# Towards a Heterogeneous Modular Robotic Team in a Logistic Chain for Extraterrestrial Exploration



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# Towards a Heterogeneous Modular Robotic Team in a Logistics Chain for Extended Extraterrestrial Exploration

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## Abstract

Future extraterrestrial exploration missions ask for robotic systems able to handle tasks with increasing complexity. A reference mission within Amundsen crater near the lunar south pole for volatiles and rogolith analysis is outlined in this paper. The focus is on implementing a logistics chain introducing various heterogeneous mobile and immobile robotic systems. Within this context the robot cooperation as well as communication architecture is outlined. The reference mission serves as base line for later field trials. Furthermore, an overview is given on the robots to be used within the terrestrial test campaign.

## 1 Introduction

Future exploration of the solar system is calling for robotic missions with increasing complexity. Scientific concepts for the exploration of the Moon and Mars ask for advanced instrumentation and experiments such as sample acquisition and return, while pushing into more hostile environments such as permanently shaded areas at the lunar poles. These missions get increasingly difficult to handle with common single rover architectures but call for the combination of multiple, specialized exploration vehicles. A first attempt in this direction is e.g. the proposed ESA/NASA Mars Sample Return (MSR) mission, including one rover for taking samples and a second rover for fetching these samples and returning them to the sample return stage [6].

The primary mission objective of the presented project seeks to extend the exploration capabilities and handle complex mission tasks in a (semi-)autonomous manner by introducing a semi-autonomous and heterogeneous team of cooperating mobile robots, able to establish a logistics chain based on stationary modules (so-called base camps) as well as portable modular payload items. The general idea of implementing a logistics chain including various robotic systems is depicted in Figure 1. An exploration rover is paired with one or more small supporting rovers (so-called shuttles) building up a logistics chain between the rover and the lander via the aforementioned base camps.

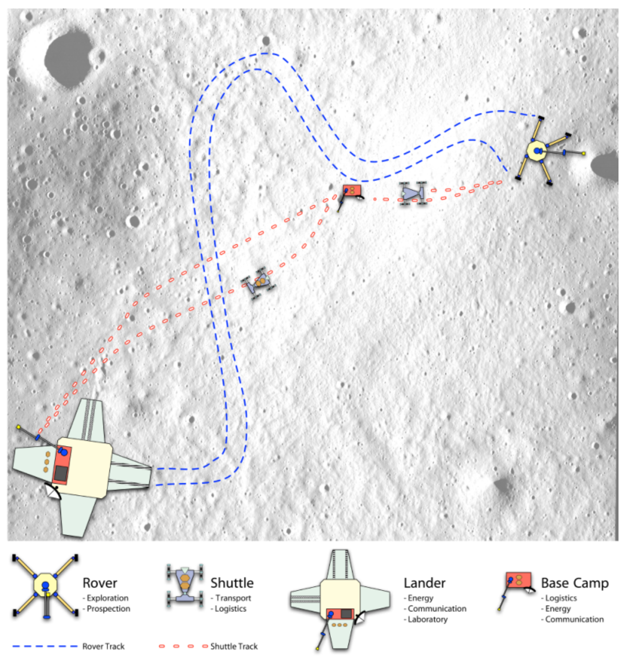



**Figure 1.** Schematic drawing of the implementation of a logistics chain using a heterogeneous team of mobile and stationary robots

In this paper a reference lunar exploration mission is outlined. First the mission concept is presented, providing the overall mission design concept as well as the mission subject and landing site. Furthermore, the mission architecture is addressed, providing an idea how the different robotic systems are working together. This mission set-up provides the basis for terrestrial implementations, tests, and demonstrations of logistics chain applications. The different robotic systems which are used for implementing a logistics chain, referencing to the previously outlined mission design, are conceptualized and introduced as well. Finally a conclusion and outlook for further work is given.

## 2 Mission Design Concept

The mission design concept is motivated by the need of robotic systems able to handle exploration tasks with increasing complexity. This includes e.g. (multi-) sample return missions as well as tasks in the field of resource utilization and even the preparation of (long term) manned missions. The overall mission concept is oriented around the implementation of a logistics chain, including various robotic systems. As shown in Figure 1, this includes: (1) a team of mobile surface robots, (2) stationary elements and (3) portable modular payload items. The proposed mission concept addresses basically the surface exploration of the above mentioned elements.

The exploration rover is the primary mobile element within the mission concept. It serves as main exploration device, able to conduct the major mission tasks and serves as transporter for the deployment of base camps.

The exploration rover is paired up with one or more shuttle rover(s). The shuttle is a compact, highly mobile system and the core element for establishing a supply chain between stationary infrastructure elements - such as lander and/or sample return stage, base camps and the exploration rover. The base camps are stationary elements providing infrastructure to support the logistics chain. They can serve as junction point as shown in Figure 1 to exchange, e.g., payload items between the different systems. Further functionality for energy harvesting, communication or scientific instrumentation may also be provided by base camps depending on the needs of the mission.

In order to implement a supply chain the shuttles need to cooperate tightly with the exploration rover. Further surface elements that may be included in the logistics chain are potentially the lander and a sample return stage. Independently of the chosen landing system, a dedicated *home base*, i.e. main supply and communication link to the ground station, is part of the mission concept. The home base serves as depot for base camps and portable payload items and may be equipped with additional scientific and/or mission relevant functionality as well.

The mission concept proposes to realize the logistics chain by including the different mobile and stationary surface elements and establish the links using a modular approach. While each of the surface elements has to satisfy specific needs to execute the mission tasks, a high interconnectivity between the different elements is envisaged. An overview of the physical connectivity between the various elements is shown schematically in Figure 2. Especially the portable and modular payload items play a key role for establishing the logistics chain. They serve

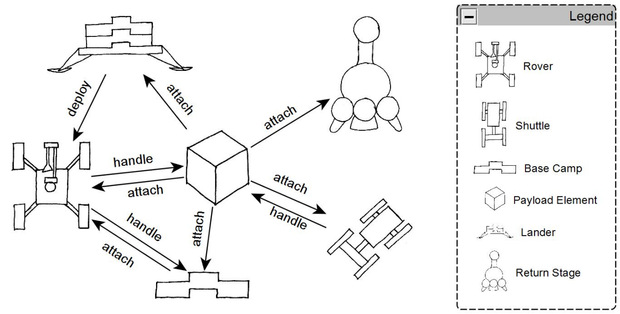


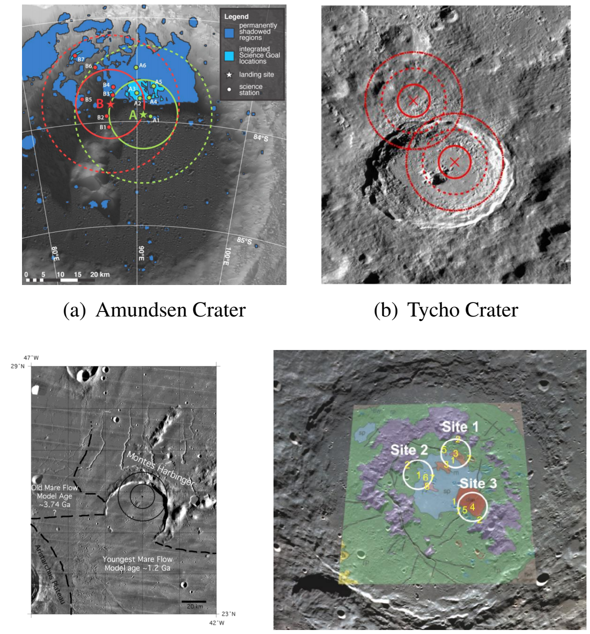

**Figure 2.** Schematic drawing of the modular interconnectivity of the different surface elements

as multipurpose payload containers which can be attached to several elements. This approach allows to add specific functionality to the various systems and to handle different tasks in a distributed manner. A closer look on the different robotic systems is provided in Section 6.

## 3 Mission Subject and Landing Site

For the reference mission scenario the robotic systems are designated to operate inside Amundsen crater, located close to the lunar south pole. This landing site was chosen based on a trade-off between different scientific goals for lunar exploration, as identified by [4, 7]. The trade-off process was conducted to identify an adequate scientific context and an appropriate landing site for the reference mission. This was done mainly with respect to which scientific mission concept would benefit the most of the previously described mission design concept. As most of the described science goals in [4, 7] require field work, like sample collection and return to Earth, four high potential sites are identified which would benefit from a logistics chain set-up. These are in particular: 1. Amundsen Crater, 2. Tycho Crater, 3. Montes Harbinger and 4. Schrödinger Basin. The four sites are shown in Figure 3, with potential landing and exploration sites highlighted as identified by [4].

The primary scientific objective within Amundsen crater is to study volatiles and their flux in the lunar pole regions. Due to its location and crater diameter of approximately 150 km, only some parts of the crater are permanently shadowed regions (PSR) (cf. Figure 3(a)). This allows to land and deploy the robots directly on the flat crater floor in a sunlit region such that no descent on a steep crater wall is required as it would be the case e.g. at Shackleton crater. Another benefit is the possibility to send the robots for short exploration excursions into the thermally and power-wise more challenging PSR environment.




(a) Amundsen Crater

(b) Tycho Crater

(c) Montes Harbinger

(d) Schrödinger Basin

**Figure 3.** The four most favorable lunar landing sites following the mission design concept [4]

The main needs which arise from the scientific mission setup with respect to the mission and system design are:

**Operation in shadowed/dark areas** Exploration and analysis tasks need to be conducted in PSR which provide continuous low temperatures. These areas are of main interest to study the accumulation of volatile materials as well as regolith processes.

**Sample analysis** The current state of volatile materials and regolith at very cold spots may need to be analyzed by in-situ measurements. Taking the samples out of its environment can change the composition drastically due to temperature change.

**Sample return to Earth** In order to study regolith composition and processes in cold areas in-situ analysis is needed. However, the science goals ask for the return of regolith samples allowing a deeper investigation within terrestrial laboratories. As proposed in [2] returning frozen samples should be considered as well, calling for sealable sample containers.

The mission needs introduce quite challenging and complex exploration tasks which would benefit from a logistics chain e.g. in terms of sample transport, energy and communication support and assembling special base stations for keeping-alive support.

Especially the deployment of different base camps can support the mission in terms of, e.g., energy supply, position tracking, and communications. Furthermore, they can serve as stationary laboratories for in-situ analysis of samples taken by the exploration rover. Paired with suitable modular payload items it would be possible to introduce instrument and/or tool change for the different rover platforms in order to handle a wide range of different tasks.

The investigation on establishing and maintaining a robotic logistics chain provides the possibility of increasing the maturity level and demonstrating the state of robotic technologies in terms of (1) robotic cooperation, (2) multi-robot mission planning and execution, (3) robotic long-term autonomy, and (4) robotic infrastructure setup and maintenance. These robotic technologies are currently considered to be main issues in preparation for (long-term) human presence on any celestial body.

The aspired mission definition provides a wide range of exploration and assembly tasks with the possibility to prepare In-Situ Resource Utilization (ISRU) and/or long-term manned missions. Especially the potential of harvesting volatile materials, e.g., for future long term manned missions makes the Amundsen crater a quite interesting place.

This concept highly depends on the logistics chain considering that the base camps will be needed as communication relay stations (cf. Section 5) and potentially for power supply and sample analysis. Especially for solar powered rover systems the base camps can be used for energy harvesting. This would allow to extend the PSR excursions of the exploration rover due to the possibility to supply recharged energy packages via the logistics chain. Most likely, however, this concept would not hold for the surface exploration as described in Section 4. For extensive PSR traversal an appropriate power supply system is needed on the exploration rover which can, e.g., be based on wireless power transmission techniques or radio thermal generators. In any case a reliable cooperation between the robotic systems is required in order to support exploration and sample analysis in PSR.

## 4 Surface Exploration

The main scientific and technical focus is on establishing a logistics chain utilizing a team of robots to sample regolith and evaluate the presence of volatile material in difficult to reach areas inside the Amundsen crater. The chosen landing and exploration site is shown in Figure 4. The image is a multi-level surface map with a satellite mosaic overlay [5], the markers for the science goals refer to [4]. The paths were chosen to avoid craters on transients using the tools available in [5].

The rover starts at the landing site $L$ and passes the

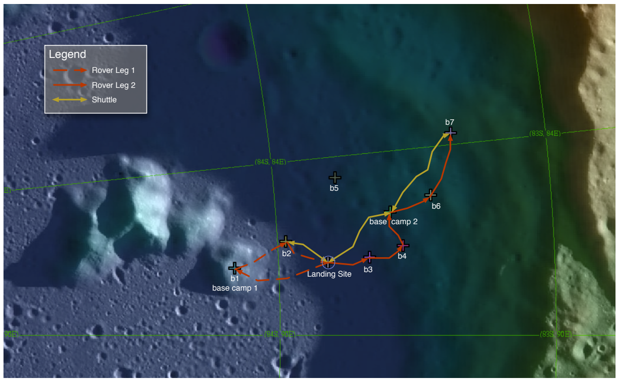



**Figure 4.** Overview of the surface exploration scenario in Amundsen crater

science sites *b1* to *b7*. The following enumeration gives more detail on the approach sequence and tasks carried out at the specific science sites:

1. Following the touchdown of the lander at landing site *B*, 83.82° S, 87.53° E (cf. Figure 3(a)) with crater floor slopes < 5°, both, the shuttle as well as the exploration rover, begin the commissioning phase.

2. After commissioning, the rover, already equipped with a base camp assembly for communication and power supply, travels towards the central peak foothills and then starts approaching point *b1* on the slopes of the central peaks.

3. At point *b1* the exploration rover deploys (utilizing it's manipulation capabilities) the base camp communication/power assembly. The elevation above the crater floor will increase visibility both to Earth and Sun for communication purposes and energy harvesting. The base camp may also be utilized for navigation purposes by serving as a beacon.

4. A second task at point *b1* for the exploration rover is to take regolith samples, which are of specific interest due to the potentially layered structure of the central peak slopes. The gathered samples do not need to be analyzed in-situ but can be stowed away in a modular sampling container (payload item) for sample return.

5. Subsequently, the exploration rover descents the central peak slopes, heading for point *b2* to take further regolith samples.

6. *b2* is also the first rendezvous point for the exploration rover and the shuttle, at which the exploration rover can reequip itself with fresh battery payload elements brought there by the shuttle, as well as exchanging the filled sampling payload elements with new ones. Additional sample containers are probably required to take samples at *b2* which is proposed for sensor calibration by [4].

   Following the first rendezvous, both robots head for the lander, the exploration rover in order to fetch the second base camp assembly (sample drop-off / power supply type) and the shuttle to deposit the regolith samples.

7. Thereafter, the exploration rover is approaching and entering the PSR heading towards point *b3* and *b4*, taking geological samples in places of utmost scientific interest due to the expected thermally trapped volatiles.

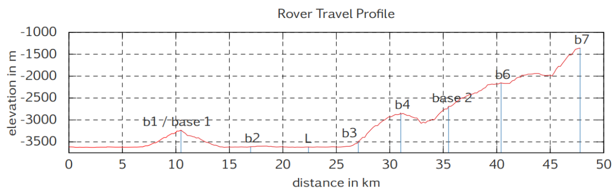
8. Having sampled at point *b3* and *b4*, the exploration rover leaves the PSR again in a left side arc toward *b6*, deploying the second base camp. At this point also a rendezvous with the supplying shuttle takes place again.

9. While the shuttle is returning exchanged sampling and battery payload elements to the lander, the exploration rover is entering the PSR again in order to sample at *b6* and *b7* subsequently while being resupplied by the shuttle.

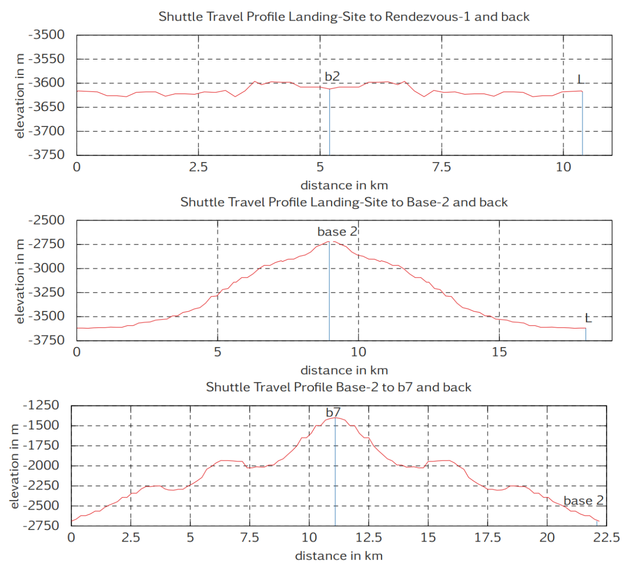
10. In an extended phase that could follow the mission procedure stated above, the exploration rover can continue to climb the Amundsen crater rim sampling the interesting heavily terraced and layered slopes looking for ancient regolith.

Following the depicted exploration scenario, the exploration rover needs to travel a total distance of approximately 47.75 km with a maximum distance from the landing site of 20 km, and 3915 m of cumulative elevation gain. In Figure 5(a) a distance profile for the exploration rover path within Amundsen Crater is plotted. The landing site, scientific exploration points of interest as well as base camp deployment locations are marked within the diagram. Accordingly, the travel profiles for the different shuttle legs are given in Figure 5(b). For each shuttle path the distances to the target and back are plotted since this is considered a typical shuttle support mission. Specifically these cover the shuttle traversal from the landing site to *b2* and back, again from the landing site to base camp 2 and back and from base camp 2 to *b7* and back.

The travel profiles follow the exploration scenario as shown in Figure 4 and outlined in the previous descriptions. For compiling the traversal profiles and distance measurements the data available in [5] were used. For all measurements the direct path between the depicted points of interests are taken into account. Hence, no additional traversal for performing exploration tasks and/or obstacle




(a) Distance profile for the exploration rover path




(b) Distance profile for the shuttle rover paths

**Figure 5.** Travel distance profiles for the exploration and shuttle rover

avoidance is considered in the given distance measurements. These need to be included during a detailed mission design process.

## 5 Communication Architecture

To allow the implementation of a logistics chain with various cooperating surface elements a proper communication architecture needs to be taken into account for operations. A short range communication ability between the exploration rover and shuttle(s) is necessary to allow the handling of cooperative tasks. For longer ranges base camps can serve as communication relays, e.g. for transmitting the relative positions of the systems for rendezvous. This implies that the exploration rover as well as the shuttle need a direct communication link to each other or at least to one base camp when trying to communicate with each other. Therefore, each base camp should be able to link to neighboring base camps to establish a supporting communication network for the surface elements.

The communication range on the Moon strongly depends on antenna heights and terrain. A direct line of sight

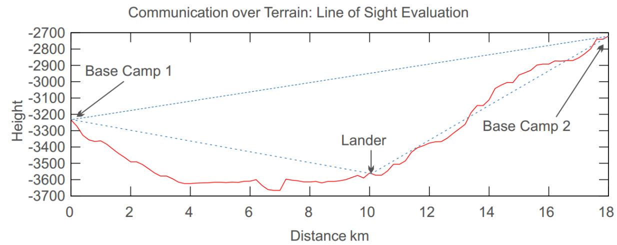



**Figure 6.** Free line of sight evaluation for communication within Amundsen crater

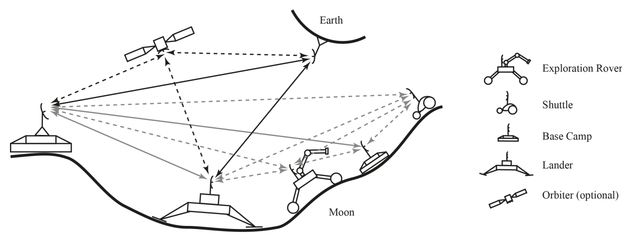



**Figure 7.** Proposed communication architecture with optional orbiter displayed. Dashed lines depict temporary and/or optional communications and solid lines mark fixed communication links.

(LoS) is necessary in order to establish communication. Figure 6 illustrates the communication possibilities over the terrain between the base camps and the landing unit representing a cross section of Amundsen crater based on the data available in [5]. As shown the LoS between the lander and base camp 2 is blocked by terrain. A communication between lander and base camp 2 is possible using base camp 1 as relay.

Using this information, Figure 7 illustrates the proposed communication architecture. As outlined previously, base camp 1 should be placed on the central peak of Amundsen crater. This has two main reasons besides the scientific mission needs: (1) As shown in Figure 6 no direct LoS can be established between the lander and base camp 2. Therefore, a relay is needed to set up a communication network, covering the points of interest *b3* to *b7*. (2) Due to the landing site at 83.82° S, 87.53° E the lunar libration with max. angles of ±7.7° longitude and ±6.7° latitude has a major impact on the LoS to Earth (cf. [3]). Placing a base camp on the central peak reduces the angle to the crater rim to ~ 2.5° while the horizon seen from the crater floor is at ~ 5°. Taking the libration into account the total time with direct communication ability to Earth increases by placing the antenna on the central peak. Optionally, communication times with mission control can be increased by introducing a lunar orbiting satellite or placing a relay on the outer crater rim of Amundsen. During the traverse of the exploration rover to the deployment destination of base camp 1 the lander is considered to serve as communication link to Earth, providing a communication back-up for the later on mission.

For cooperative tasks between the exploration rover and the shuttle(s) short range communication is required. For longer ranges base camps serve as communication relays, e.g. for communicating the relative positions of the systems for rendezvous. This implies that the exploration rover as well as the shuttle need a communication connection to each other or at least to one base camp to build up a communication link. Many aditional types of deployable units are conceivable when regarding the modular setup of the overall system. These units are for example surface deployable scientific experiments. While this modality is not depicted in Figure 7, such elements need to be connected to the local communication network set up by the base camps and lander.

## 6 Robotic Systems Overview

There are several systems involved in the approach of forming a logistics chain on a celestial body. The systems include, as mentioned above, mobile units, namely an exploration rover and one or more supporting shuttle systems. Immobile units are present in form of base camps and payload items, extended by the possibility of including the landing unit. The main tasks are distributed as follows.

The exploration rover is responsible for carrying and deploying base camps and payload items to establish the basic infrastructure of the logistics chain. By means of the payload items, the rover can be equipped with additional tools to fulfill different science tasks.

The shuttle rover has to be able to quickly (w.r.t. the exploration rover) cover rough terrain. Its task is carrying payload items between stationary nodes to the exploration rover and back, thus keeping the logistics chain active.

Payload items are containers for scientific instruments, infrastructure elements or tools. They can be connected with other payload items, base camps or mobile robots via a uniform electro-mechanical interface (EMI). Connecting different payload items into a stack allows to build up functional units from modular items.

Base camps shall provide stationary points in the logistics chain. They can be used for energy harvesting, communication relay, payload storage etc. Base camps are equipped with EMIs to be able to integrate modular payload items for extension of functionality or battery recharging.

Following the previously described reference mission, it is intended to perform demonstration scenarios in terrestrial testing facilities. The robotic systems that are employed in the context of these demonstration scenarios are based on already available systems as shown in Figure 8. The wheeled-leg exploration rover Sherpa (background), the hybrid legged-wheel shuttle Asguard (foreground) and some payload items (stack of cubes). The systems are displayed in their initial state, adaptions are currently conducted. A brief description of the core robotic systems and their adaptation to the special needs for establishing the envisioned logistics chain is given in the following sections.

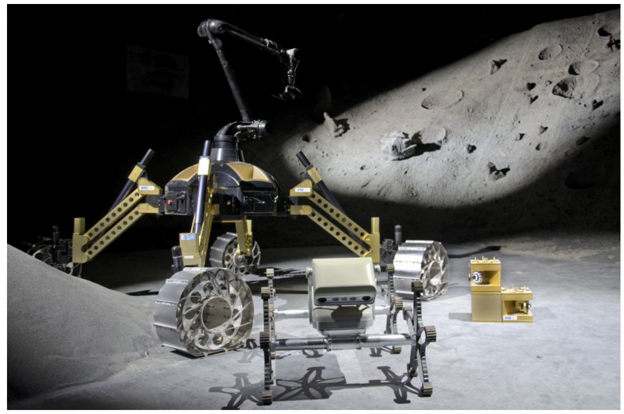


**Figure 8.** Designated systems for terrestrial proof of concept demonstration of the described scenarios

### 6.1 Exploration Rover

The hybrid wheeled-leg system Sherpa is designated as exploration rover. This system has already demonstrated its ability to work in a heterogeneous robotic system and is capable of transporting modular payload items, a partner robot, and is equipped with a manipulator for payload handling [8]. Currently, the main adaption work for Sherpa is focusing on the suspension system and a new locomotion control scheme that is being implemented.

A concept study of the Sherpa adaptation as presented in [1] is shown in Figure 9. The rover is shown with a base camp attached under its belly and a payload item attached to the manipulator arm. The main body of the rover holds four modular payload item bays for reconfiguration purposes or storage of payload containers.

The main dimensions of Sherpa are $2.4 \times 2.4 \times 1.2$ m, with a mass of $\sim$ 160 kg. The adaptation of Sherpa as shown in Figure 9 is considered to stay within this mass and size frame.

### 6.2 Shuttle

The task of a quick and highly mobile shuttle is assigned to one of the robots of the Asguard family. These robots make use of hybrid legged-wheels for propulsion.

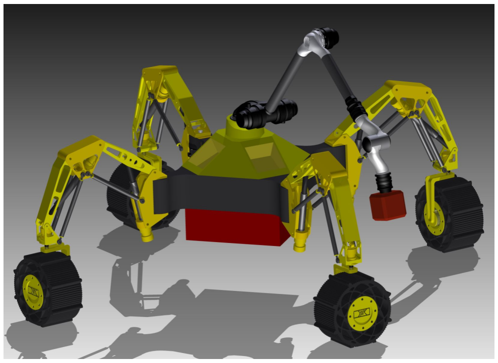


**Figure 9.** Conceptual drawing of the proposed adaptation of Sherpa as exploration rover with attached base camp and payload item

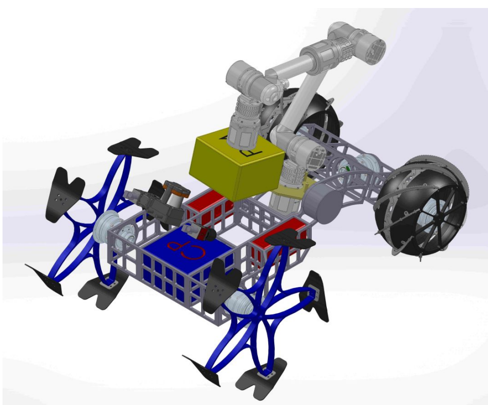


**Figure 10.** Conceptual drawing of a shuttle rover equipped with a manipulator for payload item handling

The special design of the wheels allows fast movement in very rough terrain. The system exhibits a generally low control complexity and a robust design. In its latest version, Asguard presented high autonomous capabilities while moving in rough terrain [9].

From the family of Asguard rovers an adaptation of the Coyote II rover ( cf. [10]) is considered for the terrestrial proof of concept trials. A major adaptation of the rover is to enable the transport and handling of modular payload items. An initial idea of a possible shuttle concept is given in Figure 10. The rover concept is equipped with a payload item bay and a manipulation device to handle the payload items. While Coyote II has a mass of 9.2 kg at 850 × 580 × 410 mm outer dimensions, it is considered that the adopted rover will have a higher mass due to its additional mechanisms.

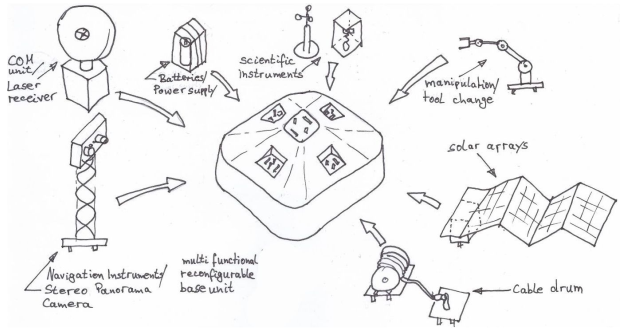



**Figure 11.** Schematic drawing of the modularity concept for a general base camp

### 6.3 Payload Items

The payload items are based on previous developments as described in [8] and shown in Figure 8. Each payload item is equipped with an EMI on the top and bottom. The EMI with its accompanying electronics is responsible for connecting payload items electronically and mechanically with other payload items or robots that provide an EMI.

The EMI and the payload items play a key role in establishing the logistics chain. They provide the modularity and reconfiguration capabilities of the different robotic systems due to a standardized EMI and payload container shape. The interface as well as the payload items allow to establish tool and system change for the remaining robotic systems and can be equipped with different tools, instruments, systems or goods. It is foreseen to use the payload item e.g. for energy supply, sample catching and positioning purposes during the planned terrestrial tests. A basic payload item has a cubical shape with 154 mm edge length and is designed for an overall mass of 5 kg. The EMI itself is designed for operation under mechanical loads of up to 300 N in order to support base camp deployment.

### 6.4 Base Camps

Base camps are considered to either serve as specialized base stations designed for a specific task or as mutlifunctional modular base stations providing the main functionality in terms of communication (cf. Section 5) and a set of EMI, for reconfiguration purposes. The general idea of modularity for a base camp is outlined in Figure 11. The base camp, equipped with several EMIs, serves as multi- functional note within the logistics chain. It can be equipped with different payload items according to the mission need and progress. This allows to provide a defined assembly point for payload items in order to build up a supply chain for the mobile robots or to build up a scientific and/or mission relevant system.

The base camps are carried and deployed by the exploration rover (cf. Figure 9). It is proposed to connect them to the bottom of the exploration rover's main body using an EMI. Therefore, the dimensions of a base camp are dependent on the rover body dimensions and are initially considered at $600 \times 600 \times 150$ mm with a mass of $\leq 30$ kg.

## 7 Conclusion and Outlook

In the previous sections a mission design concept is presented, introducing a heterogeneous modular robotic team for extended extraterrestrial exploration tasks. In order to handle tasks with increasing complexity in future exploration missions the approach of implementing a highly modular logistics chain is presented. For this, a team of mobile robots is accompanied by stationary surface elements as well as portable and modular payload items.

The analysis of present scientific questions for future lunar exploration missions yields a high potential for multi-robot missions. The proposed approach of implementing a logistics chain promises to gain benefits in terms of long term exploration, sample transport for sample analysis and return, energy and communication support and last but not least providing the ability to handle complex cooperative tasks like setting up infrastructure elements. Based on the scientific context a reference mission within Amundsen crater is presented, motivating the proposed mission design concept. The mission outline focuses on the implementation of a logistics chain, allowing to analyze volatiles and regolith processes at various points of interest within Amundsen crater. A set-up including one exploration rover and one ore more shuttle rovers is presented. These mobile robots are accompanied by stationary base camps which build up a local communication network to support the logistics chain. Furthermore, base camps are considered to be used for energy harvesting in order to provide life support within the thermally and power-wise difficult environment of Amundsen crater.

Based on the lunar reference mission a set of demonstration scenarios will be derived for terrestrial proof of concept trials. The intended robotic systems for the implementation of a logistics chain are presented along with their proposed functional adaptations. Furthermore, it is intended to analyze the benefits of all systems proposed for space exploration purposes within Earth-bound applications. This includes, e.g., search and rescue, management of maritime resources and rehabilitation. It is believed that the installation of a logistics chain and the cooperation of a heterogeneous robotic team can add major benefits to these domains as well.

## Acknowledgment

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