CONCEPT STUDY FOR THE FASTER MICRO SCOUT ROVER

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ABSTRACT

In contrast to the present Mars exploration missions future mission concepts ask for a fast and save traverse through vast and varied expanses of terrain. The goal of the FASTER[1] project is to improve the mission safety and the effective traverse speed for planetary rover exploration by determining the traversability of the terrain and lowering the risk to enter hazardous areas. In order to achieve this goal, a small scout rover will be used for soil and terrain sensing ahead of the main rover. In the present paper the problem of defining a highly mobile, all-terrain micro scout rover that can be used for soil and terrain sensing and collaborate with a primary rover is addressed by means of a concept study. Alternative concepts for the scout rover mission architecture and system bus design are treated. Based on trade-offs, a single scout rover is proposed using the primary rover as communication relay and for energy transfer while the scout rover can co-operate autonomously with the primary rover. Based on the chosen concept a terrestrial scout rover testbed has been derived, which will be used for further tests to prove the choice of the concept.

Key words: Micro Rover, Scout Rover, Mars Exploration, Multi-Rover Team, Locomotion, Mobile, All-Terrain, Hybrid-Legged Wheel, Helical Wheel.

1. INTRODUCTION

In planetary exploration missions robotic rovers must traverse vast and varied expanses of terrain. The trafficability of the areas to be explored can only be estimated on the basis of remote sensing data. As seen during the Mars Exploration Rover mission (MER), the exploration rover may suffer from a lack of detailed soil and terrain information. If the estimates are wrong, a rover may, for example, get stuck permanently in a stretch of soft sand. This happened to the NASA Mars rover Spirit in 2009.

To avoid such incidents, planetary exploration rovers today move much slower than they theoretically could, covering not more than a few meters per day. The actual travel speed of Curiosity, for example, is in the range of 0.15 to 0.45 cm/s while the theoretical maximum speed of the vehicle is about ten times higher.

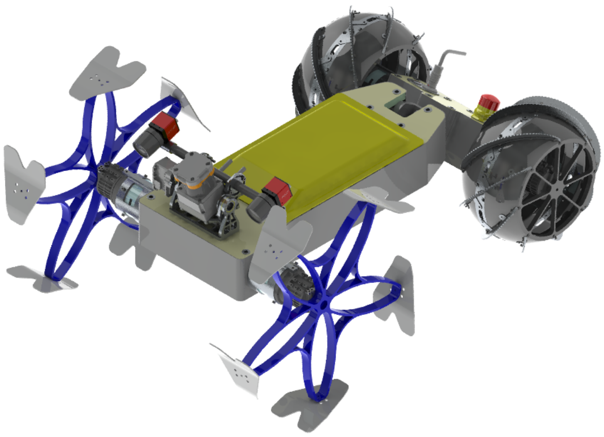


Figure 1. Rendering of the scout rover prototype

Such slow travel velocities will not be sufficient in future missions, where tenths of kilometers will have to be traveled in a few months. The planned (but abandoned) joint ESA/NASA Mars Sample Return mission (MSR), for example, will require robotic rovers to cover 10 to 20 km in about 200 days. In the FASTER project, a European consortium of six partners from five EU member states develops and demonstrates a new concept for the in-situ acquisition of soil and terrain properties on planetary surfaces. Apart from new light-weight soil sensors for the in-situ physical examination of the planetary surface, the key component of the concept is a small all-terrain rover. This rover will co-operate with a larger exploration rover and "scout" the terrain trafficability along the planned trajectory of the exploration rover. By having a better and more precise picture of the terrain ahead, the exploration rover will be able to select a path and adapt its motion behavior to the examined surface conditions to travel faster and with less risk. Therefore, the pursued objective of the FASTER project is to improve the mission safety and the effective traverse speed for planetary rovers by determining the traversability of the terrain and lowering the risk to enter hazardous areas.

This paper describes a highly mobile, all-terrain micro scout rover that will be used for soil and terrain sensing

[1]Forward Acquisition of Soil and Terrain Data for Exploration Rover

and is able to co-operate with a primary rover as part of the FASTER approach. The concept study is based on the requirements of a real Mars exploration mission and serves as input to derive a terrestrial test platform which will be build up as scout rover testbed. A rendering of the scout rover prototype, which was derived from the concept study is shown in Fig. 1. This prototype is in the first instance dedicated for maneuvers and operational tests.

2. MISSION SCENARIO

Analyzing past and future exploration missions and/or mission scenarios like the NASA MER mission or the NASA/ESA joint MSR campaign, a need arises to provide faster and saver traversal for exploration rovers.

In order to define requirements and derive operational concepts for the FASTER systems, the proposed (but abandoned) MSR joint campaign by ESA and NASA was chosen as reference scenario. Especially the ESA Sample Fetching Rover (SFR) for MSR, described in [1], was identified as potential system which could benefit from implementing the FASTER concept and therefore, serves as baseline. The key parameters for the FASTER system development and the scout rover in particular, are related to the rover speed which is required for conducting the mission. The overall surface mission duration is supposed to be 180 sols including checkout and contingencies, while 110 sols are considered for rover traversal. Within this time frame, the rover is required to travel over a distance of 20 km (including 30% margin), while the active time of traversal will be within 4 hours per sol due to power constraints. This leads to a minimum average rover speed of about 1.25 cm/s. Further mission, operational, system, hardware and software requirements were derived from the SFR mission and complemented with additional requirements directly related to the FASTER concept. This set of requirements was used as input for the scout rover concept identification and selection, while the most important key parameter will be introduced according to the scout rover's mission architecture and system design analysis (cf. Section 3 and 4).

The scout rover is an important element of the FASTER concept, since it enables the acquisition of soil and terrain data on the planed path of the primary rover which leads to a faster and safer traversal. To cover this objectives the FASTER concept introduces an autonomy subsystem and a FASTER Soil Sensing System (SSS) on the primary rover which is designated to perform the basic mission. Furthermore, a scout rover is part of the FASTER concept, which will be equipped with an additional SSS and collaborate autonomously, as a remote mobile sensor, with the primary rover.

Within the FASTER scenario, the scout rover will be used to assess the trafficability in front of the primary rover by analyzing soil and terrain properties using its SSS. The traversal of the scout rover is based on waypoints which

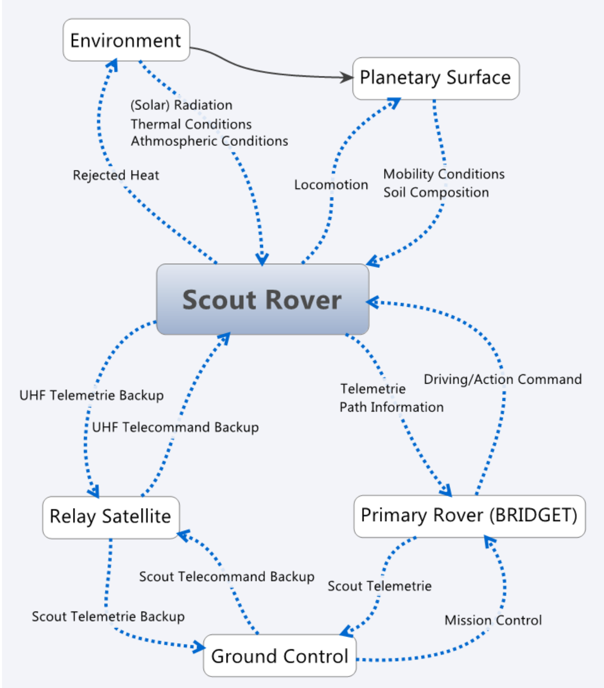


Figure 2. Scout Rover System Context

are provided by the primary rover. For the case that the scout rover detects a hazardous region it will report a low trafficabillity back to the primary rover which leads to a path re-planning and preserves the primary rover on entering this region.

3. MISSION ARCHITECTURE

The scout rover mission architecture defines how the system will work together with the other mission elements. Based on the mission scenario alternative mission architectures, dealing with operational time, communication (COM)-link architecture and level of autonomy are treated in the following sub-sections.

A general overview of the scout rover system context is given in Fig. 2. Based on the evaluation process, a single scout rover is proposed, using the primary rover as communication relay and for energy transfer while the scout is not in operation an potentially docked to the primary rover. Furthermore, a back-up COM-link via a relay satellite to ground control is considered. Within the FASTER project a terrestrial test-platform of the scout rover will be integrated. This configuration will not face any extraterrestrial environments nor simulate communication with a relay satellite, such that the architecture for the terrestrial test scenario is based on a scout rover test-bed, a primary rover test-bed[2], planetary surface conditions (which might be simulated) and to a certain degree ground control for rover operations.

[2]The ExoMars breadboard BRIDGET from Astrium Ltd. will be used as primary rover within the FASTER project.

3.1. Time of Operation

Three different operational time set-ups were distinguished for the scout rover. First, a *full time operation* scenario where the scout rover accomplishes the mission independently by using the primary rover only as communication relay. Second, a *part time operation* scenario, which allows the scout rover to operate during the four hour time slot for traversal but will be stowed in or docked to the primary rover during standby for, e. g., recharging its batteries or transferring additional data. And third, an *only when needed* operational scenario which envisages to stow the scout rover on the primary rover and only release it if the primary rover cannot clearly classify the trafficabillity of its path.

The *part time* operational scenario was identified as the most beneficiary scenario for the scout rover. Compared to *full time operation* the scout rover does not need to stay online for the duration of the whole mission which may reduce the need for a totally independent power supply. In contrast to the *only when needed* scenario, it is able to perform a trafficability analysis for the entire traversal of the primary rover which reduces the risk of entering hazardous regions and speeds up the traversal since no release and pick-up time is needed in addition.

3.2. Communication Architecture

The baseline mission scenario envisages the availability of a relay satellite in Low Mars Orbit (LMO) and requires the scout rover to be able to build up the following direct or indirect COM-links: Communication with the primary rover, communication with the relay satellite and communication with a ground station.

To fulfill the requirements four generic types of scout rover COM-links have been evaluated: link to primary rover, link to stationary relay module, link to relay satellite, direct link to ground. According to the long operational range of 20 km a link to a stationary transceiver relay was discarded as well as a direct link to ground due to mass and power restrictions. Since the two rovers are operating in a range of only a few meters to one another, a direct link between both rovers is beneficial in terms of mass, size and power consumption. Fig. 3 shows three examples for possible COM-architectures. For the FASTER scenario set-up (c) was chosen, which relays primarily on a direct link between the scout and primary rover but includes a back-up link between the scout rover and a relay satellite to allow reduced scout rover operations in case that the primary rover fails.

3.3. Level of Autonomy

Based on the mission concept the scout rover has to work at least on a semi-autonomous level as remote sensor unit controlled by the primary rover. The level of autonomy

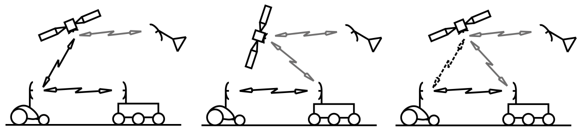


Figure 3. Alternative COM-link architectures

for the scout rover can be described, based on three general operational modes.

During *normal operation* the scout rover has to travel within a distance of 4 to 5 m ahead of the primary rover along a predefined path, representing the determined way-points of the primary rover. A detailed elevation map including a set of way-points and the initial location of the scout rover will be provided by the primary rover. The level of autonomy is considered low in this operation mode since the scout rover has only to follow the given trajectory and perform hazard avoidance. Within a *scouting operation* mode it is proposed to use the scout rover as remote navigation sensor in order to extend the elevation map. While the scout rover's navigation sensors will be used for data gathering, map building and path planning will still be done by the primary rover. This might lead to a decreasing localization accuracy provided by the primary rover, since the scout rover has most likely to go beyond the region where the primary rover's stereo camera provides detailed information. To compensate for that the scout will improve the localization of itself using it's own sensors and the information of the map, generated by the primary rover. Both, for *normal operation* as well as for *scouting operation* the scout rover relies on a functioning COM-link to the primary rover. In case of a communication loss, a *survival operation* mode needs to be initiated. To perform a simple communication recovery strategy, the scout rover needs to operate autonomously in order to re-establish communication. Therefore, it needs to localize itself in the map and plan a way back to a position where communication with the main rover was possible or even move to a position where the possibility for communication is high e.g. in a free area or on top of a small hill. A general description on the autonomous two rover collaboration is given in [2] also describing different operational scenarios in more detail.

3.4. Data Processing

For the scout rover operation the following data need to be processed: guidance, navigation and control data, telemetry, tracking and command (TT&C) data, housekeeping data and measurement data from the SSS-payload. Complementing the COM-architecture and the operational modes described in Section 3.2 and 3.3 a distributed data processing approach is proposed for the scout rover. This allows to swap tasks like guidance and navigation, which require high processing power, to the primary rover. The On-Board Data Handling system (OBDH) of the scout rover can then be designed in a less complex and power consuming way. However, it is proposed to equip the scout rover with an OBDH allowing to handle all data needed to operate the rover. This includes driving along predefined way-points, perform hazard avoidance, carry out and (pre-) process soil sensor measurements and perform simple communication recovery strategies for survival operations. To handle this tasks, the internal data processing will be distributed to different units, too, which are described in Section 4.2 in more detail.

4. DESIGN CONSIDERATIONS

Following the overall mission concept, different solutions for the subsystems of the scout rover have been investigated and evaluated within a trade-off process. This sections presents an overview of design considerations for the main subsystems of the scout rover and how they are envisaged to be implemented in a terrestrial scout rover test-bed. A system overview is given in Section 4.7, summarizing the main parameters of the chosen scout rover concept.

Based on a requirements analysis the following design drivers have been identified for the scout rover:

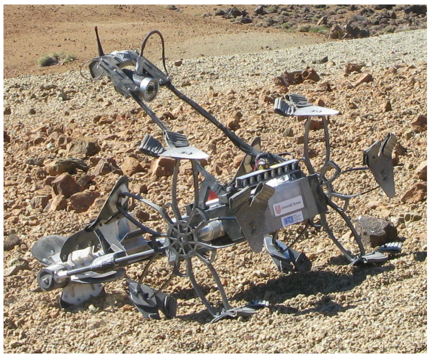
- Mass
- Mobility
- Power supply/transmission
- Navigation
- Data Handling
- Payload design (Soil Sensors)

The total mass of the scout rover including its SSS-payload is required to be $\leq 20\,\mathrm{kg}$ (incl. 20% systems margin) in order to accept the scout rover as 'payload' of the primary rover and to fit into the mass budget of the reference mission. This requirement drives the entire scout rover and subsystem design in order to achieve the needed functionality integrated in a micro rover. Furthermore, a focus is given to locomotion concepts since mobility is one of the key drivers for the scout rover design.

4.1. Locomotion System

High mobility and therefore the locomotion system is especially important for an extraterrestrial exploration rover. A wide range of alternative locomotion systems has been in the focus of researchers ranging from different types of wheeled vehicles over tracks to legged and leg-hybrid systems. Besides the comparatively high average speed of at least 1.25 cm/s for the exploration rover,

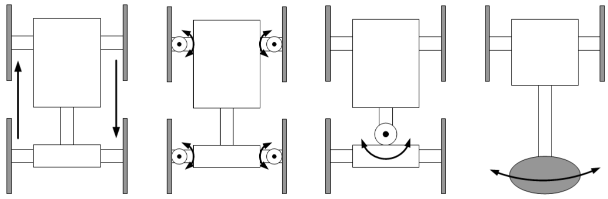
(a) Asguard v2



(b) CESAR

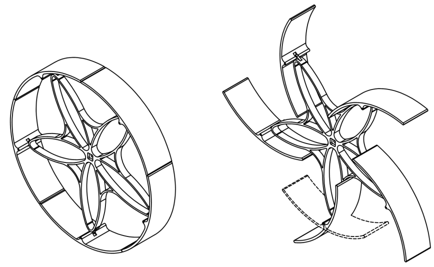
Figure 4. Scout rover inspirations

further challenging requirements were set up for the scout rover. These include first, high all terrain mobility on soft soils as well as on gravel and firm soil. Second, the capability to traverse slopes of up to 25° on firm soil and 15° on soft soil respectively as well as a static stability of 40° in all directions. And third, the ability to overcome obstacles with a height of at least 100 mm. Especially the traversability of soft soils has to be treated carefully since the scout rover should not get stuck in potential sand traps and may not create additional obstacles for the primary rover by digging over the surface. Based on an evaluation of different locomotion systems wheel-enabled systems and walking systems need to be taken into closer consideration. While walking systems provide high versatility and mobility for unstructured terrain, like e.g shown with the Scorpion robot [cf. 3, 4] or the SpaceClimber robot, which shows reduced energy consumption due to an evolutionary design approach and adaptable walking patterns [cf. 5, 6], they have drawbacks in terms of payload capacity and complexity, compared with a wheeled system [cf. 7]. In order to combine the benefits of wheeled and walking systems while keeping the complexity as low as possible, hybrid legged-wheels are envisaged for the scout rover. This kind of wheels were already used on the Asguard [cf. 8] and CESAR [cf. 9] rovers, shown in Fig. 4, and have lately been deployed in a similar manner on the Axel/DuAxel rovers [cf. 10]. All robots have shown their excellent mobility performance on various terrains, including steep slopes and soft soil. Especially for obstacle climbing and traction on soft soil, it is assumed

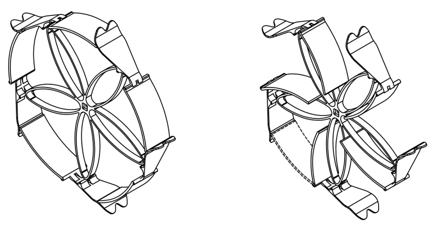


(a) Skid steering (b) Independent steering (c) Articulated steering (d) Side-to-Side steering

Figure 5. Alternative steering concepts



(a)



(b)

Figure 6. Concepts for transformable hybrid legged-wheels

that the hybrid legged-wheels provide a higher mobility with a less complex chassis, than performed by 'standard' wheels.

In order to provide high mobility on soft soil as well as on unstructured terrain, a novel locomotion concept is proposed consisting of hybrid legged-wheels in the front and helical rear wheels, allowing a side-to-side steering motion of the tail (cf. Fig. 5(d)). Different steering concepts have been investigated as shown in Fig. 5. While the skid steering in combination with hybrid legged-wheels causes heavy digging over of soft soil, independent and articulated steering increase the mass and complexity of the rover due to additional joints. The side-to-side steering concept is based on skid steering but relies on helical rear wheels (cf. Fig. 1), which allow to shift the rover's center of rotation to the front axis and therefore, reduce the skid movement of the hybrid legged-wheels. To allow smooth side movements the rear wheels are designed in a spherical shape. Furthermore, the rear axis is connected by a roll joint to the main rover body which allows to keep all wheels on the ground, even in unstructured terrain.

It is assumed that the digging effect of the front wheels can be reduced, too, by adapting the five spoke Asguard wheel. As shown with the CESAR robot, applying feet to the wheel-legs increases the traversability of soft soil and loos gravel. Fig. 6 shows further concepts for wheels, which can be transformed from a classical wheel to a hybrid legged-wheel. This would allow to drive smoothly on easy terrain and use the mobility benefits of a hybrid legged-wheel in more complex terrain. However, a transformable wheel increases the complexity and risk of malfunction, due to a lot of moving parts, interacting directly with the soil. Therefore, an adaptation of the Cesar feet is initially proposed for the scout rover prototype.

4.2. On-Board Data Handling

A distributed processing architecture is proposed for the OBDH of the scout rover, consisting of an On-Board Computer (OBC) unit and a Payload Data Handling (PDH) unit. Both, OBC and PDH are build up in a distributed manner as well. This allows to choose less powerful processors, dedicated for each task and reduces the risk of a total system failure, which is especially important in the context of a space mission. The OBC consist of a central control unit which is used for command and data handling and health monitoring. Additionally, each motor unit is equipped with its own control unit undertaking tasks like direct motor control, current, speed and position control. In order to process the SSS-payload data, it is supposed to equip each sensor with its own processing unit [cf. 11]. For the terrestrial testbed of the scout rover an embedded industrial PC will be used as main computer, providing sufficient processing power for software development and test at low power consumption. The actuator electronics are equipped with their own FPGA board as already used for SpaceClimber [cf. 6]. An overview of the general OBDH functions in terms of command and data flow is shown in Fig. 7, placing the scout rover in the FASTER system context.

4.3. Communications

As described in Section 3, the COM-architecture envisages a direct link between the primary rover and a backup link between a relay satellite and the scout rover. For scout to primary rover communication an S-band transceiver is planned, providing sufficient bandwidth for command and data transmission, including housekeepings and navigation data like stereo camera images from the scout rover and control commands and navigation data like a detailed elevation map from the primary rover (cf. Fig. 7). Albeit health monitoring and payload data processing is planned to run on-board the scout rover, it is supposed to share all relevant data with the primary rover which needs to know the status of the scout rover to plan the next mission steps and has to transmit important data to ground control. As back-up system an UHF communication unit can be used, allowing to build up a reliable back-up link between the scout and the primary rover or a relay satellite. Since a relay satellite is not considered to be taken into account during terrestrial tests,

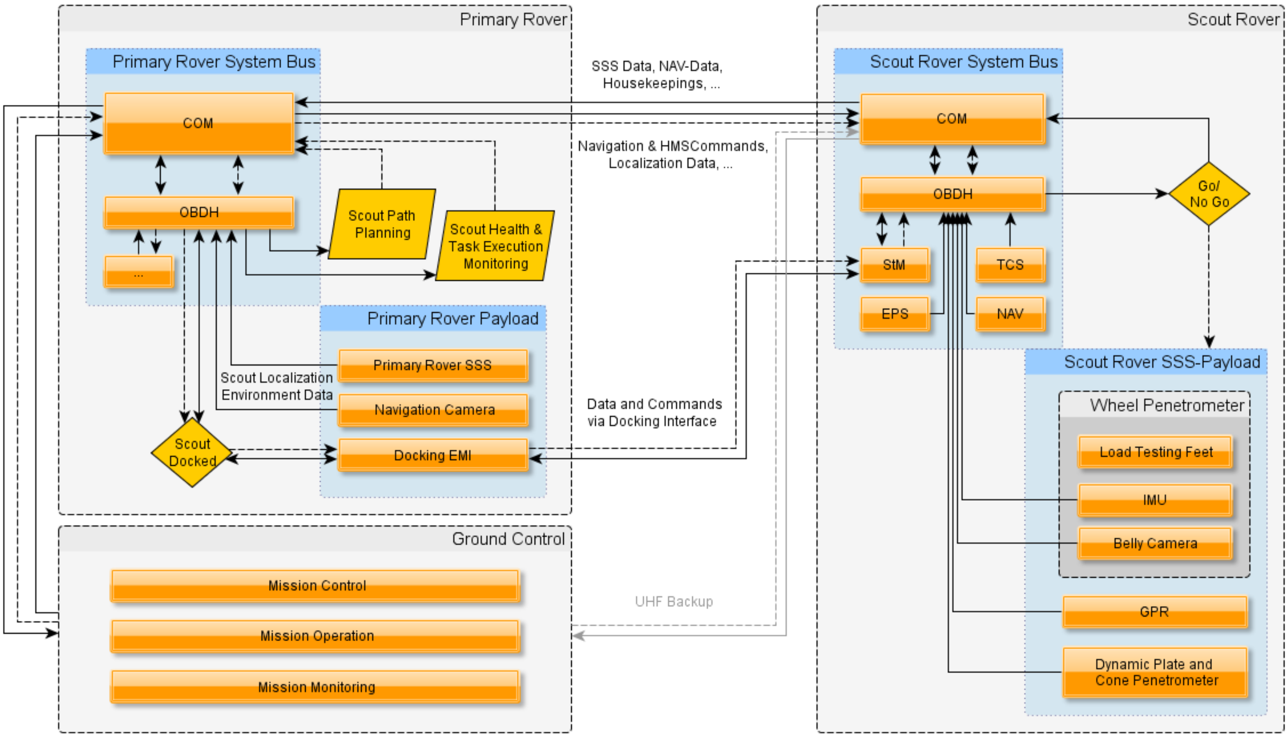


Figure 7. Genral command and data flow diagram for the scout rover system context (solid line: data flow, dotted line: command flow; electro-mechanical interface (EMI), electrical power system (EPS), ground penetrating radar (GPR), health monitoring system (HMS), navigation system (NAV), structure and mechanisms (StM), thermal control system (TCS))

the communication between the scout and primary rover testbeds will be based on W-LAN only. For safety reasons a wireless UHF-band based emergency control will be implemented to the scout rover testbed, which can be activated manually.

4.4. Electrical Power Supply

The electrical power system (EPS) has the aim to provide sufficient power for at least four hours operation of the scout rover per sol. To achieve this goal, three principle concepts have been identified: first, use of the primary rover's power source, second, installation of a sufficient energy unit on the scout rover and third, a combination of both previous concepts. Since nuclear power sources had to be discarded due to the requirements, a trade-off has been conducted, comparing a tethered scout rover vs. a scout rover with solar array (and a secondary battery and recharging during docking if needed) vs. a scout rover with primary battery which can be recharged during docking. A scout rover set-up using a tether for energy and/or data transfer was discarded due to limited operational range, flexibility, and an increasing risk based on the tether management. Therefore, the scout rover is envisaged to be equipped with a battery in combination with a docking mechanisms as described in, e.g., [12], which allows to dock the scout rover to the primary rover for energy and data transfer. Additionally, a 0.35 to 0.5 m^2 solar array can be mounted on the scout rover which can deliver a peak power of about 40 to 60 W at mid sol, regarding to [1], and would relive the power unit of the primary rover while at the same time allow the scout rover to be operated independently.

4.5. Navigation

In order to gain a highly reliable navigation subsystem, the scout rover will carry sensors for wheel based odometry as well as for visual odometry and mapping. This leads to a more fault tolerant system and enables the scout rover to perform self localization and navigation, which is especially important for scouting and survival operations. For the wheel based odometry the scout rover will be equipped with a 6 DoF IMU and rotary encoders at each wheel and the body joint, which allows the use of the eSLAM localization approach described in [13]. For visual navigation a stereo camera is considered which will be used for two tasks: first, to take stereo images which will be transmitted to the primary rover for map building and path planning and second, for hazard avoidance and occasionally for visual odometry. The scout rover prototype (cf. Fig. 1) will also be equipped with a laser scanner as reference sensor.

4.6. Payload

Four different sensor packages are considered as SSS-payload for the scout rover: load testing feet on the front hybrid legged-wheels, a ground penetrating radar, a dynamic plate and a dynamic cone penetrometer, which will be integrated into one instrument. All sensors shall be deployed in a cascaded manner to gain a reliable traficability assessment and are described in more detail in [11].

4.7. System Overview

An overview of the initial FASTER scout rover concept with integrated SSS-payload, solar array and stereo camera is given in Fig. 8. The overall dimensions supposed for the scout rover are shown in Fig. 9, including the hybrid legged-wheels with a main diameter of 400 mm and the helical wheels with a main diameter of 250 mm. Based on the FASTER mission architecture and the related design considerations for the scout rover system bus, an initial specification for a more detailed terrestrial test platform was derived. A technical overview of the so far planned scout rover testbed which will be used for further tests to prove the choice of the concept is given in Tab. 1.

5. CONCLUSION AND OUTLOOK

Unlike any previous extraterrestrial exploration mission, the FASTER concept proposes the combination of a primary exploration rover with a micro scout rover, acting as remote sensor unit. Within this concept, the scout rover plays an important role by assessing the trafficability of the primary rover's planned path and thereby allows a faster and saver traversal over long distances.

This paper shows the concept identification and evaluation for such a scout rover. Based on the FASTER mission scenario, alternative mission architectures have been analyzed, leading to a scout system able to run for the full operational time of 4 hours per sol at high autonomy, using the primary rover as direct communication and data processing relay. Different design concepts for the scout rover system bus have been treated, leading to a concept for a small and lightweight but highly mobile rover platform, able to traverse safely varies types of terrain and perform different operational tasks. To enable the high all terrain mobility, a novel locomotion concept, combining hybrid legged-wheels with helical wheels, is proposed for the scout rover.

The chosen concept will be further investigated by means of a terrestrial testbed. A first scout rover prototype (cf. Fig. 1) has been derived from the chosen concept and is technically specified. The prototype will be used for locomotion and mobility tests as well as for hardware and software tests with regard to navigation, autonomy and rover-rover collaboration. While first locomotion tests

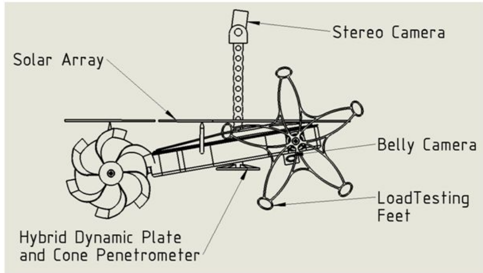


Figure 8. Initial scout rover system concept

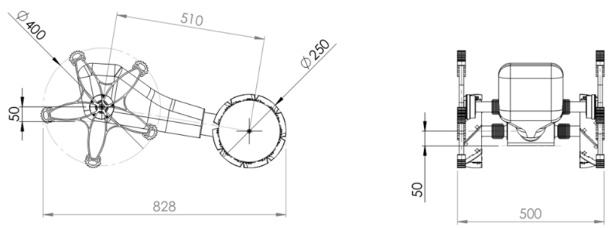


Figure 9. Main dimensions

Table 1. Scout rover testbed: technical overview

Structure and Mechanism	
Mass (excl. payload)	14.8 kg (incl. 20% margin)
Mass (incl. payload)	18.4 kg (incl. 20% margin)
Boundary Box (h × l × w)	400 × 830 × 500 mm
Chassis	1 DoF body joint in roll direction (passiv)
Locomotion and Steering	Front: hybrid legged-wheels with skid steering Rear: Helical wheels with side-to-side steering
Actuators	4 × RoboDrive with HarmonicDrive
Max. wheel torque	ca. 28 Nm
On-Board Data Handling	
OBC	Intel ULV Core i7 based embedded PC
PDH	Microcontroller based data handling of SSS-payload
Communication	
S-Band (scout to primary rover)	802.11g wifi-module at 2.4 GHz and 54 Mbps
UHF-Band	Emergency Control
Electrical Power System	
Power consumption (estimate)	100 W (average), 500 W (peak)
Power Supply	LiPo rechargeble battery (44.4 V @ 4.5 Ah)
Thermal Control	
Driving Units	Passive control with health monitoring
Electronic-Stack	Active control with health monitoring
Navigation Sensors	
Visual Sensors	Stereo camera based on Guppy by AVT Hokuyo Laserscanner
Embodied Sensors	6 DoF IMU, rotary body-joint and wheel encoder, wheel torque measurement

have already been realized with a mobile test platform, further tests will be carried out to compare different locomotion concepts and to analyze their performance. Furthermore, the integration of the SSS-payload devices into the terrestrial scout rover testbed is planned as well as conducting operational tests using the primary rover and the scout rover as autonomous rover team. Within these tests the scout rover will be used for soil and terrain classification, using its SSS-payload devices.

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