration, the drive abruptly decelerates the bucket and the material leaves the bucket and flies to the desired destination. The empty bucket is then picked up by one of the two robots and transferred back to the transfer chute. The work cycle then starts again. The loading system is described in detail in chapter 11.2.3 and the working cycle of the conveyor system is explained in chapter 12.3.

The main parts of the drive are the springs and the linear cylinder. This cylinder pretensions the springs via a plate. Afterward, the springs are released and they accelerate this plate that is connected with the mechanical gripper where the bucket is held during acceleration. After the acceleration, the plate hits a spring-damper system that decelerates the plate and the bucket abruptly. Finally, the linear cylinder picks the plate and pushes it down in order to pretension the springs again and is ready for the next acceleration. Chapter 11.2.1 contains the detailed description of the drive.

The conveyor system has to realign its target because of the movement of the excavator and the target of the conveyor is static. So, a swivel mechanism is necessary to fulfill this requirement. In detail, the conveyor must be able to swivel between 30° and 60° around the x-axis and from -90° to 90° around the z-axis. The angle range is also illustrated in Figure 9.12. The chosen concept is a combined solution: a direct engine ensures the swivel capability around one axis and linear cylinders are used for swiveling around the other axis. The approach is explained in detail in chapter 11.2.2.

Overview of the conveyor

For better visualization, a 3D model of the conveyor system has been created with a design program. The main focus is on the mechanical setup and the mechanical functionality. The level of detail of the conveyor system is low and it is shown that this system can work as described. However, the most important components/assemblies are shown in detail, such as the industrial robots of the machine loading system or the drive of the acceleration system. Surrounding components, such as cables for power supply and interconnecting of the individual systems or covers to protect against dust are missing. Other components, such as the mechanical gripper, have a lower level of detail and need to be further elaborated to be suitable for lunar applications.

The designed conveyor system approach fulfills the basic requirements of the lunar environment, especially the challenges according to lunar conveying. Moreover, the size is acceptable and it is transportable with a spaceship. The conveyor system concept can produce a material flow of 0.4 $\frac{dm^3}{s}$ which is the volume flow of the excavator. As a result, the conveyor can convey enough material to launch three rockets every two lunar days. According to the rough calculations in chapter 10, the conveyor can transport the material over a maximum of 300 m theoretically.

Outlook

This developed conveying system concept of this thesis presents a promising approach for lunar conveying as a second link in the ISRU chain. For real use on the Moon, several more development stages are necessary and many other aspects besides the mechanical setup have to be considered and focused on. Some of these aspects are presented and explained in chapter 13, and suggestions are given on how the further development of the respective aspect can look like. For example, aspects such as automation, maintenance, or energy supply are important for the further development of the system. These challenges have to be solved in an interdisciplinary way and not only by mechanical engineers. Especially, lunar dust is a major problem for humans and machines during exploration missions. So, humans and machines must be protected against dust and ways must be found to avoid dust generation. In addition, some lunar environmental conditions, such as the electromagnetic fields on the lunar surface, are still not fully explored. These conditions can also be influences for lunar conveying.

Besides its promising use for lunar conveying, the developed conveying concept can also be used for other purposes on the Moon. For example, the conveyor unit can target material where it is needed to fill holes, hollows, or entire valleys with material in order to level the surface. Furthermore, not only lunar regolith can be transported with this conveyor unit, but also other things can be accelerated with the drive of the conveyor unit and thus transported over long distances. An important role can also be attributed to the robots of the machine loading system. Due to their flexibility, they can be used not only to transfer the buckets between the transfer chute and the drive unit, but also to repair and maintain the systems using tools and other devices. They can also repair other machines and equipment, which contributes to a smooth workflow throughout the entire ISRU process.

Spin-off to the Earth

Before considering the concept of ballistic conveying, which has been developed in this work specifically for use on the Moon, some considerations must be made. In general, the two biggest differences are the atmosphere and the gravitational acceleration. The atmosphere on Earth is denser, and the gravitational acceleration on Earth is six times larger than on the Moon. Therefore, more energy is required to transport the material the same distance as on the Moon. Additionally, the weather and climate must be taken into account. In strong winds or thunderstorms, the accelerated material may be deviated from the trajectory and not arrive at the intended destination. The most important point is that the Earth is inhabited by humans and other living beings, in contrast to the Moon. When using the ballistic conveying system on the Earth, the lives of humans and other living beings must never be endangered.

Nevertheless, there are spin-offs to terrestrial applications where certain features of this conveyor concept can be used. This conveyor system can also be used, for example,in mining sites that are located in rough terrain to transport the material over the obstacles of the rough environment from the mining area to a developed area where other systems continue to convey the material. The ballisitic conveyor system would be more efficient to transport the mined material in a short period of time (e.g., a few days) than, for example, clearing large areas of rainforest to build a conveyor belt.

Another application can be: if a mining area consists of several mobile mining units working side by side and to which a ballistic conveyor is connected, each of these ballistic conveyors can transport the mined material to a collection station. From this collection station, the material can then be transported further by stationary conveyor systems.

There are also chipping machines with a ballistic conveying system when removing the chipped wood from the machine, but the possible conveying distance is limited. So another application can be to pack the chipped wood into bundles and by means of the ballistic conveyor to convey these bundles over further distances. This can be especially advantageous on rough terrain, such as steep slopes. Furthermore, this transport system can also have advantages if there are obstacles on the transport route that can only be overcome by greater effort, but this effort is not worthwhile, for example, because of too high costs or the obstacle only has to be overcome for a few days.

In addition, such a ballistic system can be used to even the terrain. For example, valleys could be leveled with the system, or after floods or mudslides, the washed-up material could be removed. Also, closed mining areas could be leveled again, or pits and holes in general could be filled again.

Furthermore, the ballistic conveying system can play an important role in supplying crisis areas in the future. Such crisis areas can arise, for example, as a result of war, floods or wildfires, where part of the civilian population is cut off from the outside world and the supply of this population is no longer guaranteed. In such crisis situations, the ballistic conveyor can transport rescue packages. For example, this conveyor system can accelerate the rescue packages and after a certain time the parachute of the rescue packages opens so that the rescue packages arrive exactly at the civilian population that is in danger. Thus, conventional rescue pilots could be supported or replaced and the rescue pilots would no longer be exposed to risk (flights over fire and war zones are risky). Similarly, isolated locations in need of care could be served. For example, outlying mountain huts that are normally served by helicopters could also be served by this system, replacing the helicopter.

Moreover, in the agricultural industry, a ballisitic conveying system can also be used. Farmers' fields tend to get larger and thus the machines that apply certain things must also get larger to achieve the desired efficiency. The ballistic conveyor can help with this by spreading fertilizers, seeds, or pesticides. These things can be bundled into packages and after acceleration by the conveyor system, the packages can open at a certain height so that the things are evenly distributed on the field.

In conclusion, the conveying concept presented in this work is a promising approach for lunar conveying to establish the entire ISRU chain for oxygen production, thus making a significant contribution to human exploration missions on both the Moon and Mars.

List of Figures

2.1 The Moon surface with mares and highlands [60] 6
2.2 Moon mares [60] 7
2.3 The Apennines on the Moon [60] 7
2.4 Crater landscape [60] 8
2.5 Orientale Basin [51] 9
2.6 Distribution of water ice at the northern and southern polar regions [29] 10
2.7 Temperature profile at the Moon´s surface [51] 12
2.8 Lunar agglutinate [51] 14

3.1 ISRU process chain [25] 19
3.2 Moonraker robot [34] 21
3.3 Backhoe as an excavator system [25] 21
3.4 Graphic of pneumatic conveyor [35] 22
3.5 Future design of a pneumatic conveyor [51] 22
3.6 Diagram of a free fall type separator [47] 24
3.7 Diagrammatic representation of an IRMS [47] 24
3.8 Different types of reduction reactors [50] 26
3.9 Sketch of the carbothermal reduction of lunar regolith [5] 27

4.1 Spirit and Opportunity [44] 30
4.2 Structure of Spirit and Opportunity [39] 31
4.3 Curiosity [41] 32

4.4 Curiosity´s turret [41] 33
4.5 Structure of Curiosity´s turret [40] 33
4.6 Perseverance [37] 34
4.7 Perseverance and its cameras [37] 34
4.8 Ingenuity [37] 35
4.9 NASA Rassor [43] 36

5.1 Vulcan Centaur [61] 38
5.2 European Large Logistics Lander [14] 39
5.3 NASA Lunar Lander [28] 40
5.4 Peregrine [2] 41
5.5 Starship: crew configuration and uncrewed configuration [56] 42
5.6 Starship payload volume [56] 43
5.7 Blue Moon [7] 43

8.1 Wheel damage on Curiosity [27] 53
8.2 Regolith Processing Rover [22] 55
8.3 FCT flexible conveyor train from the company Komatsu [24] 57
8.4 Tubular drag conveyor [57] 58
8.5 Carriers of a trough conveyor [46] 58
8.6 Different types of screws [52] 59
8.7 Different working principles of vibrating conveyors [46] 60
8.8 Elevated track for long-term transportation [27] 61
8.9 (a) Telescopic railway rover in mobile mode; (b) cross-section of the rails 62
8.10 Telescopic railway rover in working mode 62
8.11 Track-laying vehicle 63
8.12 Scissor roller conveyor [48] 64
8.13 Approach of a pneumatic conveyor in the future [51] 66
8.14 Electromagnetic conveyor [3] 67
8.15 Concept for a ballistic conveyor [51] 68

9.1 Blast wheel 75
9.2 Cylinder-piston system 76
9.3 Slingshot example 1 77
9.4 Slingshot example 2 77
9.5 Rotational slingshot 78
9.6 Bucket wheel 79
9.7 Acceleration wheel with pre-tensioned spring 80
9.8 Four-bar linkage 81
9.9 Spring drive with toothed rack 83
9.10 Spring drive with a linear cylinder 85
9.11 (a) Ballista [6], (b) Catapult [9] 87
9.12 Angular ranges 88
9.13 Rope 90
9.14 Cylinder 90
9.15 Worm gear 91
9.16 Curved cylinder 92
9.17 Linear cylinder 93
9.18 Eccentric mechanism 94
9.19 Direct mechanism 95
9.20 Gear wheel 96
9.21 Tiltable plate 97
9.22 (a) tiltable plate with Cardan joint; (b) tiltable plate with the mounted drive assembly 97
9.23 Fork system 99
9.24 Intermediate storage 102
9.25 Drum storage 103
9.26 Circular storage 105
9.27 Rotary storage 106
9.28 Vertical loading system 108

9.29 Robot system with intermediate bucket storage 109
9.30 Loading system with linear cylinders 111
9.31 Rotating plate with gates 112
9.32 Loading system with 3 robots 113
9.33 Loading system with 2 robots 115

10.1 Required initial velocity as a function of distance 118
10.2 Required energy at the start as a function of distance 119

11.1 Overview of the conveying unit 122
11.2 Side view of the conveying unit 123
11.3 Drive (a) stressed, (b) unstressed, (c) transparent 124
11.4 Cross-section of the drive (a) unstressed, (b) stressed 125
11.5 (a) detail of cross-section, (b) top view cross-section 126
11.6 Final design of the drive 127
11.7 Overview of the swivel mechanism 128
11.8 One of many possible positions of the drive 129
11.9 Overview of the machine loading system 130
11.10 Another view of the machine loading system 130
11.11 Bucket 131

12.1 Spiral excavation method 133
12.2 Line excavation method 134
12.3 Transfer chute 135
12.4 Volume flow through the transfer chute 136
12.5 Working cycle structured in 4 steps 138
12.6 Bunker 140
12.7 Collection rover 141
12.8 Collection container 141

13.1 Range extenders 145

13.2 Material turbine 150

List of Tables

2.1 Overview of properties Moon and Earth [51] 5
2.2 Gas composition of the lunar atmosphere [18] 11
2.3 Major and trace elements of regolith [51] 14
2.4 Cohesion and internal friction angle of regolith [18, 30] 15
2.5 Particle size distribution in lunar soil [10] 16

4.1 Facts about the missions Spirit and Opportunity [44] 30
4.2 The Curiosity mission [41, 40] 32

6.1 Design materials for lunar applications [63] 47

Bibliography

[1] Ahmad Anwar et al. “Vacuum Effect on Spacecraft Structure Materials.” In: *International Conference on Aerospace Sciences and Aviation Technology* 16.AEROSPACE SCIENCES (2015), pp. 1–10. DOI: `10.21608/asat.2015.22908` (cit. on p. 46).

[2] Astrobotic Technology. *Peregrine Lunar Lander Payload User's Guide*. Ed. by Astrobotic Technology. URL: `https://www.astrobotic.com/payload-user-guide` (cit. on pp. 40, 41).

[3] B.C. Eimer nad L.A. Taylor, ed. *Lunar regolith, soil, and dust mover on the Moon.* (Cit. on p. 67).

[4] Viorel Badescu. *Moon [recurso electrónico]: Prospective Energy and Material Resources*. Alemania: Springer Healthcare Ltd, 2012. ISBN: 9783642279690. DOI: `10.1007/978-3-642-27969-0`. URL: `http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10545842` (cit. on pp. 5, 13, 20, 21, 25–28).

[5] R. Balasubramaniam et al. “Carbothermal Processing of Lunar Regolith Using Methane.” In: *AIP Conference Proceedings*. AIP, 10–14 February 2008, pp. 157–161. DOI: `10.1063/1.2844962` (cit. on p. 27).

[6] *BALLISTA.....(MODIFIED VERSION OF LEONARDO DA VINCI's.....) | 3D CAD Model Library | GrabCAD*. 7.05.2021. URL: `https://grabcad.com/library/ballista-modified-version-of-leonardo-da-vinci-s-1` (cit. on p. 87).

[7] Blue Origin. *Blue Moon*. Ed. by Blue Origin. URL: `https://www.blueorigin.com/blue-moon/` (cit. on pp. 43, 44).

[8] C. I. Calle. "The electrostatic environments of Mars and the Moon." In: *Journal of Physics: Conference Series* 301 (2011), p. 012006. DOI: `10.1088/1742-6596/301/1/012006` (cit. on p. 46).

[9] *Catapulta medieval / Medieval Catapult | 3D CAD Model Library | GrabCAD*. 7.05.2021. URL: `https://grabcad.com/library/catapulta-medieval-medieval-catapult-1` (cit. on p. 87).

[10] J. E. Colwell et al. "Lunar surface: Dust dynamics and regolith mechanics." In: *Reviews of Geophysics* 45.2 (2007). ISSN: 8755-1209. DOI: `10.1029/2005RG000184` (cit. on pp. 13, 16, 17).

[11] Heather Couper et al. *The planets: The definitive visual guide to our Solar System*. First American edition. London: Dorling Kindersley, 2014. ISBN: 9781409353058 (cit. on p. 5).

[12] Dallas Bienhoff. *The Future of Commercial Space Transportation*. Ed. by The Space Review. URL: `https://thespacereview.com/article/3776/1` (cit. on p. 37).

[13] European Cooperation for Space Standardization. *Space product assurance: Kinetic outgassing of materials for space*. Ed. by ESA Requirements and Standards Division. Netherlands, 2011. URL: `https://ecss.nl/hbstms/ecss-q-tm-70-52a-kinetic-outgassing-of-materials-for-space/` (cit. on p. 46).

[14] European Space Agency. *European Large Logistics Lander*. URL: `http://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/European_Large_Logistics_Lander` (cit. on pp. 38, 39).

[15] Leo Ferguson. "What Our Future Will Look Like on Mars - Predict - Medium." In: *Predict* (7.11.2020). URL: `https://medium.com/predict/what-our-future-will-look-like-on-mars-30984b08632c` (cit. on p. 2).

[16] Hanneke Weitering. *Blue Moon: Here's How Blue Origin's New Lunar Lander Works*. Ed. by Space.com. 10.05.2019. URL: `https://www.space.com/blue-origin-blue-moon-lander-explained.html` (cit. on p. 44).

[17] Philipp Hartlieb et al. *Excavation & Conveying for Lunar Materials*. 2021. DOI: `10.5281/ZENODO.4707306` (cit. on p. xii).

[18] Grant H. Heiken, ed. *Lunar sourcebook: A user's guide to the moon*. Cambridge: Univ. Press, 1991. ISBN: 0521334446 (cit. on pp. 7, 9, 11, 12, 15, 16).

[19] Dominik Höber, Andreas Taschner, and Eric Fimbinger. "Excavation and Conveying Technologies for Space Applications." In: *BHM Berg- und Hüttenmännische Monatshefte* 166.2 (2021), pp. 95–103. ISSN: 0005-8912. DOI: `10.1007/s00501-020-01073-z` (cit. on pp. xi, 54).

[20] Alexander M. Jablonski and Kelly A. Ogden. "Technical Requirements for Lunar Structures." In: *Journal of Aerospace Engineering* 21.2 (2008), pp. 72–90. ISSN: 0893-1321. DOI: `10.1061/(ASCE)0893-1321(2008)21:2(72)` (cit. on pp. 45, 46).

[21] Telana L. Jackson, William M. Farrell, and Michael I. Zimmerman. "Rover wheel charging on the lunar surface." In: *Advances in Space Research* 55.6 (2015), pp. 1710–1720. ISSN: 0273-1177. DOI: `10.1016/j.asr.2014.12.027`. URL: `http://www.sciencedirect.com/science/article/pii/S0273117714008035` (cit. on p. 46).

[22] Jekan Thaungavelauthan, Aman Chandra, Erik Jensen, ed. *Autonomous Multirobot Technologies for Mars Mining Base Construction and Operation*. 2019 (cit. on p. 55).

[23] Zilong Jiao et al. "Outgassing Environment of Spacecraft: An Overview." In: *IOP Conference Series: Materials Science and Engineering* 611 (2019), p. 012071. DOI: `10.1088/1757-899X/611/1/012071` (cit. on p. 46).

[24] *Joy 4FCT Flexible Conveyor Train - Underground Mining | Komatsu Mining Corp.* 21.11.2020. URL: `https://mining.komatsu/product-details/flexible-conveyor-train` (cit. on p. 57).

[25] G. H. Just et al. "Parametric review of existing regolith excavation techniques for lunar In Situ Resource Utilisation (ISRU) and recommendations for future excavation experiments." In: *Planetary and Space Science* 180 (2020), p. 104746. ISSN: 00320633. DOI: `10.1016/j.pss.2019.104746` (cit. on pp. 19–21).

[26] K. Hadler, D. J. P. Martin, J. Carpenter, and J. J. Cilliers, ed. *A UNIVERSAL FLOWSHEET AND TERMINOLOGY FOR IN SITU RESOURCE UTILIZATION (ISRU)*. 2019 (cit. on p. 19).

[27] David Kornuta et al. "Commercial lunar propellant architecture: A collaborative study of lunar propellant production." In: *REACH* 13 (2019), p. 100026. ISSN: 2352-3093. DOI: `10.1016/j.reach.2019.100026`. URL: `http://www.sciencedirect.com/science/article/pii/S2352309318300099` (cit. on pp. 53, 61).

[28] L.D. Kennedy. *NASA Lunar Lander Reference Design*. Ed. by National Aeronautics and Space Administration. Marshall Space Flight Center and Huntsville, Alabama 35812. URL: `https://ntrs.nasa.gov/citations/20190033128` (cit. on pp. 39, 40).

[29] Shuai Li et al. "Direct evidence of surface exposed water ice in the lunar polar regions." In: *Proceedings of the National Academy of Sciences of the United States of America* 115.36 (2018), pp. 8907–8912. DOI: `10.1073/pnas.1802345115` (cit. on p. 10).

[30] Tianxi LIU et al. "Simulation and Analysis of the Lunar Regolith Sampling Process Based on the Discrete Element Method." In: *TRANSACTIONS OF THE JAPAN SOCIETY FOR AERONAUTICAL AND SPACE SCIENCES* 57.6 (2014), pp. 309–316. ISSN: 0549-3811. DOI: `10.2322/tjsass.57.309` (cit. on p. 15).

[31] James G. Mantovani and Ivan I. Townsend. "Planetary Regolith Delivery Systems for ISRU." In: *Journal of Aerospace Engineering* 26.1 (2013), pp. 169–175. ISSN: 0893-1321. DOI: `10.1061/(ASCE)AS.1943-5525.0000248` (cit. on p. 65).

[32] *Mars 2020 Perseverance Landing Press Kit | Introduction*. 7.03.2021. URL: `https://www.jpl.nasa.gov/news/press_kits/mars_2020/landing/` (cit. on pp. 33, 34).

[33] Mike Brown. *SPACEX STARSHIP: STUNNING IMAGE SHOWS HOW IT MAY DEPLOY 240 STARLINK CRAFT*. Ed. by Bustle Digital Group. NYC 315 Park Avenue South 12th Floor NY 10010, 17.6.2020. URL: `https://www.inverse.com/innovation/spacex-starship-stunning-image-shows-how-it-may-deploy-240-starlink-craft` (cit. on p. 42).

[34] "Moonraker robots dig for victory in lunar challenge." In: *New Scientist* 204.2731 (2009), p. 21. ISSN: 02624079. DOI: `10.1016/S0262-4079(09)62803-7` (cit. on p. 21).

[35] Robert P. Mueller, IIIIvan I. Townsend, and James G. Mantovani. "Pneumatic Regolith Transfer Systems for In Situ Resource Utilization." In: *Earth & Space 2010*. Ed. by Gangbing Song and Ramesh B. Malla. Reston, VA: American Society of Civil Engineers, 2010, pp. 1353–1363. ISBN: 9780784410967. DOI: `10.1061/41096(366)122` (cit. on p. 22).

[36] Robert P. Mueller et al. "Regolith Advanced Surface Systems Operations Robot (RASSOR)." In: *IEEE Aerospace Conference, 2013*. Piscataway, NJ: IEEE, 3/2/2013 - 3/9/2013, pp. 1–12. ISBN: 978-1-4673-1813-6. DOI: `10.1109/AERO.2013.6497341` (cit. on pp. 35, 36).

[37] NASA. *Mars 2020 Perseverance Launch Press Kit*. 6/2020. URL: `https://www.jpl.nasa.gov/news/press_kits/mars_2020/launch/` (cit. on pp. 33–35).

[38] NASA. *Mars Exploration Rover Landings Press Kit*. 1/2004. URL: `https://mars.nasa.gov/internal_resources/826/` (cit. on p. 31).

[39] NASA. *Mars Exploration Rover Launches Press Kit*. 6/2003. URL: `https://mars.nasa.gov/internal_resources/827/` (cit. on pp. 30, 31).

[40] NASA. *Mars Science Laboratory Landing Press Kit*. 7/2012. URL: `https://www.jpl.nasa.gov/news/press_kits/MSLLanding.pdf` (cit. on pp. 31–33).

[41] NASA. *Mars Science Laboratory: Curiosity Rover*. 1/2013. URL: `https://mars.nasa.gov/files/resources/MSLLithoSet2013.pdf` (cit. on pp. 31–33).

[42] NASA. *Opportunity's Mission Is Complete*. 2/2019. URL: `https://mars.nasa.gov/mer/mission/rover-status/#recent` (cit. on pp. 29, 30).

[43] NASA. *Regolith Advanced Surface Systems Operations Robot (RASSOR) Excavator*. 2/2013. URL: `https://technology.nasa.gov/patent/KSC-TOPS-7` (cit. on pp. 35, 36).

[44] NASA. *The Mars Exploration Rovers: Spirit and Opportunity*. 12/2013. URL: `https://mars.nasa.gov/system/downloadable_items/44694_MER10-YearAnniversaryLithograph.pdf` (cit. on pp. 29, 30).

[45] *NASA Bucket Drum Double-Helix | 3D CAD Model Library | GrabCAD*. 4.11.2020. URL: `https://grabcad.com/library/nasa-bucket-drum-double-helix-1` (cit. on p. xi).

[46] Heinz Pfeifer. *Grundlagen der Fördertechnik*. 5., verbesserte Auflage. Viewegs Fachbücher der Technik. Wiesbaden: Vieweg+Teubner Verlag, 1989. ISBN: 9783322901323. DOI: `10.1007/978-3-322-90132-3` (cit. on pp. 56, 58–60).

[47] J. N. Rasera et al. "The beneficiation of lunar regolith for space resource utilisation: A review." In: *Planetary and Space Science* 186 (2020), p. 104879. ISSN: 00320633. DOI: `10.1016/j.pss.2020.104879`. URL: `http://www.sciencedirect.com/science/article/pii/S0032063319301266` (cit. on pp. 23–25).

[48] *Rollenbahnen - nicht angetrieben | KRAUS*. 23.11.2020. URL: `https://kraus-austria.com/produkte/rollenbahnen-nicht-angetrieben` (cit. on p. 64).

[49] Kurt Sacksteder and Gerald Sanders. "In-Situ Resource Utilization for Lunar and Mars Exploration." In: *Aerospace Sciences Meetings*. [Place of publication not identified]: [publisher not identified], 2007. ISBN: 978-1-62410-012-3. DOI: `10.2514/6.2007-345` (cit. on pp. 18, 50).

[50] G. B. Sanders and W. E. Larson. "Progress Made in Lunar In Situ Resource Utilization under NASA's Exploration Technology and Development Program." In: *Earth and Space 2012*. Ed. by Kris Zacny, Ramesh B. Malla, and Wieslaw K. Binienda. Reston, VA: American Society of Civil Engineers, 2012, pp. 457–478. ISBN: 9780784412190. DOI: `10.1061/9780784412190.050` (cit. on pp. 26, 50).

[51] David G. Schrunk. *The moon: Resources, future development, and settlement*. 2. ed. Springer-Praxis books in space exploration. Berlin: Springer, 2008. ISBN: 9780387360553 (cit. on pp. 4, 5, 9–15, 17, 18, 20, 22, 61, 65–68).

[52] Karl Schwister and Volker Leven. *Verfahrenstechnik für Ingenieure: Ein Lehr- und Übungsbuch (mit umfangreichem Zusatzmaterial)*. 4th ed. München: Hanser, 2020. ISBN: 9783446465008 (cit. on p. 59).

[53] Siceloff S. *Engineers Building Hard-working Mining Robot*. Ed. by Kennedy Space Center. 1/2013. URL: `https://www.nasa.gov/topics/technology/features/RASSOR.html` (cit. on pp. 35, 36).

[54] Hermann Sicius. *Erdalkalimetalle: Elemente der zweiten Hauptgruppe: Eine Reise durch das Periodensystem*. 1. Aufl. 2016. essentials. Wiesbaden: Springer Fachmedien Wiesbaden, 2016. ISBN: 9783658118778. DOI: `10.1007/978-3-658-11878-5`. URL: `http://gbv.eblib.com/patron/FullRecord.aspx?p=4178835` (cit. on p. 47).

[55] *Soviet Missions to the Moon*. 3.03.2021. URL: `https://nssdc.gsfc.nasa.gov/planetary/lunar/lunarussr.html` (cit. on p. 4).

[56] Space Exploartion Technologies Corp. *Starship Users Guide*. Ed. by Space Exploartion Technologies Corp. URL: `https://www.spacex.com/media/starship_users_guide_v1.pdf` (cit. on pp. 42, 43).

[57] Christoph Tilke. *Methodische Entwicklung von Stetigförderern am Beispiel eines neuen Fördergerätes für Agrarrohstoffe: Zugl.: München, Techn. Univ., Diss., 2012*. München: Fml, 2012. ISBN: 9783941702318 (cit. on pp. 57–60).

[58] Torbjørn Cunis, Wendelin Fischer, Florian Gillmann, Max van gen Hassend, Christina Hempfling, Frederik König, Helge Lauterbach, Helge Mohn, Dennis van der Wals, Kai Werner, Tobias Wenzel, Martin Wißmiller. "MOON BASE 2030." In: (2014) (cit. on p. 64).

[59] Wolfgang Torge. *Geodäsie*. 2., vollständig überarbeitete und erw. Aufl. De Gruyter Lehrbuch. Berlin and New York: De Gruyter, 2003. ISBN: 3110198177 (cit. on p. 10).

[60] Erich Übelacker and Frank Kliemt. *Der Mond*. [Nachdr.] Vol. 21. Tessloff Wissen. Nürnberg: Tessloff, 2010. ISBN: 9783788602611 (cit. on pp. 6–8).

[61] United Launch Alliance. *Vulcan Centaur* (cit. on p. 38).

[62] Otis R. Walton, C. Pamela de Moor, and Karam S. Gill. "Effects of gravity on cohesive behavior of fine powders: implications for processing Lunar regolith." In: *Granular Matter* 9.5 (2007), pp. 353–363. ISSN: 1434-5021. DOI: `10.1007/s10035-006-0029-8` (cit. on p. 53).

[63] Wolfgang Weissbach, Michael Dahms, and Christoph Jaroschek. *Werkstoffe und ihre Anwendungen: Metalle, Kunststoffe und mehr*. 20., überarbeitete Auflage. Springer-Link Bücher. s.l.: Springer Vieweg, 2018. ISBN: 9783658198916. DOI: `10.1007/978-3-658-19892-3` (cit. on pp. 46, 47).

[64] Don E. Wilhelms, with sections by McCauley, John F., and Newell J. Trask. *The geologic history of the Moon*. 1987. DOI: `10.3133/pp1348` (cit. on pp. 7, 8).

[65] Elmar Witten, ed. *Handbuch Faserverbundkunststoffe: Grundlagen, Verarbeitung, Anwendungen*. 4th ed. Wiesbaden: Springer Fachmedien Wiesbaden, 2013. ISBN: 9783658027544. URL: `http://lib.myilibrary.com/detail.asp?id=601673` (cit. on p. 47).