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Studies on Mechatronics

Study on a robotic arm for sampling lunar regolith

Spring Term 2020

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Preface

As a part of the Bachelor of Science ETH in Mechanical Engineering with Focus Specialization in Mechatronics, we are required to complete scientific research and critically evaluate literature within the field of Mechatronics. The present report is the outcome of the Studies on Mechatronics project at the Robotic Systems Lab in collaboration with Airbus Defence and Space about robotic space-graded manipulators and sampling tools.

Doing this project helped me to gain experience in engineering problem solving and the way of thinking in a collaboration. The research within this project enhanced my knowledge about robotic arms, and space engineering, immensely.

I am grateful to have worked on this project to gain my first engineering experience.

Abstract

In-situ resource utilization is a key technology to reduce the cost of space exploration and increase the duration of manned missions. While the chemical concept of resource utilization exists, the question of sampling and transporting regolith to the reactor chamber remains unsolved.

As part of the Studies on Mechatronics, first an overview over space manipulators and science tools is given. Building on this overview, the Studies on Mechatronics aims at developing a concept for a robotic arm and operational concept, which is placed on a commercial landing platform with tight space. The arm is aimed to sample regolith from the lunar surface and performs various pick and place tasks on the lander.
A 7-DOF robotic arm placed underneath the lander platform with a two-finger gripper end-effector is the foundation to solve the problem. The robotic arm is combined with a dedicated "universal" interface that allows to pick up regolith sampling tools and serves as an interface for manipulating. The manipulations that are required to be done are very diverse including filtering, filling, and twisting, and more.

Symbols

Acronyms and Abbreviations

ETH	Eidgenössische Technische Hochschule
RSL	Robotic Systems Lab
ISRU	In-situ resource utilization
ROXY	Regolith to Oxygen Conversion
NASA	National Aeronautics and Space Administration
MER	Mars Exploration Rover
Sol	Martian solar day
DOF	Degrees of Freedom
LED	Light-emitting diode
IDD	Instrument Deployment Device
IDA	Instrument Deployment Arm
IDC	Instrument Deployment Camera
FOV	Field of view
APXS	Alpha Particle X-Ray Spectrometer
MSL	Mars Science Laboratory
SUV	Sport Utility Vehicle
CHIMRA	Collection and Handling for In-situ Rock Analysis
CDA	Charge and Discharge Area
LTR	Left-to-Right
UI	Universal Interface
F/T	Force/Torque

Chapter 1

Introduction

Space exploration remains expensive, as all the resources have to be brought from Earth. The ability to use extraterrestrial resources at exploration destinations and process them into propellants or life support consumables would reduce the dependency on Earth-based resources [1]. This emerging technology is known as in-situ resource utilization or ISRU and has the potential to significantly reduce the launch mass, cost, and risk of future space explorations. The main focus of ISRU as of today is on the extraction of metals, alloys, and oxygen from lunar regolith, as it can be used for propellant, life support systems, and additive manufacturing [2].
The access of space as a service being commercialized leads to simplified and cheaper missions through private companies like Astrobotic Technology. This company offers to deliver payloads on lunar landers to the moon for relatively low cost, exactly $1.2M/kg [3].

In this context, Airbus developed an emission-free and cost-effective technology for ISRU based on molten salt electrolysis of lunar regolith, named ROXY. ROXY is a new way of clean metals and alloys production that is universally applicable to many different materials. The process reduces various oxides from sampled regolith to produce high-quality metals or alloys powder with pure oxygen as the only emission. This powder is ideal for usage in additive manufacturing processes. At this point, Airbus contacted the RSL for collaboration in their project. The task was to review existing technologies and develop a concept of a compact and lightweight robotic system on-board a demonstration lander. The Peregrine Lander by Astrobotic in Figure 1.1 is used as a reference lander for the concept of the robotic system.

Figure 1.1: Peregrine Lander from Astrobotic [3]

Figure 1.2 and Figure 1.3 show the top view and side view of the Peregrine Lander with the first concept developed by Airbus where an intended robotics area for the system is sketched. The main function of the robotic system is to *fill* the reactor on the lander with lunar regolith. To perform this function properly a few subfunctions have to be performed as well: *survey* the lunar terrain, *transport* components, *sample* lunar regolith, *filter* lunar regolith, *open/close* a thermally isolated lid and *control* the height of a volume in the reactor.

Figure 1.2: Top view of the first concept sketch

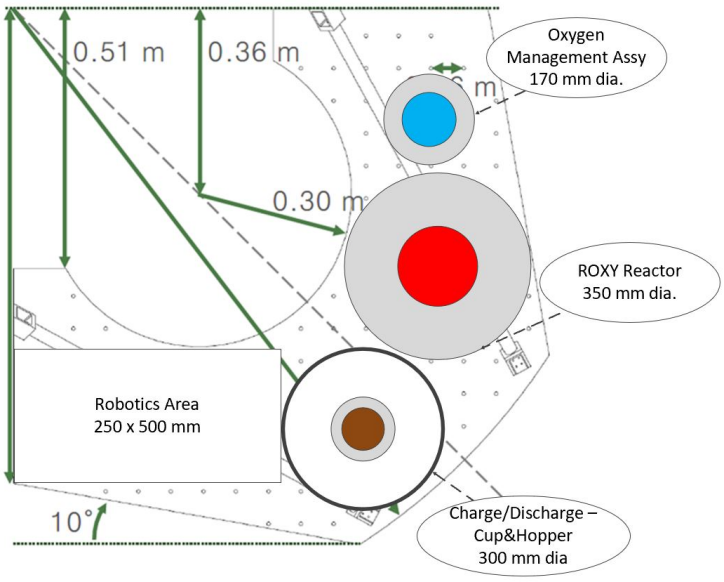
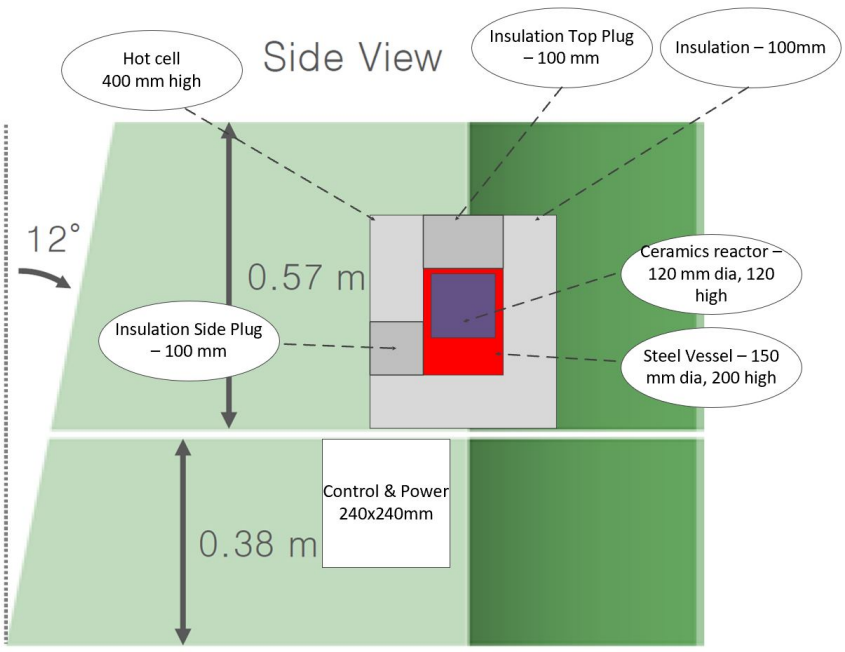


Figure 1.3: Side view of the first concept sketch



Chapter 2

Research

Before coming up with solutions to the concept of the robotic operation, literature research on space graded manipulators has been done. This helped to develop knowledge of manipulators used in recent space missions, which could potentially be adapted. The focus of this research lies on the robotic arms and end effectors used in rover and lander missions performed by NASA.

2.1 Mars Exploration Rover

In 2003 NASA launched two rovers as part of their Mars Exploration Rover (MER) mission. The identically built twin rovers named MER-A *Spirit* and MER-B *Opportunity* are six-wheeled robots powered by solar panels and batteries [4], pictured in Figure 2.1. The goal of the mission is to measure and discover the detailed geochemistry and morphology of the Martian surface [4]. The rovers landed in January 2004 and were active much longer than the planned duration of 90 martian solar days (Sols), which are slightly more than 92 solar earth days [5]. *Spirit* last communicated with the earth in March 2010 after 2210 Sols, while *Opportunity* continued to operate for a total of 5111 Sols until 2018, when communication was lost due to a dust storm on Mars [6].

Figure 2.1: The Mars Exploration Rover *Opportunity* [7]

The rover has a five degrees-of-freedom (DOF) robotic arm illustrated in Figure 2.2, with an overall reach of approximately 0.75 meters [8], mounted beneath the

solar panel in the front. The arm weighs 4.4 kg with all cabling for the science instruments included [8]. The robotic arm acts as an Instrument Deployment Device (IDD) since it carries an end-effector toolbox with a mass of 2 kg [8]. The toolbox contains four scientific instruments for geologic measurements of rocks and soil [4].

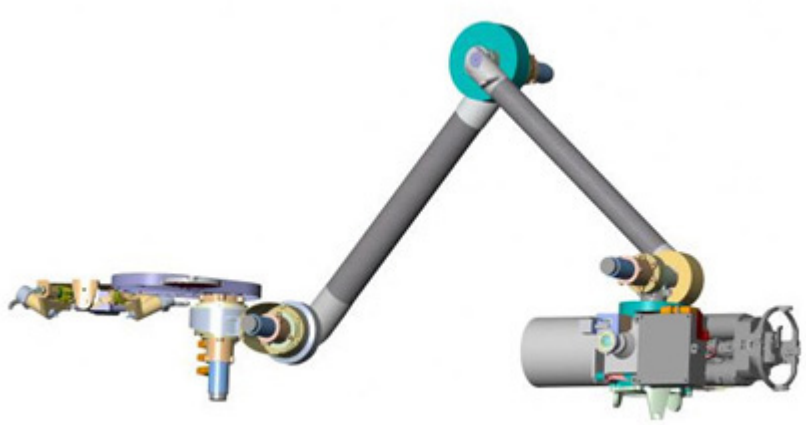


Figure 2.2: MER Instrument Deployment Device [9]

The IDD has flexibility through three joints: a shoulder, an elbow, and a wrist joint including five rotary actuators to accurately place the instruments against rocks and soil to perform its measurements [4]. The joints are driven by Maxon RE016 brushed motors with a 5535:1 gear ratio [10]. The instrument toolbox, illustrated in Figure 2.3, includes a Microscopic Imager (MI) that provides close-up images, an Alpha Particle X-Ray Spectrometer (APXS) to determine the elemental chemistry of rocks and soils using alpha particles and X-rays, a Mössbauer spectrometer (MB) to analyze the composition and quantities of iron-bearing minerals in the samples, and a Rock Abrasion Tool (RAT) for exposing fresh material under the surface [4].

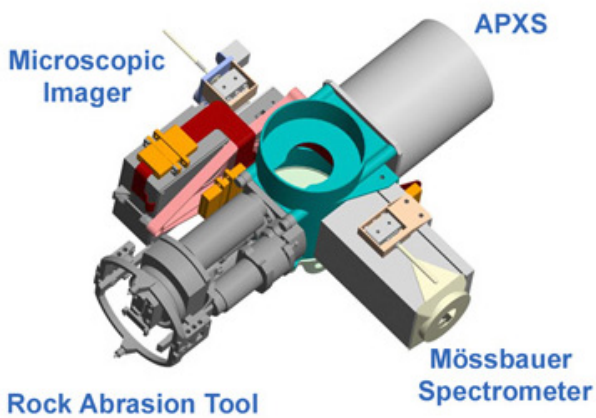


Figure 2.3: MER end-effector toolbox [9]

2.2 Curiosity Rover

The Curiosity Rover is a part of the Mars Science Laboratory (MSL) mission that landed on Mars in August of 2012 and is still operating today. It is the largest and heaviest rover that landed on the surface of Mars to date, with a total weight of 899 kg and the size of a small SUV [11] shown in Figure 2.4. The mission's main objective is to investigate if past or present conditions are favorable for microbial life and the acquisition and processing of rock samples [12]. To perform these functions, the six-wheeled Curiosity has a robotic arm placed in the front of the rover with five scientific instruments on it.

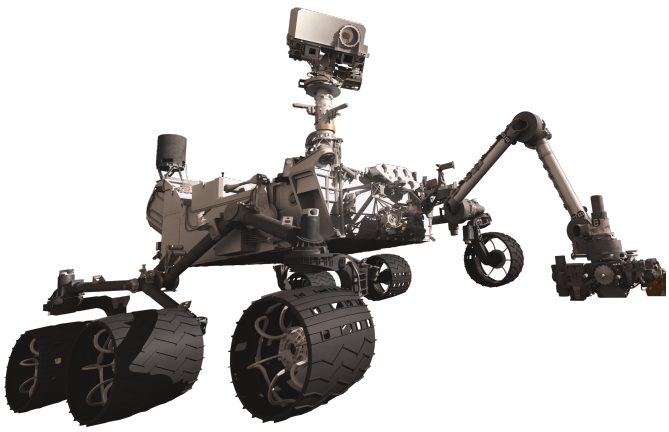


Figure 2.4: The Curiosity Mars Rover [7]

The 5-DOF robotic arm consists of two links with an end-effector instrument suite and measures 2.2 meters in outstretched length from the base to the center of the end-effector [12] depicted in Figure 2.5. The arm is mostly of Titanium 6AL-4V and weighs 67 kg without the 34 kg end-effector instrument suite attached [12]. The whole robotic arm can withstand temperatures in the range of -128℃ to +50℃ [12]. The arm is driven by five rotary actuators. In detail, an azimuth and elevation joint in the shoulder, an elbow, a wrist ,and a turret [12] that can spin through a turning range of 350-degrees to make use of the different science instruments [13]. The actuators are built of Vascomax C250 steel and weigh 7.8 kg each (elevation, azimuth, and elbow) respectively 4.2 kg (wrist and turret) [12].

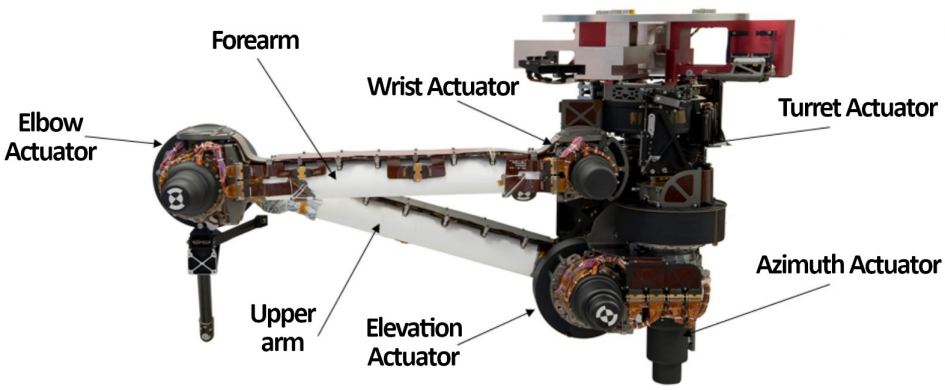


Figure 2.5: Curiosity robotic arm [12]

This turret at the tip of the arm has five instruments mounted on it, which can be seen in Figure 2.6. These are the Mars Hand Lens Imager (MAHLI) camera, an APXS, a drilling system to collect rock samples, a Dust Removal Tool (DRT) for better rock analysis and CHIMRA for the analysis of the samples [13].

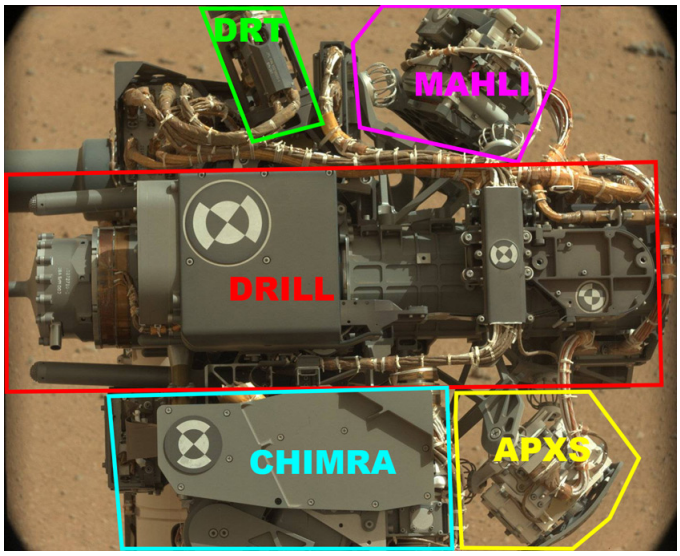


Figure 2.6: Science instruments on Curiosity's robotic arm [14]

2.2.1 Force/Torque Sensors in Space

Tasks like sampling, constructing, and assembling done in space increase in complexity, which requires more precise interaction with its surroundings [10]. This demands to better sense the interaction forces and torques in the process, which also leads to lower design margins, and thus can lead to a lower mass [10]. Helmick et al. [10] compared different techniques for sensing forces in planetary manipulations. They conclude that a six-axis F/T sensor, the ATI Mini-45 SI-145-5 in their case, performs best in terms of accuracy, repeatability, and configuration independence [10].

F/T sensors have been used in previous missions like the MSL. Where Curiosity places the driller directly on martian rocks to sample regolith. This leads to forces in different directions, which could potentially damage the robotic arm. To monitor excessive forces that exceed expectations, a force/torque sensor is present at the arm [15]. This sensor gives force feedback from all directions to stop all motion if needed. There are multiple force sensors from Strainsert mounted all over the rover, that act for safety reason [16].

2.3 Phoenix Lander

The Phoenix Lander, pictured in Figure 2.7, was part of the first Mission of NASA's Mars Scout Program. A campaign for low-cost robotic missions to Mars, where Phoenix touched the polar region on Mars in May 2008 [17]. The lander stopped operating in November 2008 when no more signals were received due to low power resulting from a dust storm that covered the solar panels [18].

Figure 2.7: The Phoenix Lander [7]

The Phoenix is based on the spacecraft of the Mars Surveyor Programm 2001 (MSP 01), that never launched to Mars due to the unsuccessful Mars Polar Lander (MPL) mission [18]. Many components have been adapted and modernized using the learnings from failed missions [20]. The Phoenix Mars mission aims to study the past presence of water in the martian arctic by digging into the dry and icy soil below the surface and analyzing the chemical composition [19]. The soil samples are collected with the help of a robotic arm that delivers them into an analyzer on board of the lander.
The robotic arm is a 4-DOF manipulator with an overall length of 2.4 meters [19] that can bee seen in Figure 2.8. The two existing links are made of aluminum with titanium end fittings that sum up to an overall weight of 9.7 kg [21]. The whole robotic system is built to survive in conditions with temperature changes from -90°C to -20°C and low pressure [19]. The designed arm provides motion through four brushed DC motors which are actively heated[19]. It reaches the positions through the shoulder azimuth and elevation, an elbow, and a wrist pitch [19]. A Robotic Arm Camera (RAC), which is mounted on the forearm of the arm right behind the wrist joint [19], helps with surface inspection and precise sample unloading into the analyzer on board. The RAC is a variable-focus color camera that can take pictures down to a scale of 23 μm/pixel with objective ranging from macro 1:1 to infinity [22]. The camera has a total mass of 0.415 kg with two LED lights for illumination and a field of view of 54° x 27°at infinity [22].

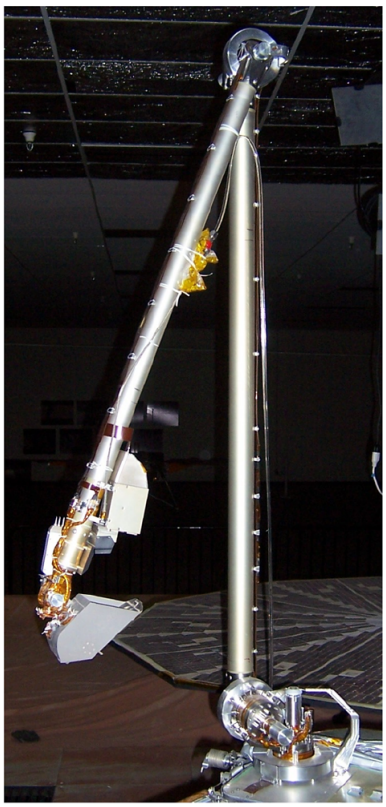


Figure 2.8: Phoenix robotic arm [19]

The end-effector, illustrated in 2.9 consists of a Thermal and Electrical Conductivity Probe (TECP) tool for relative humidity measurements and a shovel to sample the martian regolith [19]. The sampling tool has a rasp attached at the back to

gather icy soil samples and an integrated channel guide which can be seen in Figure 2.9. The channel guide helps to precisely fill the sampled regolith into the analyzers on board of the lander. To improve precision for a successful sample delivery, the scoop is positioned above the analyzers opening port where a live image acquired from the RAC is compared to a similar image taken while testing [19]. The images where then overlayed to perform corrections in the positioning of the arm [19].

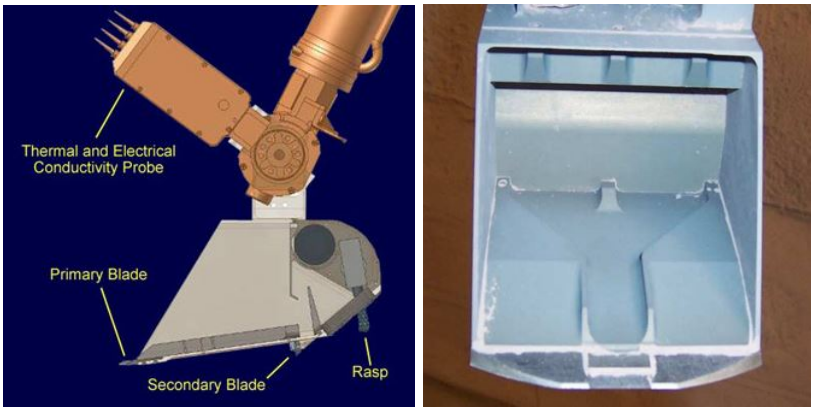


Figure 2.9: Phoenix end-effector and shovel with channel guide [23, 19]

2.4 Mars InSight Lander

All the previous missions on Mars have investigated the surface, but the inner space remained unexplored. The InSight lander in 2018, short for Interior Exploration using Seismic Investigations, Geodesy and Heat Transport, changed that [24]. The lander, as pictured in Figure 2.10, builds on the design of the successful Phoenix Lander with two solar panels for energy generation [24].

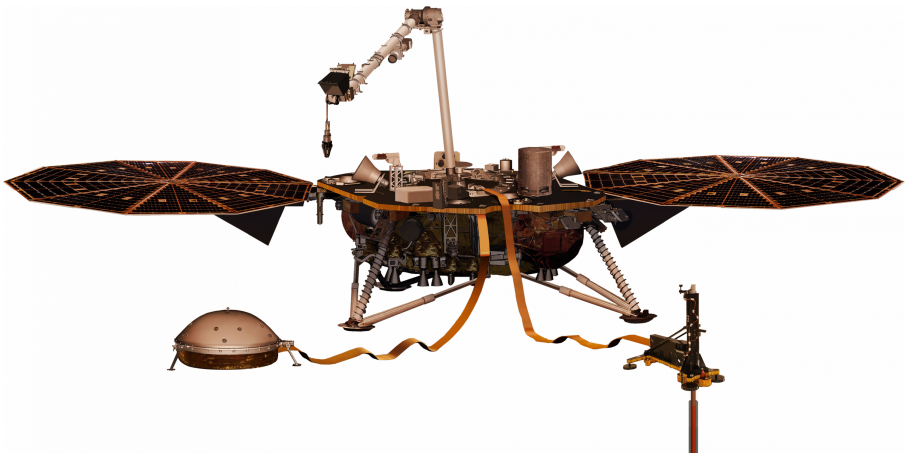


Figure 2.10: The InSight Lander [7]

The main goals were to understand how other terrestrial planets formed and evolved through the investigation of the interior of Mars and understand how much and how powerful the seismic activity is on Mars [24]. To reach these goals, two scientific instruments had to be placed on the Martian surface: the Seismic Experiment for Interior Structure (SEIS) to measure the level of tectonic activity and the Heat Flow

and Physical Properties Package (HP3) that provides information about the internal temperature and the heat flows of the planet [25]. To place these science instruments on the surface of Mars, a lightweight robotic arm, the Instrument Deployment Arm (IDA) illustrated in Figure 2.11, is utilized.

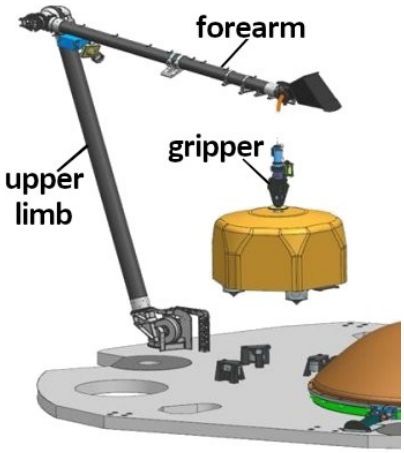


Figure 2.11: InSight IDA transporting the SEIS instrument [26]

The aforementioned IDA was originally intended for the canceled Surveyor 2001 mission and put out of its storage container after 13 years for the new mission [24]. It has 4-DOF and is structurally identical to a human arm with an upper limb of one-meter length linked to a 0.8-meter forearm [26]. These two links are built from carbon-fiber composite material, namely XN-70 and XN-80 with a thickness of 0.8 mm and 1.1 mm [24]. The robotic arm weighs only about 3.4 kg due to the extremely lightweight material and actuators used [24]. The IDA of InSight has the same actuator configuration as the Phoenix lander with a shoulder azimuth and elevation joint, an elbow, and a wrist. While the shoulder actuators weigh 1.11 kg combined, the elbow weighs 0.55 kg and the wrist 0.31 kg [24]. All the actuators are driven by graphite brushed motors in combination with a planetary gearbox and a 50K Ohm potentiometer for absolute position feedback to operate precisely in the workspace [24].

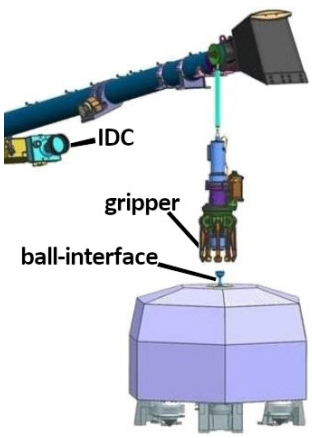


Figure 2.12: InSight Gripper with ball-interface on SEIS [26]

To place the scientific instruments with a weight of up to 29 kg on the Martian surface, a five-claw gripper mechanism hangs from the end of the IDA that closes

around a ball interface on top of the instruments for safe transportation [26] depicted in Figure 2.12. Additionally, a 45-degree field of view full-color Instrument Deployment Camera (IDC) is mounted on the forearm to monitor the workspace and help to deploy the scientific tools [27]. The scoop with a capacity of 500 grams of soil from the Surveyor remains on the lander, but to prepare the surface for instrument deployment [24].

Chapter 3

Method

Similar to any robotic system design approach, an iterative process was used that had three main outputs of work. The first step was to define the mission more precisely. This resulted in a *list of requirements* on the robotic system. Next, functions were determined and specified. Which led to a flow chart of the *function structure* demonstrating the whole robotic operation. With all the constraints and required functions defined, the first conceptual solutions have been searched and sketched. To systematically proceed with all the possibilities, a *morphological box* has been made multiple times to choose the most suitable solution for each function. These solutions combined resulted in a final concept of the robotic system and its operation.

3.1 Requirement List

A detailed list of requirements was created after the kick-off meeting with Airbus and frequently updated during the project. Most of the requirements could be extracted from the existing concept design documents from Airbus or the Payload User's Guide [3] of the Astrobotic Peregrine Lander. The list includes about three A4 pages seen in Table A.1, but many of the non-functional requirements are too detailed and did not need to be considered in this conceptual phase of the project. Others, like the geometrical and functional requirements, were very important in the concept design.

3.1.1 Geometrical Requirements

As mentioned in the introduction 1, the project considers the Peregrine Lander as a representative for a commercially available lander. The system should be limited to a quadrant of the lander platform and must be fully inside the defined payload envelope [3], colored in shades of green in Figure 3.2. Since the reactor and oxygen management system are mounted on the same quadrant, the available space is very limited. Two crossbars, that hold the platform, set even more constraints on the building and working space of the robotic system on top of the platform as one can see in Figure 3.1. Although the building space is very limited, the arm shall reach the lunar surface at any given landing condition to sample regolith. This means in particular that the distance from the platform to lunar the lunar surface is 0.78 - 1.18 meters depending on the landing conditions [3], where the worst-case scenario is shown in Figure 3.2. The robotic arm shall be very compact to fit into the payload envelope and still be able to reach the surface to sample.

Figure 3.1: Top view of a quadrant with the first concept

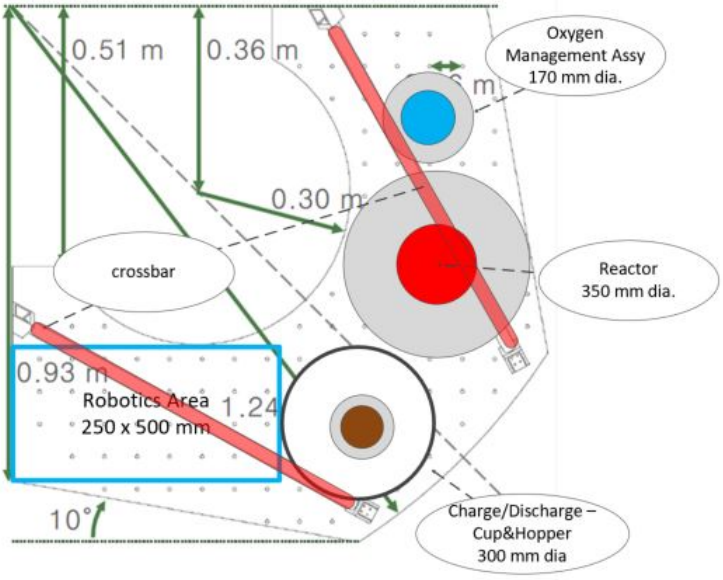
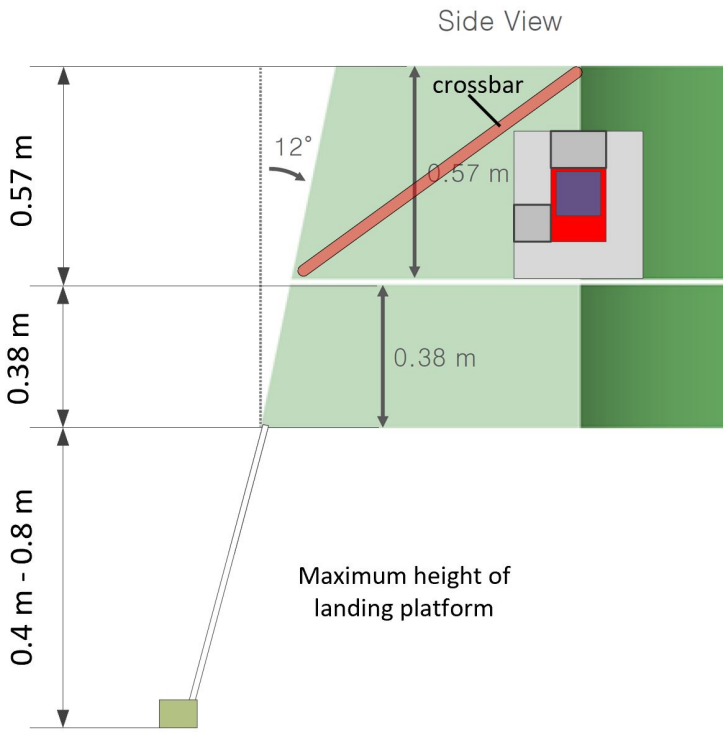


Figure 3.2: Side view of the Peregrine Lander



3.1.2 Functional Requirements

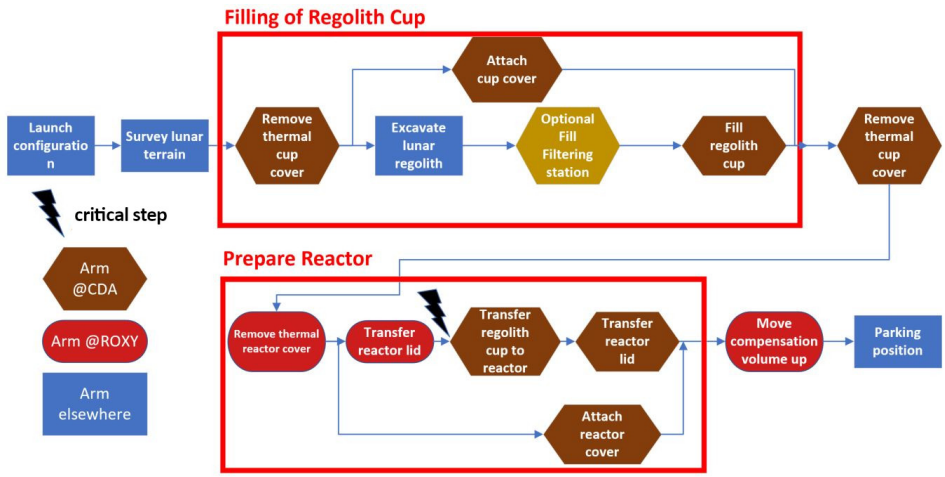
To successfully fulfill the mission's goal of converting lunar regolith into oxygen, several crucial steps have to be performed first. These functional requirements are the main design driver for the robotic system besides the geometrical restrictions mentioned at 3.1.1.

First, the robotic arm shall inspect its surroundings to spot favorable spots for sampling regolith. Furthermore, it shall transport thermal covers from the reactor to a Charge and Discharge Area (CDA) for temporary storage. While the cover is stored, the arm shall sample a total amount of 200 ml of regolith per process run with a maximum particle size of 1 mm. The sampled regolith shall then be filled into a regolith cup, stored in a container in the CDA. The arm shall then open and close the insulating lid of the reactor. The last requirement of one process run is to control the height of the 671 ml compensation volume to flood the reactor with a molten salt composition.
The operation requires the arm to do many different functions, evidently different tools are needed. Since tool changes can be risky and the tools need for the scarce space, they should be minimized and simplified.

3.2 Function structure

To visualize the workflow and position of the robotic arm and all the components, a function structure illustrated in Figure 3.3 has been set up.

Figure 3.3: Function structure of the robotic operation



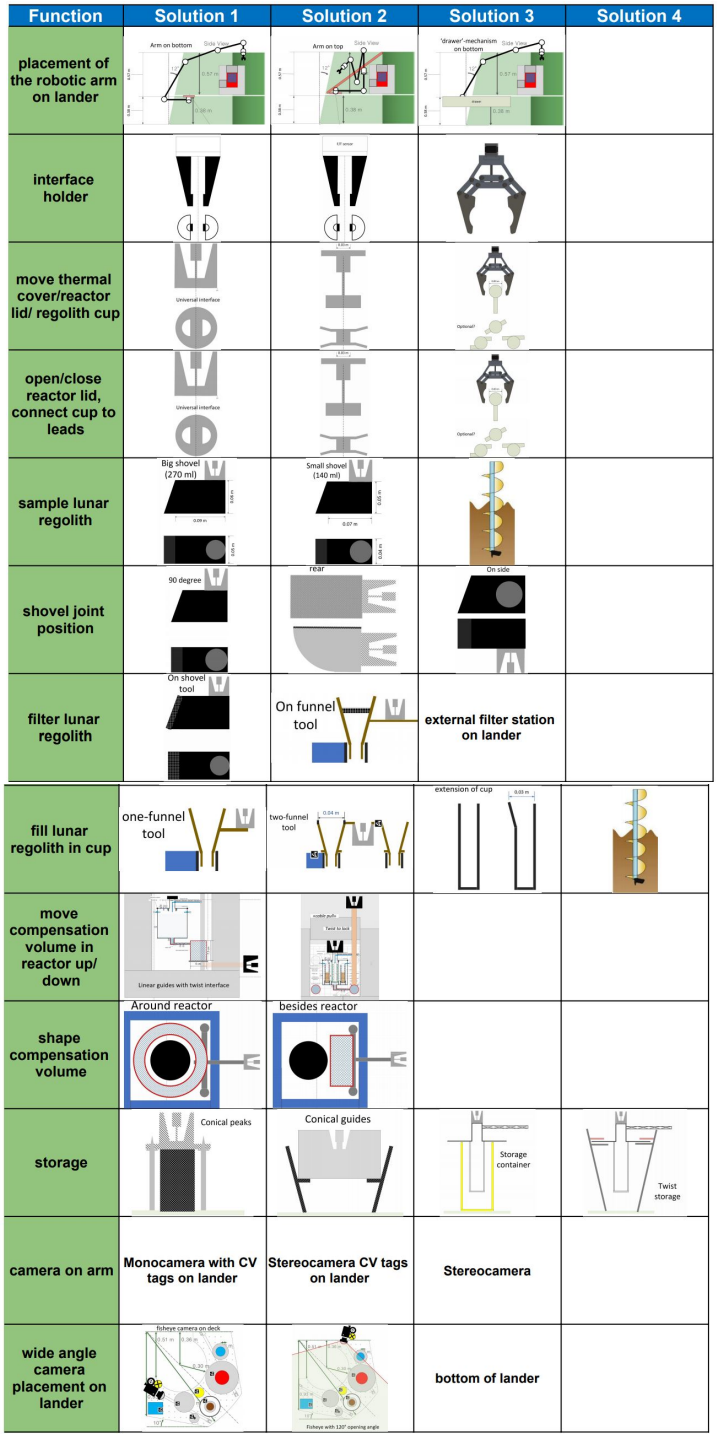
The function structure helped to specify subfunctions and detect possible critical steps. Once more, the limited space became an issue in the process flow indicated with the lightning. At this point in the workflow, the lander should be able to store the regolith cup, the regolith cup cover, the reactor cover, the reactor lid, and some tools for the defined functions. Thus, a realization of the robotic arm underneath the lander seems favorable as disscussed in 3.3.1.
This was the point where it was considered mounting the robotic arm on the bottom of the lander which is discussed in 3.3.1.

3.3 Morphological Box

In the following, concepts are developed for subfunctions identified in the function structure. This process step started with a lot of candidate solutions on a consistent concept level that fulfills a requirement. The solutions were then put into perspective in a Morphological Box depicted in Figure 3.4. The concepts were then

analyzed with the different trade-offs, that provide pros and cons for each solution. In the final phase, the most suitable solution for the overall concept is chosen. The following section covers the solutions to the subfunctions and argumentation for the selected concept.

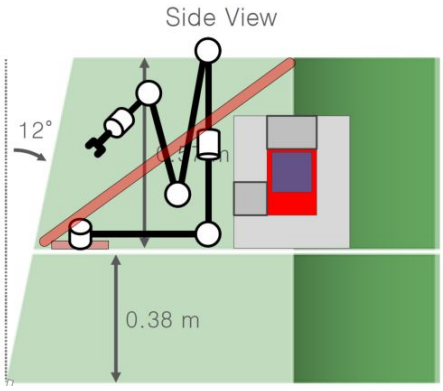
Figure 3.4: Morphological Box



3.3.1 Robotic Arm

The very first concept by Airbus had the intended robotics area on top of the lander. Therefore the first sketch also had it placed there. Without going too much into detail on the DOF, link lengths, or joints, it was clear that the space above the lander is very limited as one can observe in Figure 3.5. The biggest problems are identified to be the launch configuration inside the payload envelope and the crossbars that limit the working space of the robotic arm. Additionally, more space would be available for a tool changing station and the storage of the other components, if the arm is mounted on the bottom of the platform. Due to these arguments, the concept of the robotic arm on top has not been developed any further.

Figure 3.5: Robotic arm on top of the lander platform



The concept robotic arm on the bottom of the lander measures around 1.8 meters and has 7 DOF to be fully redundant in its workspace, however, the degrees of freedom could be reduced after optimization of the workspace and modelling of the robotic arm. The link lengths and joint orientations sketched in Figure 3.7 are chosen by best practice to reach all the important positions in the operation, e.g., lunar surface, reactor, CDA and fit into the payload envelope in the parked position. Those configurations can be seen in Figures 3.6 and 3.7. The concept of the robotic arm has not been iterated further due to time constraints.

Figure 3.6: Robotic arm in parked position under the platform

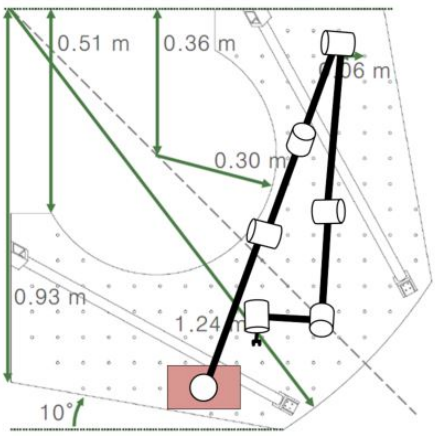
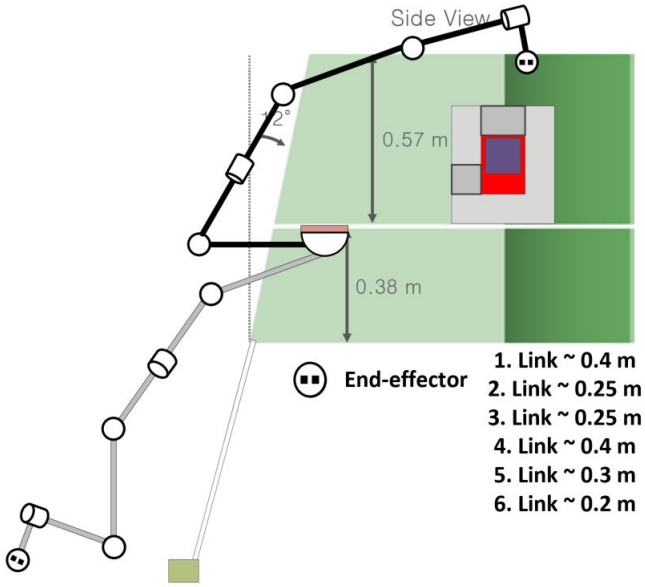


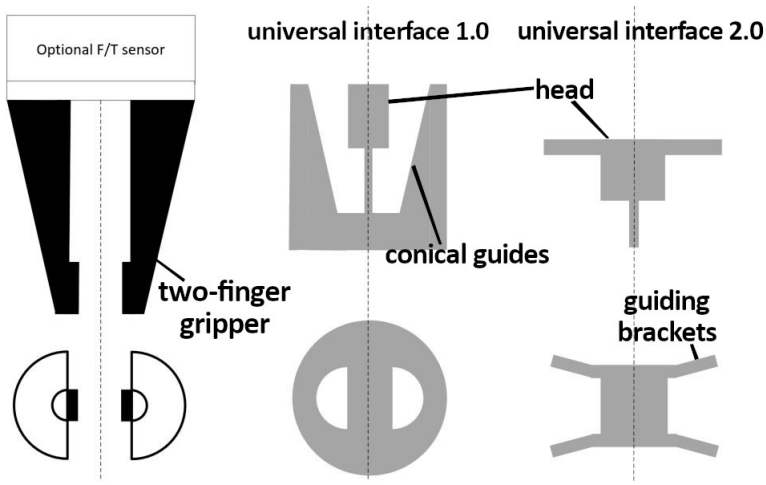
Figure 3.7: Two configurations of the robotic arm



3.3.2 Pick Up Components

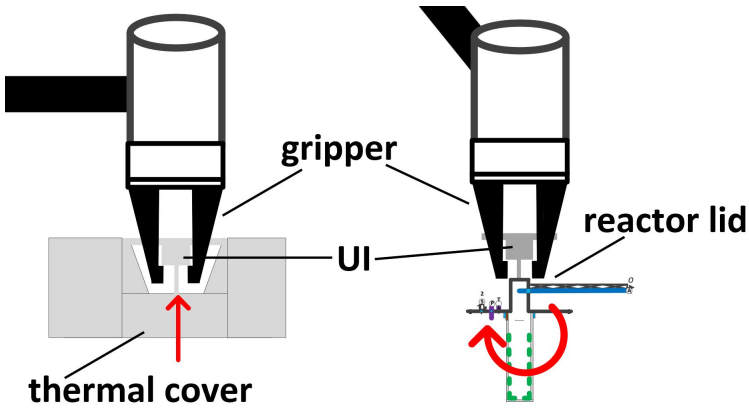
Picking, transporting, and placing components are the most used functions in the robotic operation. Those have to be performed multiple times, which is why a universal interface (UI) throughout all the components on the lander is. To hold the interface inspiration was taken from the gripper end-effector with the ball interface used on the Insight Lander (2.4). But since a multi-claw gripper is not necessary for this problem, it was decided to use a simple 2-finger gripper as a UI holder. The first concept was a form-fit UI for the fingers of the gripper with conical guides to correct for positioning errors seen in Figure 3.8. This concept was only intended for the picking and placing function performed with the head of the interface. But quickly the idea evolved into the key feature of the robotic concept. A universal interface, that can easily be added to new components if needed.

Figure 3.8: Side and Top view of the gripper, first and final concept of the UI



The UI and two-finger gripper have then been iterated to perform twisting and picking motions used in the operations pictured in Figure 3.9. The gripper has an optional, but recommended F/T sensor attached to monitor the forces at the end-effector, to protect the system from overload and to estimate the regolith sampled by the tool as described in 3.3.3. To lower the required positioning accuracy to grab the UI, it is designed with a wider opening, the guiding brackets, which guide the gripper into the right position. These brackets are also used to perform twist motions of the interface. The form-fit UI can be used on every component manipulated and even act as a very simple and safe tool change mechanism.

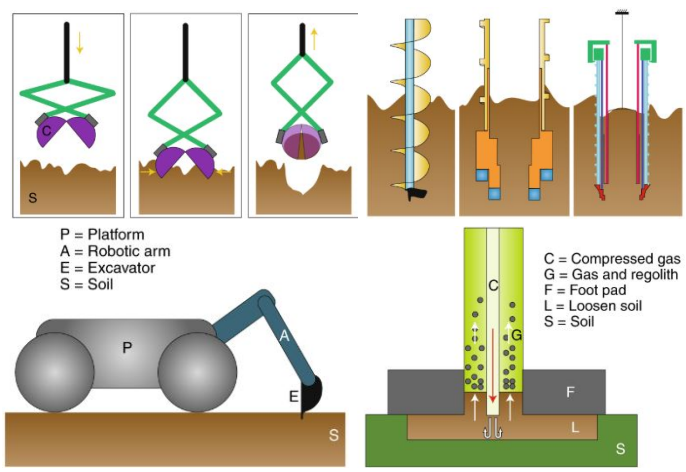
Figure 3.9: Gripper performs picking and twisting with the UI



3.3.3 Sample Lunar Regolith

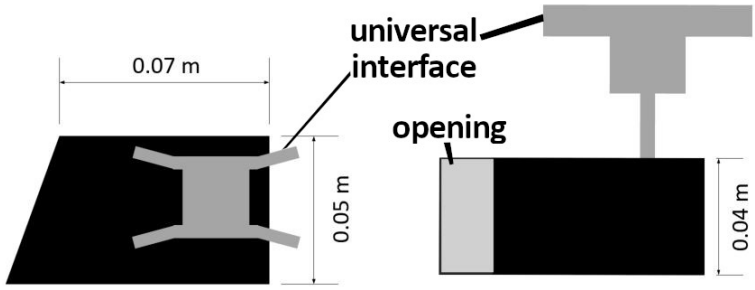
Sampling regolith has been extremely important in past missions for understanding the geological structure and gather scientific information [28]. It is also a crucial function in this mission since, without the regolith, no oxygen conversion can be made. One process run requires a total amount of 200 ml regolith from the surface. Ideally, the sampling tool should be equipped with the same universal interface discussed in 3.3.2 used in other components. Zhang et al. [28] helped coming up with different sampling techniques. Where in Figure 3.10 some are presented.

Figure 3.10: Different extraterrestrial regolith-sampling techniques [28]



Complex mechanisms should be avoided because of increased effort for qualification and risk of failure, which is why a claw or driller has not been used. It is easy to sample a big amount of regolith because it sits loosely on the surface of the Moon. Due to this, a simple shovel tool as shown in Figure 3.11 is used to excavate the regolith. This tool has the universal interface mounted on the side, which helps to easier control the shovel tool for filling and emptying.

Figure 3.11: Side and top view of the shovel tool

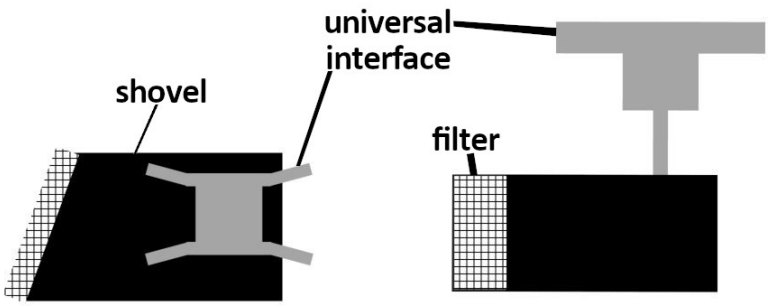


It was decided to use a shovel with a volume of around 140 ml instead of a bigger one with 270 ml. Mainly for security reasons, because the sampled amount of regolith can not exactly be controlled. Getting multiple small batches helps to control the amount already sampled and makes the filling into the small regolith cup much easier. A bigger shovel can sample more regolith at once which makes it way faster, but as time is not a limiting factor this has not been considered. At this stage, the filling level can be estimated with the force torque sensor or a robotic arm camera.

3.3.4 Filter Lunar Regolith

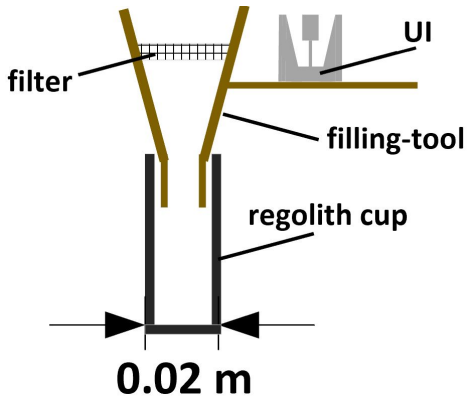
The particle size of the sampled regolith is very important for the conversion to be successful. The sampled regolith on the surface of the Moon is expected to be rather fine without many large particles with a mean particle size of $60 - 80$ μm [29]. The requirement is that only particles of a size smaller than 1 mm shall be transferred into the regolith cup. Although the expected particle size is smaller, it is still required to filter the regolith if bigger particles occur. The concepts to filter the regolith differentiate in the placement of the filter. One suggests to place it on the sampling tool the other on an external tool or intended filter station. The easiest solution is to place the filter in the front of the shovel illustrated in Figure 3.12, that only small particles can be sampled. But combining these two functions can be critical because clumping could make sampling more regolith impossible.

Figure 3.12: Filter mounted on shovel tool



Another approach was to combine filling and filtering, pictured in Figure 3.13 with a tool attached to the cup, where the same difficulties occur. Additionally, the tool has to get rid of the bigger particles before sampling more regolith. The clumping could be solved with a specific filter station on the lander. But since space is very limited and the goal is to be as light as possible, it makes more sense to use the straightforward solution with the filter on the shovel tool. To still be redundant if clumping occurs, a second identical shovel could be used.

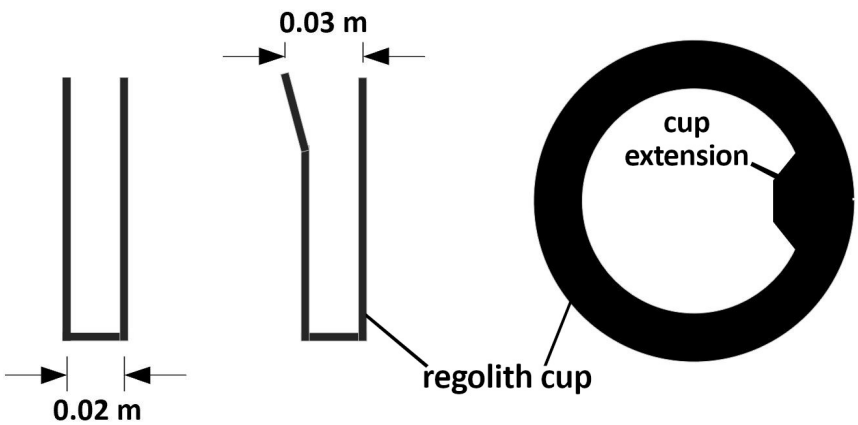
Figure 3.13: Filter mounted on a cup-filling tool



3.3.5 Fill Lunar Regolith

As mentioned in 3.3.3, the toroidal regolith cup is very small and difficult to fill. To maximize the amount filled into the cup and not spill any regolith onto the lander, a method for precise filling needs to be considered. This can be done with a funnel, an intelligent mechanism or structure in the shovel, like the channel used on the Phoenix IDA 2.3 or an extension of the regolith cup illustrated in Figure 3.14.

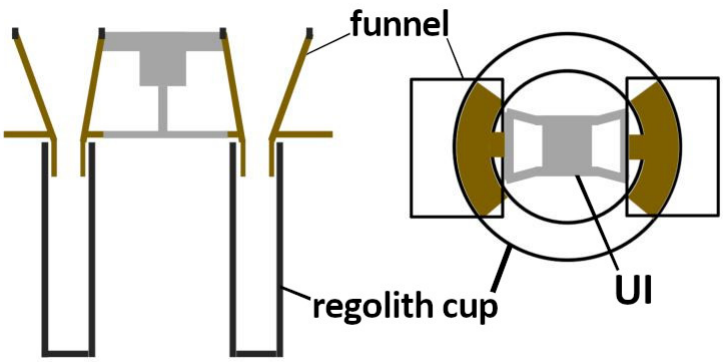
Figure 3.14: Side and Top view of the extension in the regolith cup



Although the extension of the regolith cup would be the easiest and simplest solution, it is not possible to implement because of the space restrictions and interfaces in the reactor. The funnel tool attached to the cup, depicted in Figure 3.15, is the safest solution where there is no need to design a complicated and risky mechanism that potentially requires to be actuated. The funnel tool can be transported on

the regolith cup with the universal interface, it has two toroidal segments to fit the cup best. The two openings are designed to be redundant if a problem on one side happens. This funnel can also be combined with a channel inside the shovel to fill the regolith precisely.

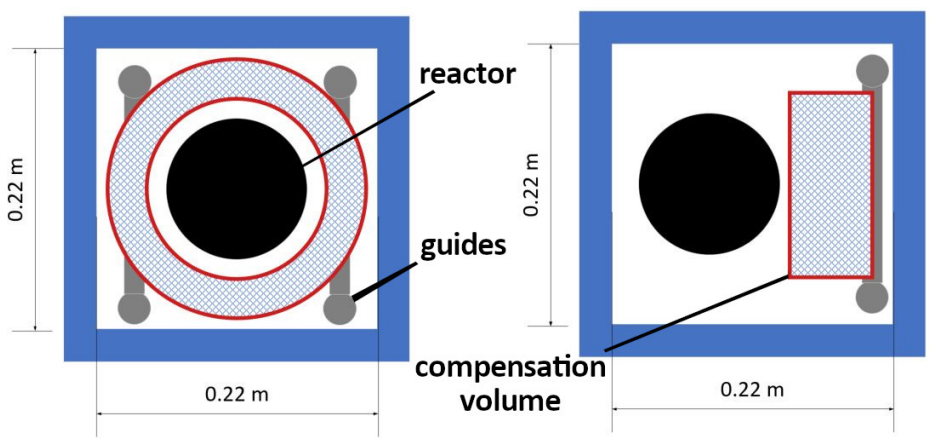
Figure 3.15: Side and top view of the funnel tool on regolith cup



3.3.6 Move Compensation Volume

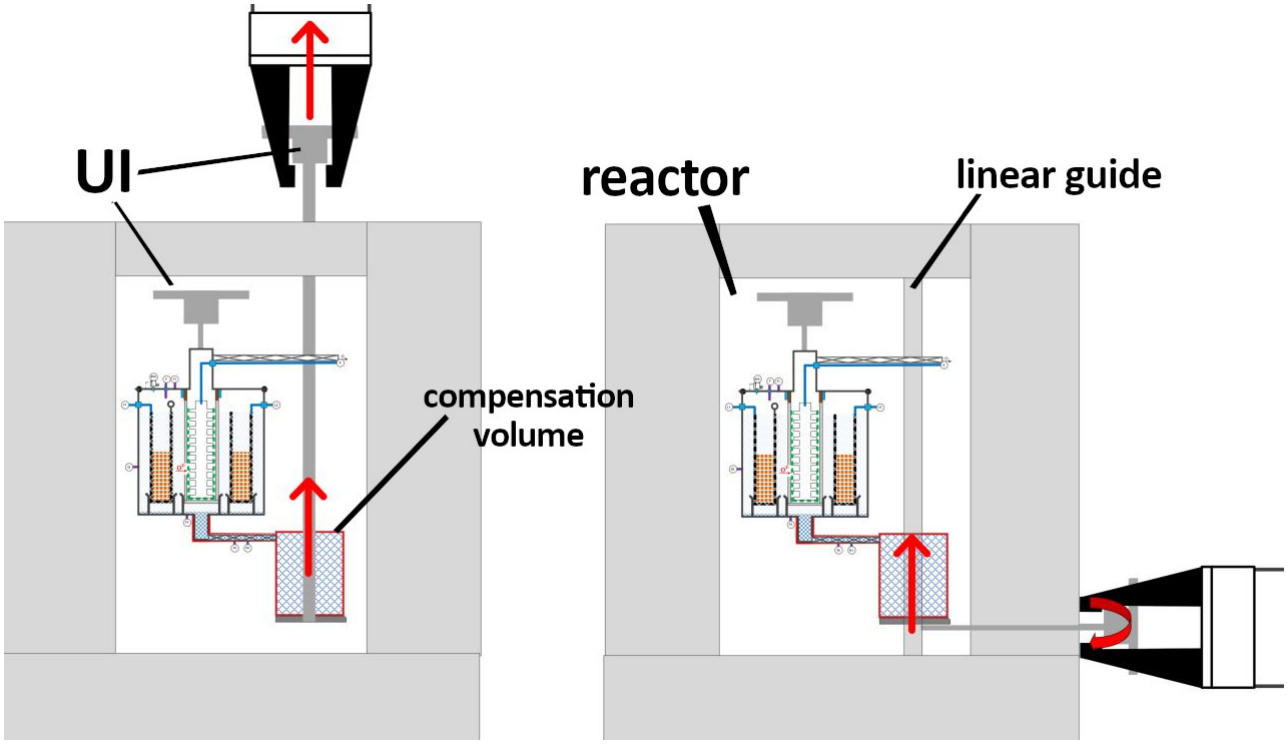
To extract the oxygen from the lunar regolith, a compensation volume of 671 ml has to be moved up and down to fill and empty the reactor with molten salt. The critical part of this function is to perform this task with the thermal isolation remaining. The robotic arm must manipulate a part outside of the reactor to control the volume.
The volume needs to be guided through its movement that no unforeseen action can happen. First concept sketches, situated left in Figure 3.16, had a volume in toroidal shape around the reactor, which makes the concept symmetrical and distributes the volume equally in the reactor. The downside of this concept is that multiple guides need to be mounted in the reactor to stabilize the volume. As reasoning of this, a concept with a change of the volume's shape is presented. The new volume has a rectangular shape and sits beside the reactor, which makes the construction asymmetrical but decreases the complexity and difficulty to control the volume.

Figure 3.16: Different shapes of the compensation volume in the reactor



To indirectly move the volume, two solutions emerged from the research, illustrated in Figure 3.17. The first is a cable pull for the robotic arm, that can be fixed with a twist after the volume is elevated. The second approach uses the universal interface's twist motion to guide the volume through the reactor.

Figure 3.17: Concepts to move the compensation volume



Even though the reactor and compensation volumes would need to be changed a bit, the concept with the guided movement through a twist motion is preferred. The main reason for this choice is security aspects in the reactor.

3.3.7 Storage

The space on the lander is limited, this means that the storage concepts need to be thought out carefully. Two storage types are differentiated in the operation, a temporary and a fixed storage. The temporary storage stores parts for a short amount of time and only during the robotic operation. Components stored in this type are the thermal covers and the reactor lid. All the tools are stored and locked in a fixed storage, as they stay there during the journey to the moon. First, concepts independent of storage types were sketched.
To be as simple as possible, the first concept is a conical guide where the components like the thermal covers can be stored in as one can see in Figure 3.18. The conical shape helps to lower the end-effector position accuracy requirement, including linear and rotational errors. In this simple concept, the components just lay on a platform and are not in a fixed position. This makes it more difficult to grab and store the tools in the tool station. In the second concept illustrated in Figure 3.19, conical peaks are used for more fixed storage on the lander. To make use of the peaks, the tools stored on them need to have an interface that fits them. The storage concepts could be used for either of both types, temporary or fixed. For the fixed

components, located in the tool station, the conical peaks are needed to maintain their exact position and orientation.

Figure 3.18: Thermal cover stored in temporary storage concept

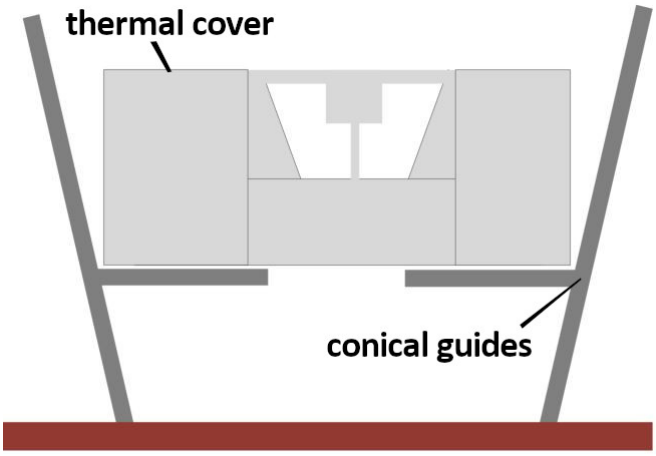
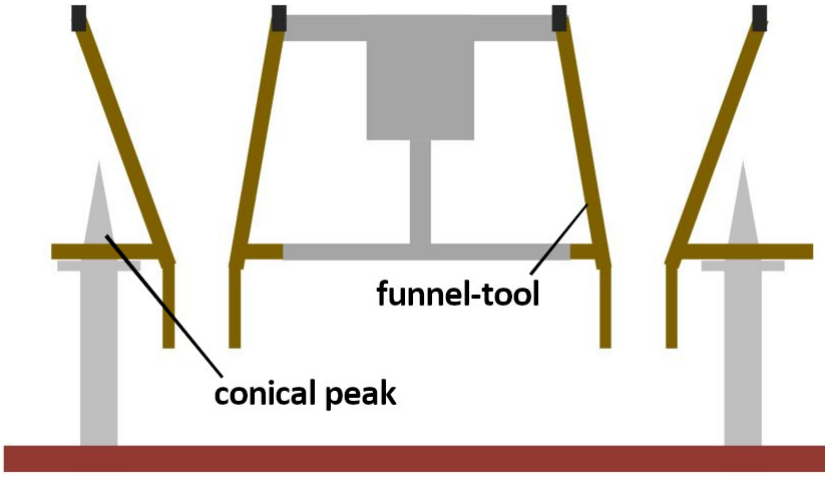


Figure 3.19: Funnel tool stored in fixed storage concept



3.3.8 Cameras

For safe operation of the robotic arm and the inspection of the lunar terrain, cameras are needed. The main question is, where to place them and how many cameras are minimally required. A robotic arm camera shall be used to survey the terrain and monitor the single robotic steps. This camera is placed on the last link and combined with multiple computer vision tags on board of the lander for relative positioning shown in Figure 3.20. The camera can be monocular or stereo, to provide redundancy and help by providing depth information. The camera on the robotic arm has a foreseen field-of-view (FOV) of 45-degrees similar to the camera used on the InSight IDA in Section 2.4. To monitor the process on top of the lander, a camera with a 120-degrees FOV is used. This camera can be positioned at either of the crossbars, where the chosen one in Figure 3.21 has a better view of

the components to be manipulated. Additionally, the same camera can be used on the bottom of the lander for monitoring the sampling of the lunar regolith.

Figure 3.20: Robotic arm camera with computer vision tag

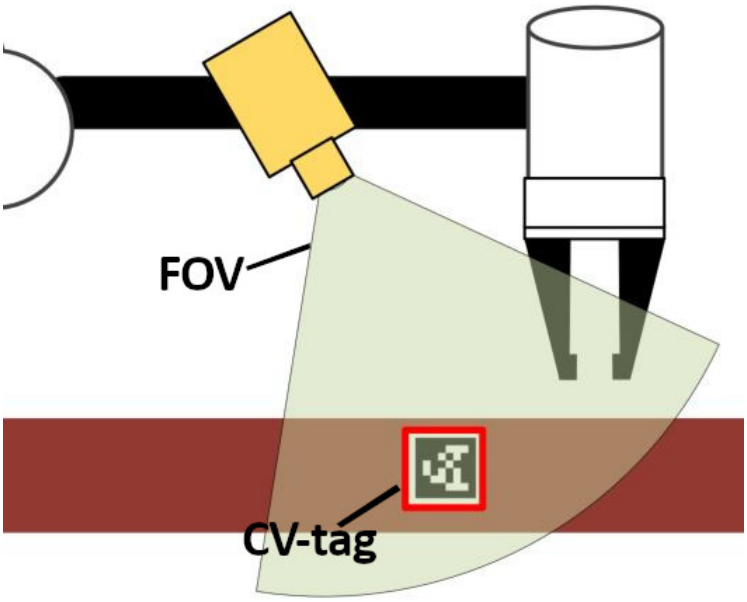
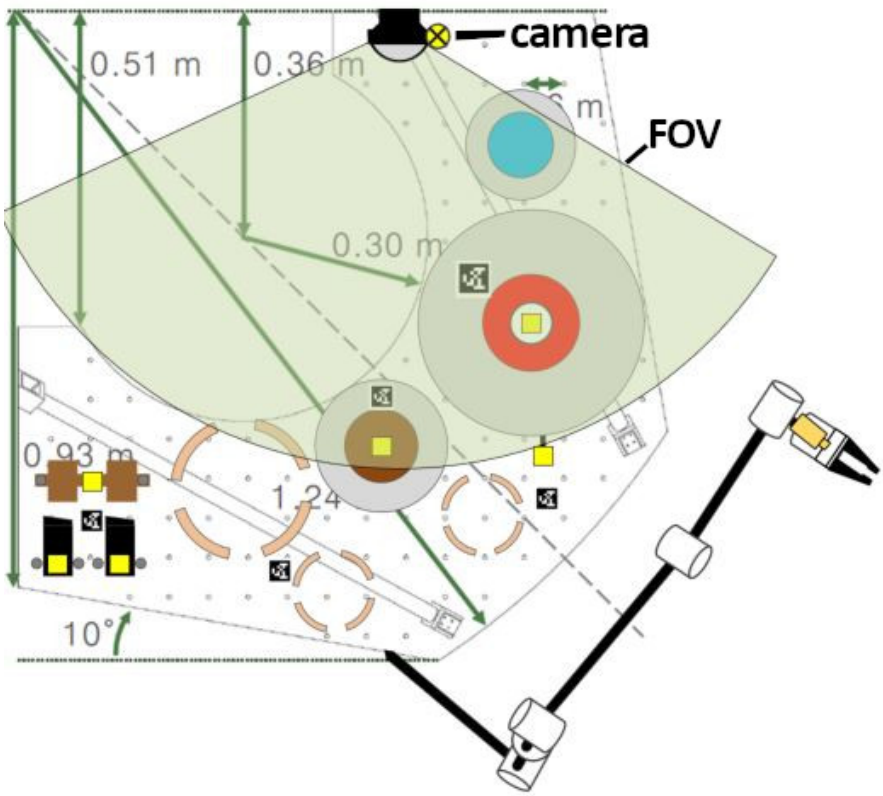


Figure 3.21: Lander with large field of view camera



Chapter 4

Final Concept

The final operational concept emerged of all the iterations done in the previous steps. To visualize all the subfunctions and concepts within the process, it is now presented in a picture sequence of one process cycle from the launch configuration to the end of the oxygen extraction in the reactor.

4.1 Survey Terrain

During the launch and transfer to the Moon, the robotic arm and all the components are stored in a fixed launch configuration. One can see the top of the lander quadrant on the left and the bottom with the stored robotic arm on the right side of Figure 4.1. After a travel time of one month, the Moon lander hit the surface and the robotic operation can start.

Figure 4.1: Top and bottom view of the launch configuration

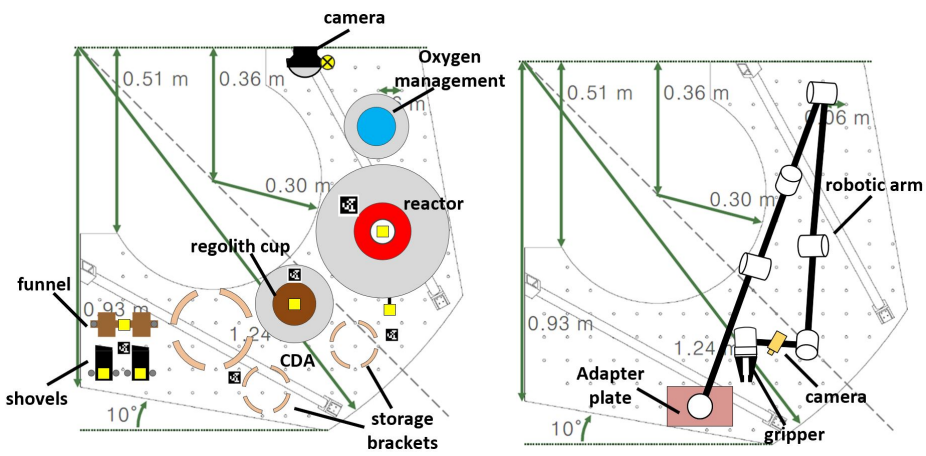
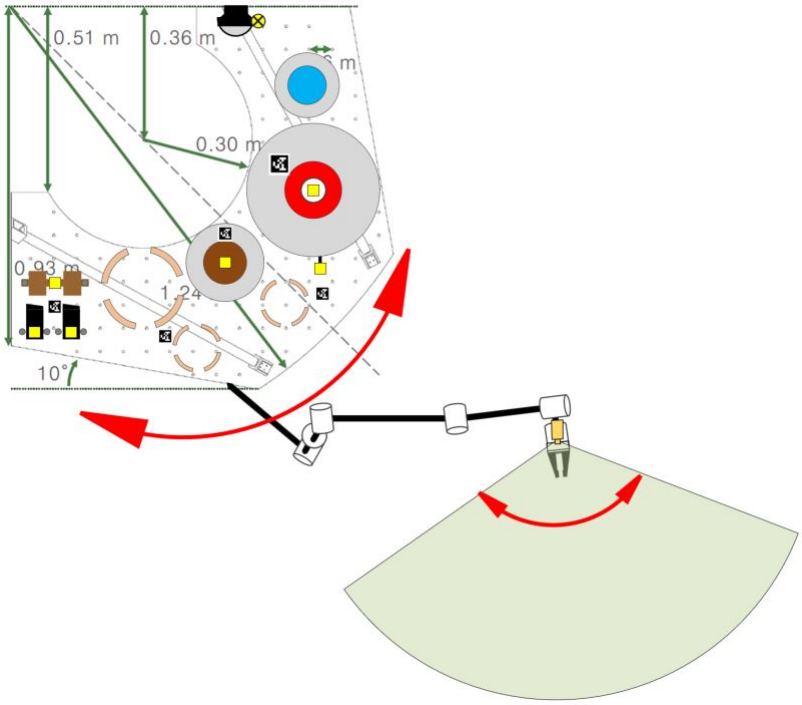


Figure 4.2 shows the first step of the process, which is surveying the lunar terrain with the robotic arm camera. This helps to localize favorable spots for sample acquisition and gather information on the surroundings, in general, to safely operate during the mission.

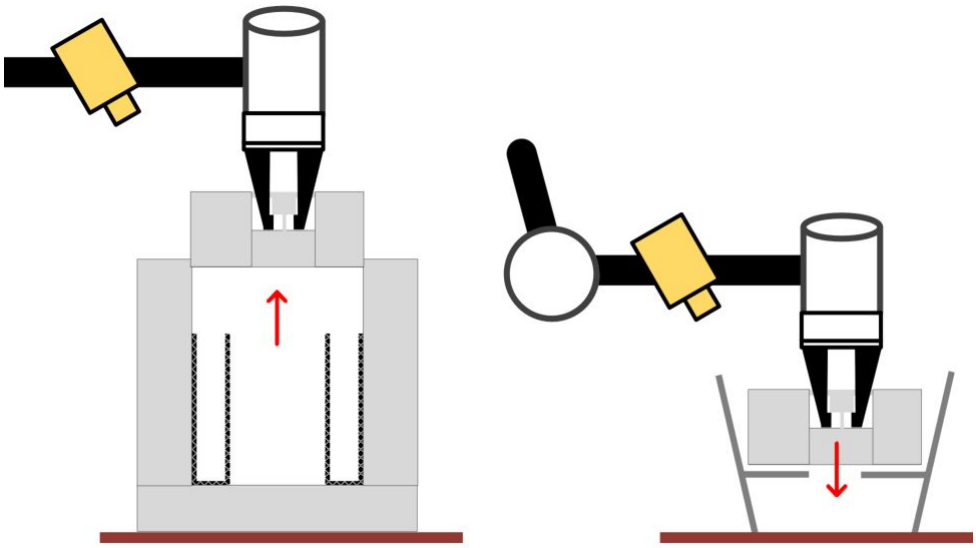
Figure 4.2: robotic arm camera surveys the lunar terrain



4.2 Remove / Store Thermal Regolith Cover

The thermal cover of the regolith cup needs to be removed and transported on the temporary storage concept located in the CDA. Figure 4.3 shows the transport and storage of the regolith cup cover in detail.

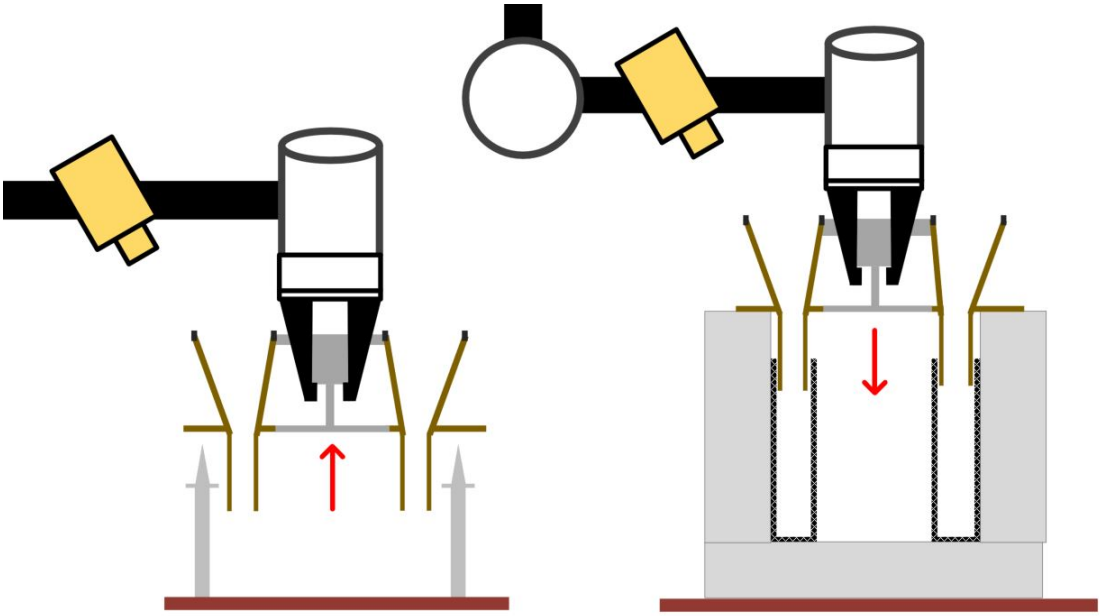
Figure 4.3: Removal and storage of the regolith cup cover



4.3 Attach Funnel

Figure 4.4 illustrates the funnel tool that needs to be picked up at the tool station in order to perform precise filling of the regolith cup in step 4.6. The tool is stored and locked on the fixed storage concept to stay in its place during the travel.

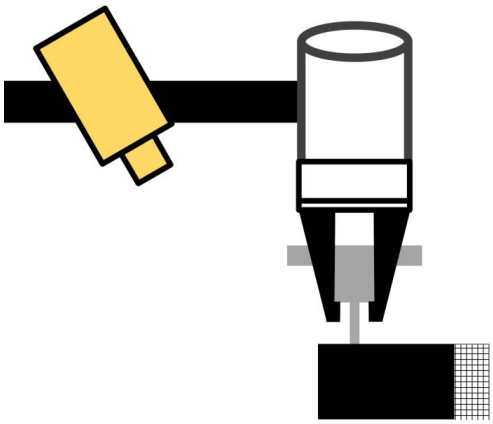
Figure 4.4: Funnel tool attached on regolith cup



4.4 Attach Shovel

Before sampling, the robotic arm needs to pick up the shovel tool displayed in Figure 4.5. As mentioned in 3.3.4, two shovel tools are placed in the tool station for redundancy.

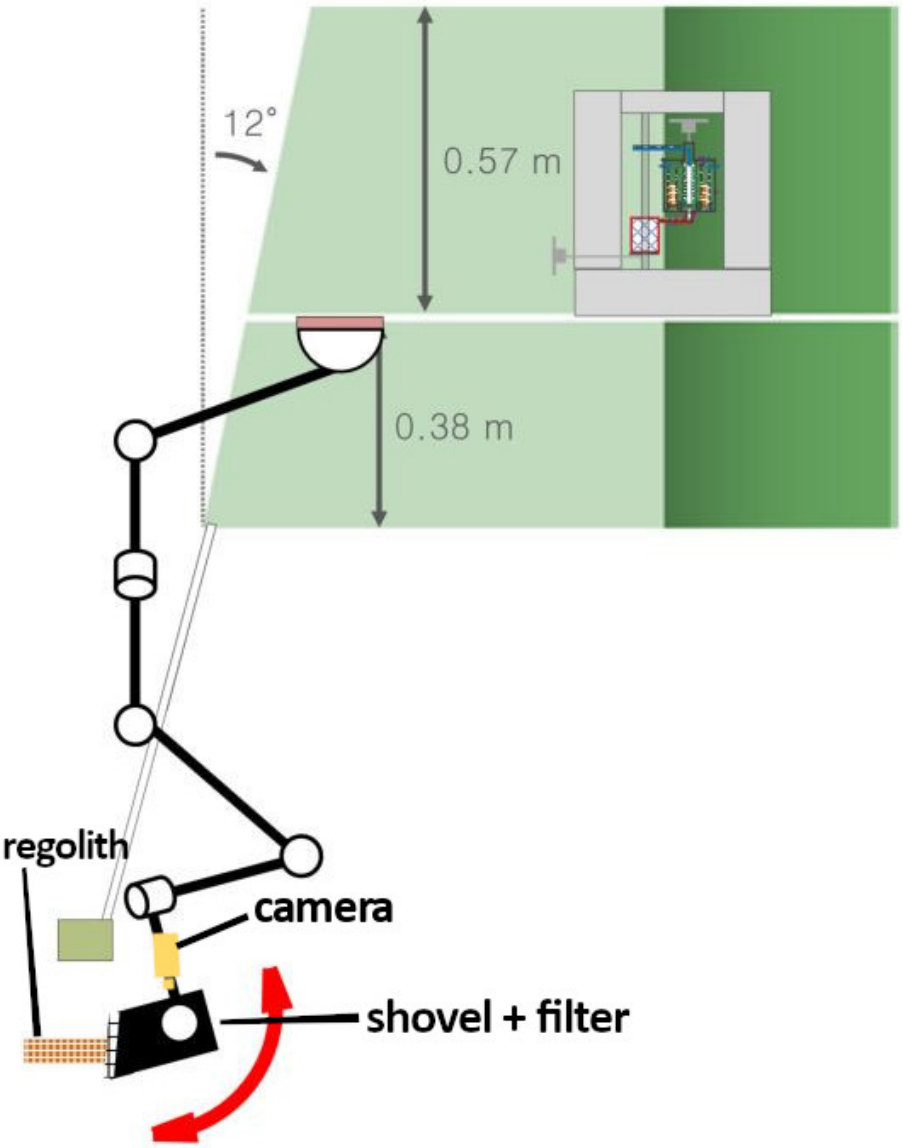
Figure 4.5: Shovel tool picked up



4.5 Sample / Filter Regolith

The sampling of lunar regolith is depicted in Figure 4.6, where the wrist joint facilitates to fill the shovel with regolith. The filter grid in the front of the scoop makes sure to get the required particle size of less than one millimeter.

Figure 4.6: Sampling of lunar regolith



4.6 Fill Regolith

Figure 4.7 and 4.8 show the filling process into the regolith cup through the funnel tool. The steps 4.5 and 4.6 need to optimally be repeated twice, to get the required amount of approximately 200 ml of regolith. The filling status is estimated with the optional F/T-sensor and/or visually observed with the robotic arm camera. After the regolith is in the cup, the shovel tool can be stored in the tool station.

Figure 4.7: Filling of the cup with lunar regolith

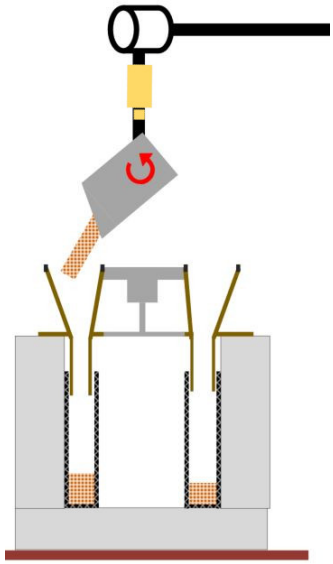
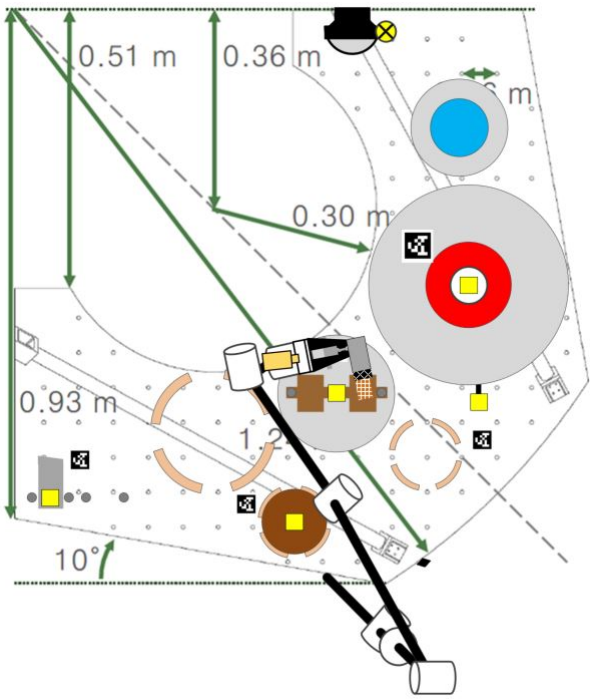


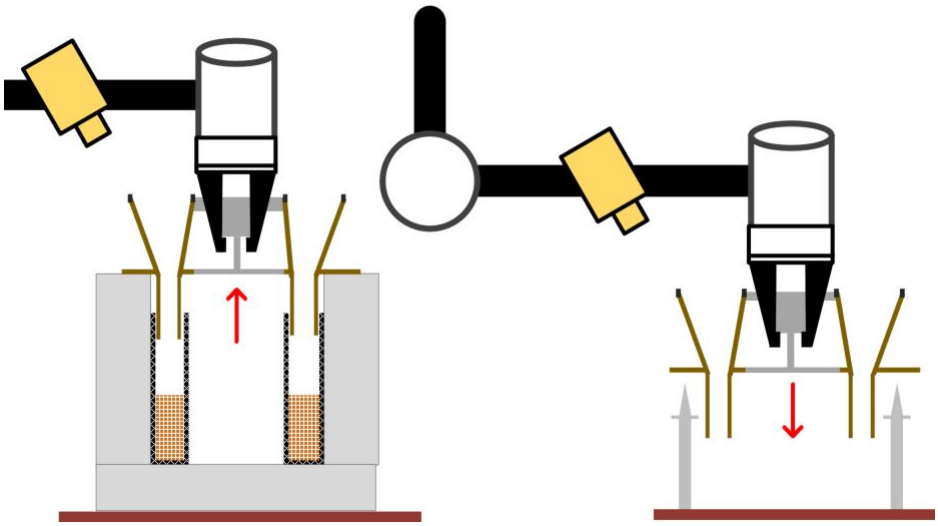
Figure 4.8: Top view of the filling process



4.7 Remove Funnel

To further proceed, the funnel tool has to be stored back at the tool station, pictured in Figure 4.9, until it is used again in a second process run.

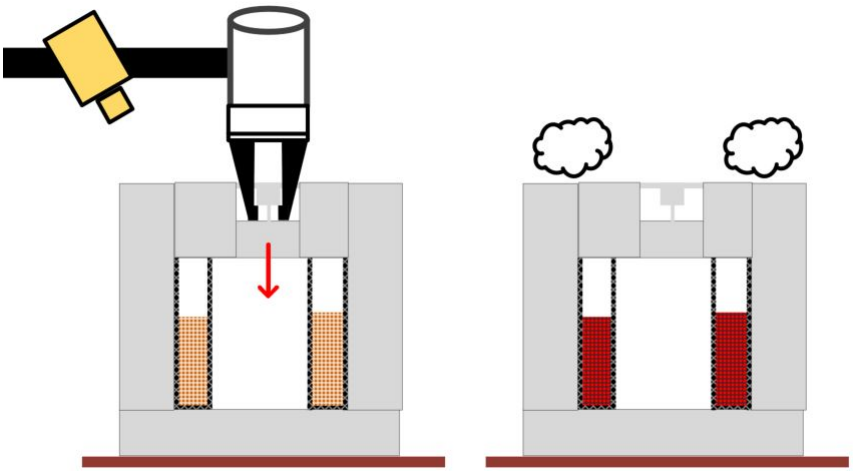
Figure 4.9: Removal and storage of funnel tool



4.8 Attach Thermal Cover

The thermal cover of the regolith cup needs to be attached again to heat the cup and evaporate the volatile elements illustrated in Figure 4.10.

Figure 4.10: Heating of cup to release volatiles



4.9 Remove / Store Thermal Cup Cover

After the volatiles are evaporated, the cup cover can temporarily be stored again identical to step 4.2.

4.10 Remove / Store Thermal Reactor Cover

To prepare the reactor for the oxygen extraction, the reactor cover needs to be removed, depicted in Figure 4.11 and placed in the storage area similar to step 4.2. Figure 4.12 shows the CDA after the cover transportation is performed.

Figure 4.11: Storage of the reactor cover

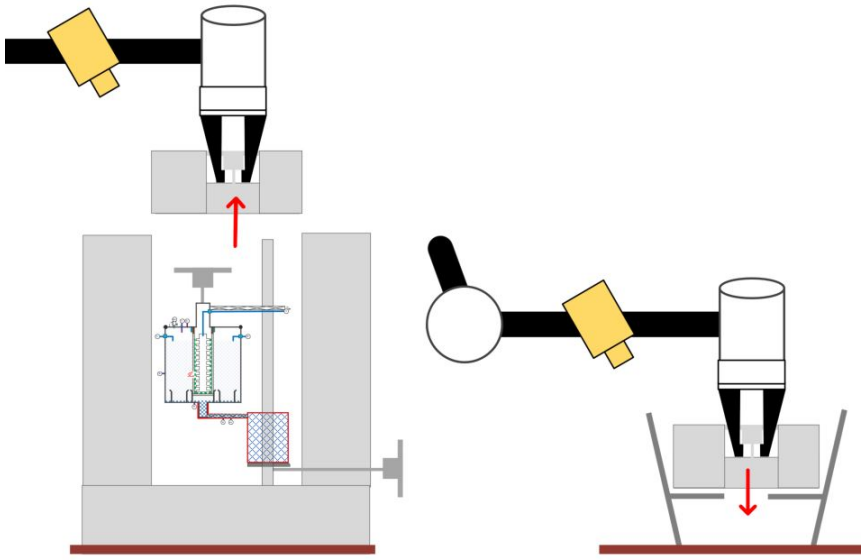
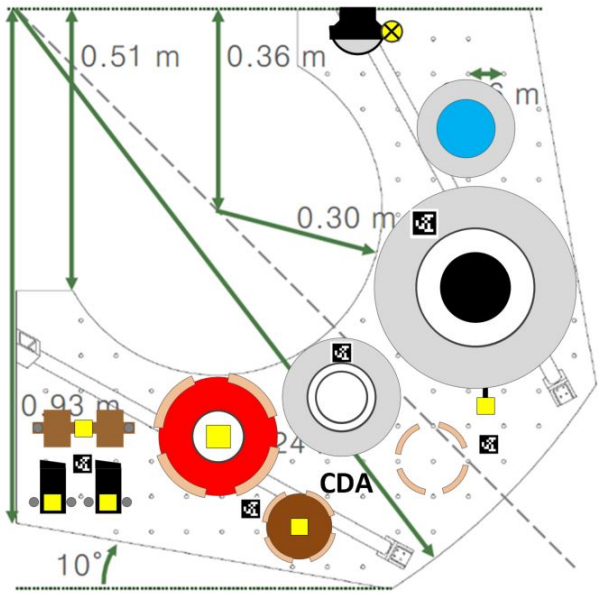


Figure 4.12: CDA



4.11 Remove / Store Reactor Lid

Figure 4.13 illustrates the twist motion to open the bayonet mount that connects the reactor and its lid. The lid is then temporarily stored in the CDA as depicted in Figure 4.14.

Figure 4.13: twist and transport reactor lid

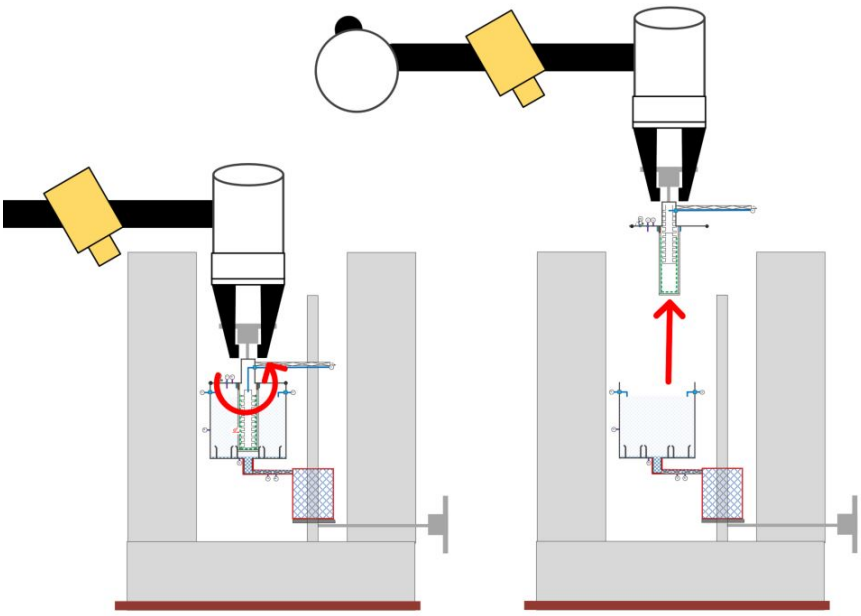
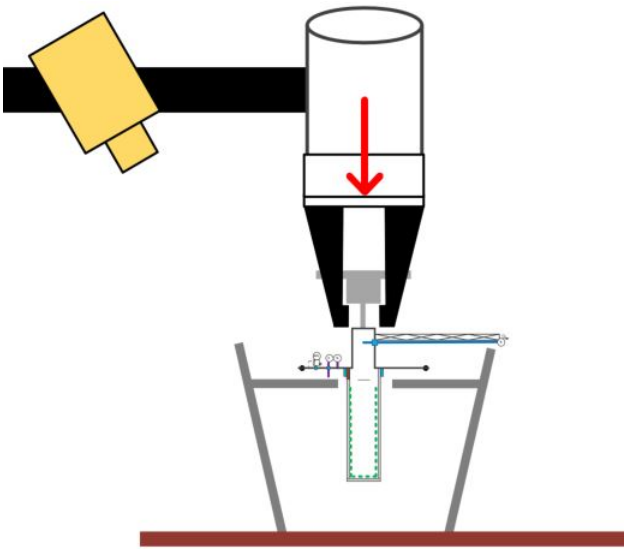


Figure 4.14: storage of the reactor lid



4.12 Transport Regolith Cup

The full regolith cup can then be transported into the reactor chamber pictured in Figure 4.15 with a smaller version of the UI. To fulfill the process, it has to be connected to electrical leads performing a twist motion. The guiding brackets shown in Figure 4.16 simplify the positioning of the cup in the reactor.

Figure 4.15: transport of the regolith cup into the reactor

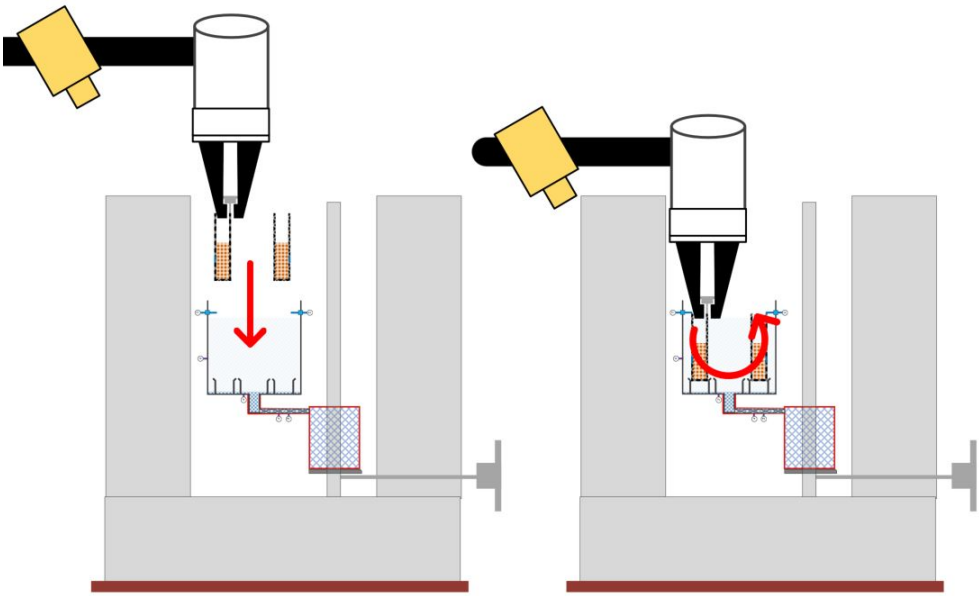
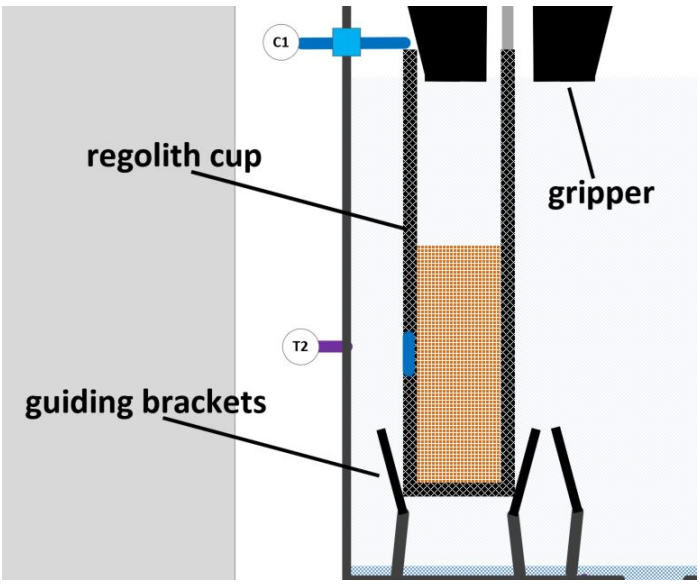


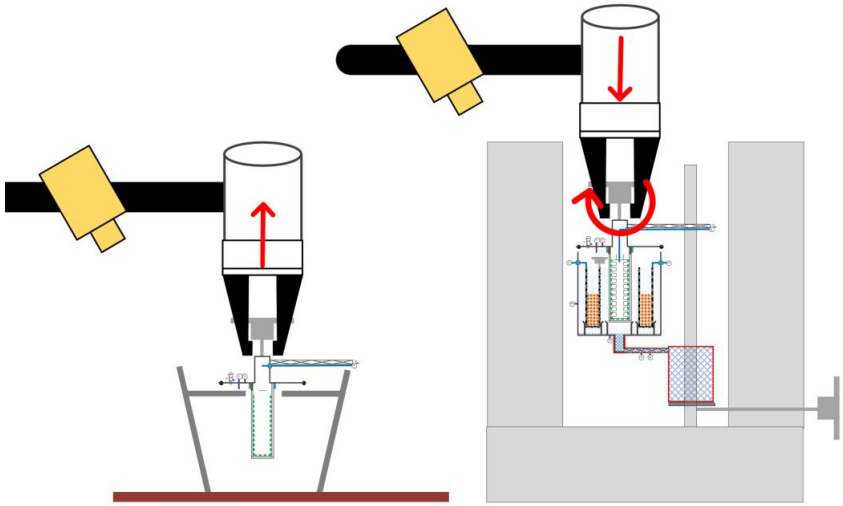
Figure 4.16: close up view of the guiding brackets in the reactor



4.13 Transport reactor lid

To close the reactor, the lid needs to be picked up and twisted onto the reactor, depicted in Figure 4.17.

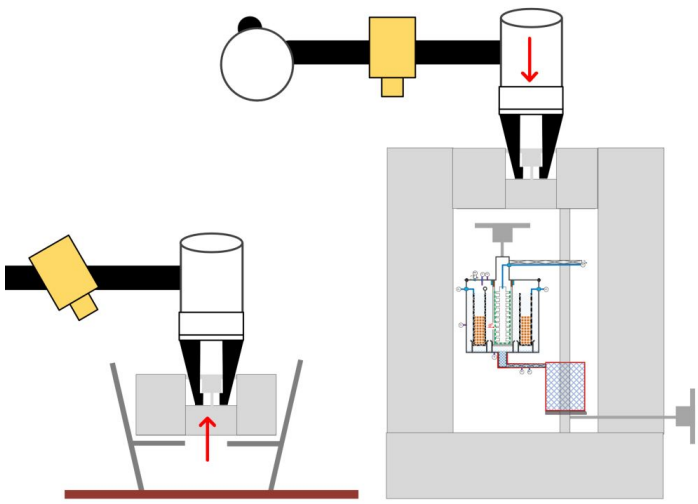
Figure 4.17: transport of the reactor lid into the reactor



4.14 Attach Thermal Cover

In Figure 4.18 the thermal cover to isolate the reactor is attached again. After the reactor is thermally isolated, it is fully prepared for the regolith to oxygen conversion.

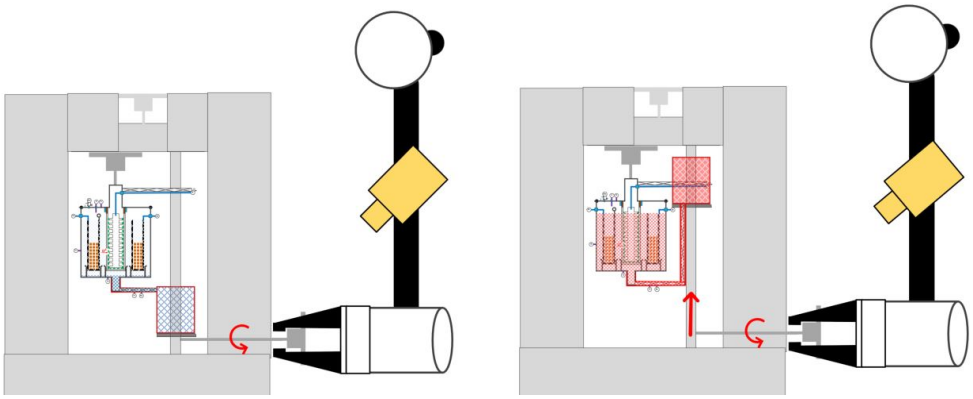
Figure 4.18: Attach the thermal cover onto the reactor



4.15 Move compensation volume

After the salt electrolyte inside the compensation volume is heated up, the volume can be moved. The twist outside the reactor transforms into a linear motion that controls the compensation volume towards the upper position illustrated in Figure 4.19. This allows the molten salt to flood the reactor volume and extract the oxygen. After the reaction is done, the compensation volume is moved into the lower position to remove the salt electrolyte of the reactor.

Figure 4.19: Movement of the control volume with twist



This is the final step of one robotic process run, which is repeated three times to sample a total amount of 600 ml regolith.

Chapter 5

Discussion

5.1 Robotic Arm

The concept sketch of the robotic arm with the chosen link lengths and joint configuration can reach all needed positions in the workspace and perform all the required functions. It can easily be folded into a very compact form for launch or storage due to the many joints used.
Although the main functional requirements are met, the design is not optimized yet. As the joints and link configurations are chosen on a visual base, the actual performance of the arm can be improved. The seven joints help to minimize the storage volume and for full redundancy to reach all end-effector poses, but actuators also increase the weight as seen in Chapter 2. A detailed task space analysis in a simulation would help to iterate the robotic arm towards an optimzed solution.

5.2 Universal Interface

The usage of a universal interface throughout the whole robotic process provides an easy solution for all manipulations performed. Combined with a gripper, the interface is an easy mechanism to pick up different tools and could easily be adapted to other components to perform more functions if needed.
However, the interface sets new geometrical constraints to the surroundings on the components used. As seen in step 4.12, the interface needs to be small due to limited space inside the reactor while being able to transfer sufficient torques to lock components. The question of how small the interface can be and still perform all functions needs to be answered to prove this concept idea.

5.3 Tools

The sampling, filtering, and filling can easily be performed with the shovel and funnel tools. As all the tools are very simple built and straight forward in usage they provide a solid solution for the requested requirements.
With two shovels and a funnel, the goal of avoiding tool changes was not achieved. For weight and space improvements, the mentioned tools could be combined into an all-in-one tool that combines sampling, filtering, and controlled filling. Furthermore, the sampling tool in this concept is not able to measure the amount of regolith sampled. This can complicate the estimation of the regolith already in the cup, which could lead to an under or overfilled cup.

Chapter 6

Conclusion

The goal of this thesis to develop a concept for a robotic operation for ISRU on a commercial landing platform was achieved. Although the concept was developed to the constraints given by the Peregrine Lander, it can be adapted to other commercially available landers with minimal changes. The concept is the result of literature research on space manipulators and sampling tools combined with an iterative design process described in the previous chapters.
The main challenge was to come up with a robotic system that samples regolith and carries out steps to perform ISRU. One difficulty was to fit the system on a very limited space, this was solved by placing the robotic arm on the bottom of the lander to keep space clear for a storage and tool station area on the top. Since multiple different manipulations have to be done during the operation, a further challenge was to simplify and combine them as much as possible. A universal form-fit interface on every component has proven to be a well-working concept to reduce complexity in the robotic process.
The final concept developed already provides a good starting point for the implementation of the robotic operation. For future work, the full concept needs to be discussed with Airbus since it is a collaborative project. After those refinements are made, the concept must be optimized and verified with in simulation that could point out weak spots in the concept.

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Appendix A

Appendix

Table A.1: List of Requirements

Page: 1/3	**List of Requirements**			
	Study on a robotic arm for sampling lunar regolith			
D/W	Requirement	Value	Source	Date
	Geometry			
D	Maximum Geometry (lenght x width x depth)	<250x500x570mm>	Bohn	4/5/2020
D	Height of the payload envelope to ground may vary	400-800mm	User Guide p.41	4/5/2020
D	Maximum angle of the lander wrt ground	< 12 degrees	User Guide p.27	4/5/2020
W	Robotics area should be minimized	< 0.25 m^2	Bohn	4/5/2020
	Kinematics			
D	Number of DOF shall be minimized		Bohn	4/5/2020
D	The arm shall reach all points within the manipulability ellipsoid while avoiding singularities	tbd -> predicted workspace file	Bohn	4/5/2020
D	Joint (peak) torques shall be minimized		Kolvenbach	4/7/2020
	Forces			
D	Robotic arm shall allow for maximum force at EE	Force at distance tbd	Bohn	4/5/2020
D	The robotic arm shall be lightweight	tbd (max 25 kg)	Kolvenbach	4/7/2020
	Energy			
D	Energy consumption of the robotic arm shall be minimized	standby: < 20W ; peak: ~ 200W	Seidel	4/15/2020
	Heritage			
W	Components with high TRL should be used		Kolvenbach	4/7/2020
	Functional			
D	The arm shall open/close the insulation of the reaction chamber		Bohn	4/5/2020
D	The arm shall fill the reaction container with lunar regolith		Bohn	4/5/2020
D	The end effector shall sample regolith from the lunar surface	~ 200ml / process (3x)	Concept Design 3B	4/15/2020
D	The arm shall transport the sampled regolith to the reaction container		Bohn	4/6/2020
D	The number of tools shall be minimized		Bohn	4/6/2020
W	A toolchange should be avoided		Bohn	4/6/2020
W	The arm should be illuminated for visual inspection		Bohn	4/7/2020
D	The arm shall have high end effector position accuracy	accuracy tbd	Kolvenbach	4/7/2020
D	the arm shall filter regolith	size < 1mm	Concept Design 3B	4/15/2020

Page: 2/3				
D	**Study on a robotic arm for sampling lunar regolith**	vol CV = 671.133 cm^3	Seidel	4/15/2020
	Interfaces			
D	Electrical Connector	tbd	Seidel	4/15/2020
D	The robotic arm shall operate with bus voltage	tbd	Seidel	4/15/2020
D	The robotics area shall fit the mechanical interface of the lander	M5 bolts, spaced 63.5mm apart or adapter plate	User Guide p42	4/8/2020
D	The robotics area shall connect to the common ground of the lander		User Guide p43	4/8/2020
D	Connection to the lander shall be thermally isolating		User Guide p43	4/8/2020
	Signals			
D	Cameras shall survey operation for visual inspection and confirmation		Bohn	4/5/2020
D	EE Forces/Torques shall be reported		Kolvenbach	4/7/2020
D	Joint position and torques shall be reported		Kolvenbach	4/7/2020
D	Transmission rate shall lie within data budget	tbd	Seidel	4/15/2020
D	System shall be robust against sudden loss of contact to Earth		User Guide p47	
	Safety			
-	Range Safety		User Guide p45	4/5/2020
-	EMI Safety	MIL-STD-461G	User Guide p39	4/7/2020
-	Regulate own thermal environment		User Guide p43	4/7/2020
-	Robotic arm shall be released from launch configuration at mission start		Kolvenbach	4/7/2020
-	The system shall be protected against dust		Kolvenbach	4/7/2020
-	Safety factors shall be considered	Factors tbd	Kolvenbach	4/7/2020
	Operation			
D	Dust creation shall be avoided		Kolvenbach	4/7/2020
W	Arm should have a high level of autonomy		Bohn	4/5/2020
	Round trip latency for telecommands	10s	Bohn	4/7/2020
	Durability			
D	The arm shall survive one lunar day	14 earth days	Bohn	4/7/2020
	Environment			
(D)	(The design shall be scalable to survive lunar surface temperature)	define lunar area	Kolvenbach	4/7/2020

Page: 3/3				
(D)	(The robotic system shall be scalable to surface cosmic radiation)	27 krad total ionizing dose 12 krad without contingency	Kolvenbach	4/7/2020
(D)	(The robotic system shall be scalable to work in the vacuum of space)		Kolvenbach	4/7/2020
D	The robotic system shall be scalable to work in lunar gravity		Kolvenbach	4/7/2020
	Costs			
D	Price of the robotic arm shall be minimized	~1.2Mio. / kg	User Guide p3	4/5/2020