Advanced Robotic Systems in the Context of Future Space Exploration

Wiebke Brinkmann[a]*, Sebastian Bartsch[a], Roland U. Sonsalla[a], Florian Cordes[a], Daniel Kuehn[a], Frank Kirchner[a,b]

[a] *German Research Center for Artificial Intelligence (DFKI), Robotics Innovation Center, Bremen, Germany*,
[b] *University of Bremen, Research Group Robotics, Bremen, Germany*
firstname.lastname@dfki.de
* Corresponding Author

Abstract

Future space exploration is calling for more sophisticated robotic solutions for various applications. Plans are made by the prime space agencies for challenging and complex missions, ranging from orbital servicing to deep space exploration with a strong focus on robotic and manned missions to Moon and Mars. In order to cope with these upcoming mission goals a need arises for capable robotic solutions, bringing together innovative technologies and software algorithms to provide reliable, highly integrated robotic systems with advanced autonomous behavior. The German Research Center for Artificial Intelligence - Robotics Innovation Center (DFKI RIC) has a traditionally strong background in the field of space robotics. This paper aims at presenting an overview of the robotic systems developed at DFKI RIC in the context of advanced space missions. Based on current mission roadmaps, an overview of upcoming space missions is presented and evaluated, to identify and cluster the mission targets and most demanding needs for robotic systems in future robot-based or -assisted missions. The type of systems range from advanced (mobile) manipulators to humanoid and multi-legged walking and climbing robots as well as highly mobile rover platforms to autonomous underwater vehicles. The paper presents the main system features, their aspired application scenarios as well as evaluation results gained in analogue missions or relevant test scenarios. The robot control ranges from human-in-the-loop control approaches of single systems to fully autonomous exploration missions of heterogeneous robot teams. With a view to the aspired future missions, the robotic systems are discussed in context to the upcoming mission needs and evaluated against their suitability. Furthermore, an outlook for the enhancement of the systems is given as well as a potential view beyond the current space mission roadmaps.

Keywords: space robotic systems, planetary exploration, surface exploration, multi-robot systems, autonomy

Acronyms/Abbreviations

DOF – Degree of Freedom, EMI – Electromechanical Interface, MRS - Multi-Robot Systems, PLI – Payload-Item

1 Introduction

The interest of human beings to explore its surrounding and in a bigger scope also space lies in the curiosity to understand the complex contexts of life. Especially the exploration of the universe attracts people. Since human beings are not able to stay for a long time on extra-terrestrial celestial bodies and not all planets are accessible for humans, robotic systems are the most promising possibility for space exploration.

In the past, explorations to Moon, Mars and asteroids were carried out by single systems with limited technical functionalities and locomotion capabilities. They are specially designed for their mission task but can hardly be applied to cover the needs for aspired complex future missions. As an example, the past and current rovers are build for comparably flat terrain and are not designed to operate e.g. on a crater wall. In this case legged robotic systems can offer a better approach. However, the payload of legged robots is limited to maintain mobility. In addition, functionalities like soil sampling, mapping, navigation and others are indispensable, as well as the ability to work autonomously. An advanced level of autonomy is essential since the delays of the long communication path, e.g., to Mars, limit the possibilities of teleoperations and thereby operating speed.

In order to carry out complex exploration missions on celestial bodies multi-robot systems are one of the most promising solutions. Multiple heterogeneous robotic systems with different functionalities can work with each other in a team or connect together via an interface in order to perform various mission tasks.

The collaborating robots can work as a "team" of coordinated robotic systems, carrying out site preparations such as infrastructure assembly, site maintenance functions, and remote science investigations. The developed robotic systems of DFKI are also able to work as a single system, in a team or as a “new” system when connected with other robotic systems.

This paper gives an overview of existing planetary exploration systems deployed in space and continues with robotic systems developed at DFKI for the purpose of space applications. Provided capabilities like locomotion, manipulation, perception and autonomy as well as further features are described. Furthermore, a roadmap with planned space missions is discussed and concluded with the individual characteristics of the developed robotic systems at DFKI in relation with future space mission needs by consideration of the mission road map of space missions.

2 State of the Art

Contemporary mission objectives include long-range mobility and highly instrumented in situ explorations. Previous and current semi-autonomous mobile science platforms on Moon and Mars are single systems with various tasks.

On Moon, the first robotic space vehicle was Lunokhod 1, a mobile robot. This vehicle along with the Lunokhod 2 robot, both deployed in the early 1970s, have been the only two automatic laboratories guided by remote control in 40 years with the aim of exploring and sending images of the lunar surface. Other robotic vehicles on Moon were the three sent forward Lunar Roving Vehicles (Apollo Missions 15, 16 and 17) used by the astronauts on their move on the lunar surface in the same decade. The definition of robotic systems for space exploration was extended later to the concept of remotely operated vehicle for emplacement and exploration when the Sojourner robot was used in the Mars Pathfinder mission of NASA in 1997. Regarding the ability of the robot systems, Sojourner conducted chemical analysis and took pictures of Mars. The approach of driving the rover can be considered a hybrid method, making use of real-time commands and autonomous control.

In recent missions for robotic space explorations NASA’s Curiosity robot, a successor of the Mars Exploration Rover (MER) Spirit & Opportunity, discovers Mars since 2012 using ten scientific instruments with experiments and sensing systems.

At the end of 2013, China deployed Yutu robot, a six-wheeled exploration vehicle, on the Moon`s Mare Imbrium region. Yutu is equipped with a robotic arm to position its alpha particle x-ray spectrometer (APXS) near a target sample. The Yutu rover carries a ground-penetrating radar and spectrometers (APXS and infrared spectrometer) to inspect the composition of the soil and the structure of the lunar crust beneath it. In addition, the rover could transmit live video, and has automatic sensors to prevent it from colliding with other objects [1].

The future generation of planetary rovers and other space robotic systems respectively is described in Section 4 in context of the mission roadmap of the space missions.

It is remarkable that used planetary exploration systems are either wheeled robotic systems or landers equipped with manipulators like InSight [2]. For micro-gravity environments on, e.g., asteroids hopping robotic platforms like the hedgehog rover, MASCOT or MINERVA are considered [3].

The key factor on the mentioned systems is their high level functionality which is gained mainly without or at least a very limited degree of modularity. Such approaches constrain the system’s interaction and reconfigurability and thus limit the potential extent of deviating from the original mission scenario or building upon existing systems for subsequent missions.

3 Space Robotic Systems at DFKI RIC

This section provides a short introduction to several different robotic systems developed, integrated and tested at DFKI RIC. Single robotic systems as well as the combination in heterogeneous multi-robot systems are addressed. The section is structured along the type of systems.

3.1 Walking and Climbing Robotic Systems

Numerous walking and climbing robots have been developed in the past at DFKI RIC. This section highlights the eight-legged Scorpion robot, the six-legged Mantis and the siblings SpaceClimber and CREX as well as the four-legged hominid Charlie and ARAMIES in a chronological order of development.

3.1.1 Scorpion

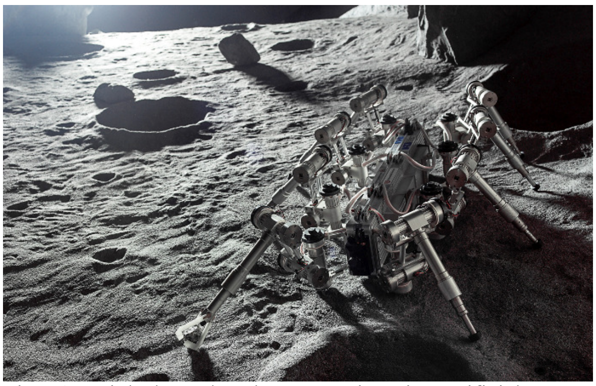

Fig. 1. Eight-legged robot Scorpion in artificial crater environment (credit: DFKI GmbH)

The Scorpion is an eight-legged walking robot with 24 degrees of freedom (DOFs) designed for operations in hazardous outdoor-terrain. It uses a biomimetic control concept, which allows very flexible walking movements over different terrain with a low control effort [4]. The locomotion approach is based on the one of real scorpions in order to keep the control effort low while maintaining high adaptability. The system has been tested in a variety of environments and can move in terrain where wheel-driven systems reach their limits. It has also been proven that the robot is still able to maneuver even after the failure of up to two legs [5]. Therefore, it can use one leg to fix objects on the body for transport without losing its mobility. The system's properties make it ideal for use in unstructured and harsh environments such as on extraterrestrial surface exploration missions.

Dimensions: 0.60m x 0.40m x 0.30m (L/W/H) in M-shape position. Mass: 10.5 kg.

3.1.2 ARAMIES

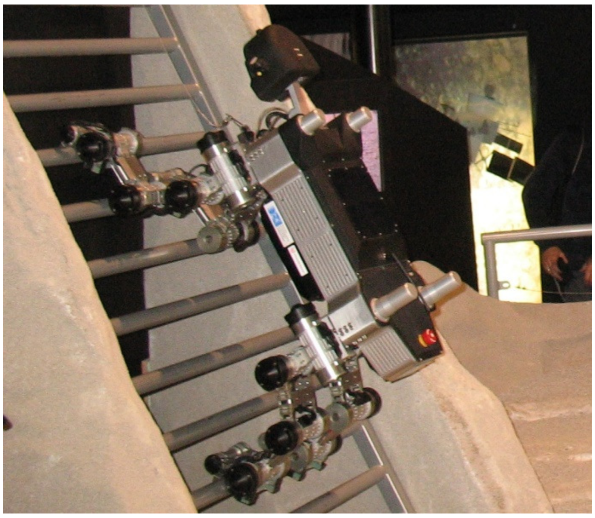

Fig. 2. Four-legged ARAMIES robot climbs at the Paris Air Show in Le Bourget (credit: DFKI GmbH)

ARAMIES is a four legged walking robotic system with 26 active joints [6]. One major advantage in comparison to other walking robots is its actuated claw which is used to get a hold in steep inclinations. In laboratory tests the system was able to climb up a rung wall with an inclination of 70°. Each claw is equipped with five pressure sensors and an additional special IR-distance sensor which are used for robust ground contact detection.

Its task is autonomous operation in extremely difficult environments, especially very uneven and steep terrain, e.g., the slopes of Martian / Moon canyons or craters.

Dimensions: 0.70m x 0.45m x 0.60m (L/W/H). Mass: 28 kg.

3.1.3 SpaceClimber and CREX

Based on the experience gained during the development of the SCORPION and ARAMIES walking robots, the six-legged SpaceClimber robot was specially designed for exploration in hard-to-reach but scientifically interesting areas such as boulder fields, crater and canyon walls. Special attention was paid to robustness, energy efficiency, reliability and autonomy of the robot. In addition, a future space qualification was taken into account during development, which required particular consideration when selecting the components used and regarding the overall system design. Each of the six legs of the system consists of four identical actuator modules. The development of the joints took place with the aim of making it easier to space-qualify the entire system if a single actuator has already been qualified. These intelligent, powerful, highly integrated joint modules are able to compute and carry out the necessary control tasks locally in the joint. Like the Scorpion robot, the system uses a biologically inspired low-cost approach to control locomotion. It has been proven that the robot is capable of handling inclines of up to 35° on sandy surfaces and crossing obstacles with a height of 400mm [7].

Dimensions: 0.82m x 1.00m x 0.22m (standard posture). Mass: 25 kg.

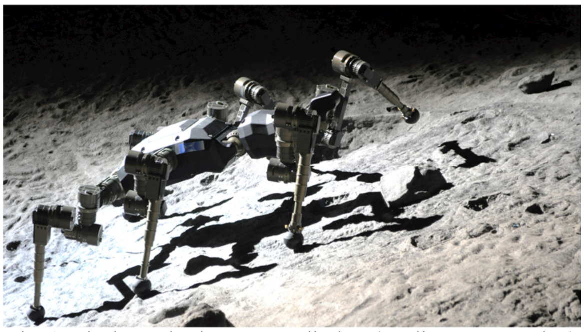

Fig. 3. Six-legged robot SpaceClimber (credit: DFKI GmbH)

CREX is a direct descendant of SpaceClimber. CREX is shown in Fig. 4. The robot has the same morphology and similar sensor equipment. Additionally, the robot is equipped with a general electromechanical interface (EMI) for integration into a multi-robot system; see also Section 3.4.

Dimensions: 0.82m x 1.00m x 0.22m (standard posture). Mass: 27 kg.

Fig. 4. Six-legged scout robot CREX (credit: DFKI GmbH)

3.1.4 Charlie

Based on the possible range of applications for robotic systems, it seems necessary to develop kinematically complex systems that feature several different operating modes. The morphology of the hominid robotic system Charlie [8] is oriented on the multi-talented chimpanzees to be able to cope with a multitude of different requirements. Therefore, Charlie (shown in Fig. 5) has the possibility to walk with different gaits in different postures, due to its electro-mechanical structure and the degrees of freedom in its arms and legs. The robot can change its posture independently from a quadrupedal into a bipedal stance and the other way around without external assistance.

A quadrupedal gait like crawl allows the robot to traverse safely and stable over rough terrain. A change into the humanoid, bipedal posture enables the robot to realize a better overview of the surrounding as well as to move in man-made environments.

The robotic feet of Charlie play an important role, since these structures are necessary to ensure an effective and stable locomotion in these two poses. In addition, a technical realization of the functional principle of biological spine is implemented in Charlie. These additional degrees of freedom increase the robot's locomotion and manipulation capabilities and enable the robot to perform movements, which are not possible without an artificial spine.

To control such a complex system, a multitude of sensors is installed within the robot's main bodies and the structures. A central processing of all sensor data would not be feasible, therefore a local and decentralized preprocessing is realized and local electronics are implemented within the different structures of Charlie. Due to this local preprocessing, behaviors on the lowest level of robot control can be realized, providing additional stability-features for the robot.

Dimensions: 0.66m x 0.43m x 0.75m (standard posture). Mass: 18 kg.

Fig. 5. Hominid robot Charlie (credit: DFKI GmbH)

3.1.5 Mantis

Mantis [9] was developed with the aim to provide high mobility and manipulation capabilities in uneven and unstructured terrain. The intended operations of the system will include more complex manipulation tasks than in-situ investigation or sample collection, as for instance the building up and maintenance of infrastructure will be required to support and sustain human presence on extraterrestrial bodies in future missions. Therefore, the robot possesses six extremities for locomotion, each having six active degrees of freedom. In addition, Mamtis is able to erect its body and free the two fore-most extremities to use them as arms, both featuring three-fingered hands for dual arm manipulation and a bracket to walk on it. The main electronic compartment (power management, high-level processing and overall robot control) is located in the rearmost body segment, the abdomen, providing a counterweight for the upper body and thus shifting the center of mass towards the frame articulation. This feature facilitates switching between the locomotion and manipulation postures. The head and end-effectors of the extremities are equipped with various sensors to acquire data on the environment.
Dimensions: 2.96m x 1.84m x 0.32m (locomotion posture). Mass: 107 kg.

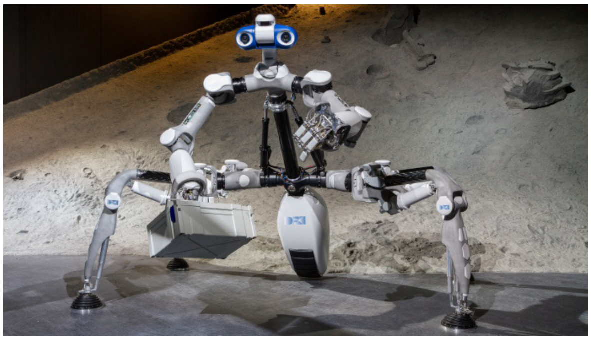

Fig. 6. Six-legged robot Mantis (credit: DFKI GmbH)

3.2 Wheeled and Hybrid-Wheeled Systems

Hybrid systems combine different locomotion-principles for performance gain. More specifically, the benefits of high locomotion capabilities of legged systems are combined with energy-efficiency of wheeled systems. The results presented in this section are legged-wheel robots using a rimless wheel and wheeled-leg robots using limbs ending in a "regular" wheel.

3.2.1 Artemis

Artemis [10] is a highly mobile system that offers the ability of autonomous Navigation, map acquisition, object recognition and manipulation in unstructured terrain. The Rover is equipped with a six-wheel chassis with passive suspension similar to the ExoMars concept. Therefore, the system is characterized by high mobility in difficult terrain. The central sensor mast houses a Velodyne HDL-32E sensor, which is able to generate high-resolution point clouds of the environment with high repetition frequency. Colour cameras allow objects to be detected and their position to be estimated remotely, taking into account known colour values and geometries. Furthermore, the system has a manipulator with six degrees of freedom and an end effector with simple gripping functionality. Next to the attachment point of the manipulator, a line laser scanner is mounted on a tilting unit, with which an exact measurement of the position and orientation of the object to be manipulated can be carried out. The Artemis rover been successfully used during the german space robotics competitions SpaceBot Cup and SpaceBot Camp, hosted by DLR in 2013 and 2015.
Dimensions: 1.20m x 0.80m x 1.07m. Mass: approx. 75 kg.

Fig. 7. Artemis in the Space Exploration Hall (credit: DFKI GmbH)

3.2.2 CESAR

Fig. 8. CESAR during the ESA Lunar Robotics Challenge (Credit: DFKI GmbH)

CESAR is a lightweight mobile robot with a hybrid wheel/leg locomotion concept that combines the benefits of wheeled and walking systems while keeping simplicity [11]. The system is able to move into a crater with a slope of up to 40° covered with soil and to return to the crater rim. A scoop device enables to collect soil samples whereas a flexible camera head and spotlights support navigation in the dark area of the crater. CESAR took part and won the ESA lunar robotic challenge for crater exploration in 2008.

Dimensions: 0.82m x 0.98m x 0.69mm. Mass: 13.3 kg.

3.2.3 Coyote III and Asguard v4

Fig. 9. Coyote III during a field test (credit: DFKI GmbH)

Both, Coyote III [12] and Asguard v4 are micro rovers, designed for autonomous operation in rough terrain. They are equipped with hybrid legged-wheels on a passive suspension system, providing high mobility in steep slopes, and a wide variety of soils, ranging from soft sandy soils to a rocky unstructured terrain as shown in Fig. 9. Both rovers are equipped with laser range finders and cameras, allowing to map and explore their surrounding and perform autonomous operations.

While Asguard v4 was initially build as search and rescue platform, it was lately deployed in a lava tube to demonstrate environment modeling and navigation for robotic space exploration. The rover has bounding-box dimensions of 0.935m x 0.65m x 0.50m and gains a mass of 16kg.

Coyote III is designed as a modular platform with focus on exploration tasks on Moon or Mars. Its performance was demonstrated during a field test campaign in a Mars analogue environment [13]. It is equipped with two EMI's allowing to dock additional payloads as e.g. a manipulator module to the rover. Coyote III is able to cover slopes of more than 45° inclination and handle loose soils as well as rocky environments. Besides a stand-alone usage, Coyote III may be deployed as a scout or shuttle rover within a multi rover set-up. The rover has a mass of 12.5kg and overall dimensions of 0.994m x 0.584m x 0.38m.

3.2.4 YEMO 1.1

The robot YEMO 1.1 is an underwater micro rover that features extraordinary high agility and mobility at the seafloor. Beyond that, YEMO 1.1 can also be deployed on earth surface [14]. It was engineered based on the already successfully deployed ASGUARD robot platform. The central element of the robot's drive is a passive joint between front and rear axis. The main sensor of the system is a 360 degree field of view camera. This allows a gapless coverage of the entire environment of the robot at all times. A position sensor with compass is available. In applications ashore, a GPS integrated in the robot is able to capture the robot's absolute position; in underwater applications, it can be approximated by the use of an alternative GPS integrated in the buoy. This sensor setup allows autonomous applications, e.g. avoiding collision with obstacles detected in the camera's images.

YEMO 1.1 was used to test new approaches in the astronaut-robot interaction. Therefore, the astronaut's suit is equipped with sensors that allow the recognition of gestures performed by the astronaut using arm and hand movements. This gesture input was used to control the robot.

Dimensions: 1.10m x 0.70m x 0.90m. Mass approx. 27 kg.

Fig. 10. YEMO 1.1 in the Spanish desert during a field test (credit: DFKI GmbH)

3.2.5 Sherpa and SherpaTT

Sherpa and its successor SherpaTT are both hybrid wheeled-leg exploration rovers. The active suspension system of a Sherpa-type-of-robot is composed of four legs ending in drivable and steerable wheels. The main difference between both systems is that the newer version's suspension (SherpaTT) allows 6DoF body movements independent of the wheels' position. A comparison of both systems and their kinematics is provided in [15].

Additionally to the four legs, a centrally mounted manipulator is used for handling payloads and modular containers in a multi-robot setting, see Section 3.3. The arm further serves the purpose of locomotion support as illustrated with the Sherpa robot in Fig. 11.

A set of experiments concerning the locomotion performance of a hybrid wheeled-leg rover is published with [16], indicating high performance in terms of body angle control and active wheel-ground force distribution.

The performance was confirmed in a four week field trial [13], a detailed analysis is presented in [17].

Dimensions of SherpaTT: Variable, smallest foot print: 1m x 1m. Biggest foot print: 2.40m x 2.40m. Height ranges from 0.80m to 1.80m, Mass 150 kg.

Fig. 11. Sherpa using its manipulator to lift front wheels off the ground (credit: DFKI GmbH)

Fig. 12. SherpaTT equipped with modular components (credit: DFKI GmbH)

3.3 Underwater robotic systems for space exploration

In order to be able to explore deep space locations like on Jupiter's moon Europa, it is necessary to develop underwater robotic systems as well as their carrier systems.

3.3.1 Iceshuttle Teredo and AUV Leng

The Teredo IceShuttle is a robotic probe which is capable to transport a payload through an ice-shield towards an environment located beneath the ice. Within the scenario the IceShuttle transports the autonomous underwater vehicle (AUV) Leng as its payload. The propulsion through the ice is generated by a thermal drill. Besides transportation the IceShuttle functions as a stationary base station. It provides a docking interface as well as a set of additional sensors to support the AUV's navigation.

Due to the given requirements and the necessity to carry Leng within Teredo the two systems and their design are highly integrated and adjusted towards each other [18].

Further features are the possibility of autonomous navigation, localization and obstacle avoidance.

Dimensions Teredo: Ø 0.28m x approx. 6.75m. Mass: 160 kg.

Dimensions Leng: Ø 0.22m x approx. 3. 5m. Mass: 73 kg.

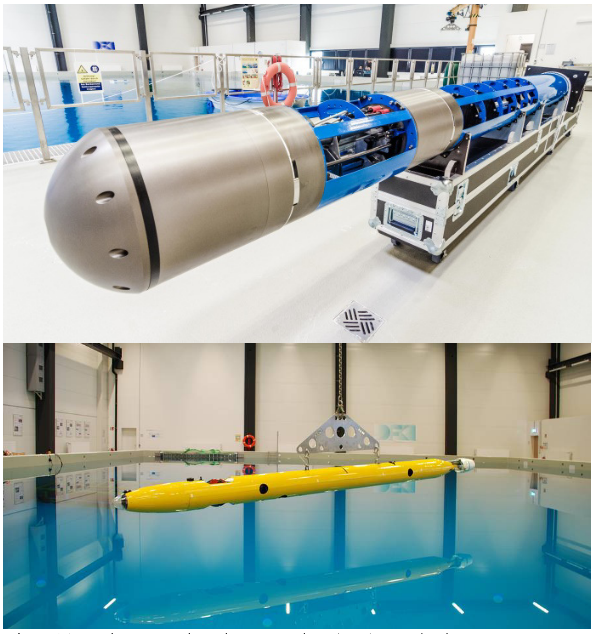

Fig. 13. The IceShuttle Teredo (top) and the AUV Leng (bottom) (credit: DFKI GmbH)

3.4 Heterogeneous Multi-Robot Systems

Combining different robots each being specialized in a certain application area into one multi-robot system bears the potential for overall system performance increase. This section illustrates a multi-robot system built from individual robots presented in the previous sections.

3.4.1 TransTerrA

Fig. 14. Payload exchange between SherpaTT and Coyote III in the context of the TransTerrA multi-robot system

Within the project TransTerrA a modular robotic system for semi-autonomous cooperative exploration of planetary surfaces including the installation of a logistics chain was developed [19]. In order to achieve these objectives the robots are designed to be augmented with modular elements for different exploration scenarios, which can be additionally controlled by humans using a man-machine-interface. The experiences, gained through the predecessor project RIMRES allowed to improve the development of the robotic systems in TransTerrA. The main mission scenario is to extend the exploration capabilities and handle complex mission tasks by introducing a heterogeneous team of robots. This team consists of mobile and immobile robotic elements including the rovers SherpaTT and Coyote III which are able to establish a logistics chain using immobile elements in the form of a BaseCamp (stationary module) as well as portable modular payload-items (PLIs). To establish the logistics chain, all robotic systems are equipped with at least one modular electro-mechanical interface (EMI), allowing to connect the different systems with each other using a male part ("passive") and a female part ("active") [20].

4 Mission road map of space missions

The exploration of the Solar System is one goal of humans on Earth. Thus, a cooperation of 14 space agencies, the International Space Exploration Coordination Group (ISECG), yearly works on a Global Exploration Roadmap to highlight the aims.

Concerning the third edition of the Global Exploration Roadmap the importance of Moon on the pathway to Mars is described [21]. ISECG space agencies visualize that by the mid 2020`s the proximity of the Moon will open the space frontier for human exploration of the Moon, Mars and asteroids. Utilizing this path with a partially reusable lunar lander, human missions to the lunar surface are envisioned. These missions will also advance some capabilities and technologies needed for the exploration of Mars [21].

The Global Exploration Roadmap contents robotic resource prospecting missions to the Moon between 2020 and 2030. Robotic Mars Sample Return missions on Mars are planned in the timeframe until 2035.

Planned future robotic missions to the Moon and Mars are important for answering new science questions and closing strategic knowledge gaps related to human space exploration.

The goals of the planned robotic missions on Moon, as shown in Table 1, are to demonstrate technologies for human missions and to perform surveys or sample returns for science as well as resource and environment assessment by robotic systems. The missions include, among other things, exploration of the surface, communication, drill technology demonstration and mapping for navigation.

Table 1: Future Lunar Robotic Missions (source: [21])

Misson	Agencies/ Launch Date	Objectives/Strategic Knowledge Gaps Adressed
Chandrayaan-2	ISRO/2018	Polar scientific orbiter, lander and rover
Chang`E-4	CNSA/2018	Far side scientific lander and rover. Communications relay satellite
Chang`E-5	CNSA/2019	Near side sample return
KPLO	KARI/2020	Polar scientific orbiter
Luna 25 / Luna Glob	Roscosmos / 2020	Lunar volatile prospecting. Soft landing technology demonstration
SLIM	JAXA / 2020	Technology demonstration
Polar Sample Return	CNSA / around 2020	Polar volatiles sample return
Luna 26/ Luna-Resurs Orbiter	Roscosmos / 2022	Polar scientific orbiter. Polar volatiles mapping
Resource Prospecting Mission	NASA / early 2020`s	Polar science, volatile prospecting and acquisition. Drill technology demonstration
JAXA`s Resource Prospector	JAXA / early 2020`s	Polar lander and rover. Polar science and volatiles prospecting
Luna 27 / Luna-Resurs Lander	Roscsomos, with ESA / 2023	Polar science, volatile prospecting and acquisition. Drill technology demonstration
ISRU Demo	ESA/2025	ISRU technology demonstration
Korea Lunar Lander	KARI	Technology demonstration
Luna 28/Luna Grunt	Roscosmos	Cryogenic polar volatiles sample return

In Table 2 the mission goals for the coming Mars exploration are listed. Mars sample return is of high priority for the global planetary science community. It will advance the search for life in the Solar System.

Table 2: Future Mars Robotic Missions (source: [21])

Mission	Agencies/ Launch Date	Objectives/Strategic Knowledge Gaps Adressed
InSight	NASA with CNES, CSA, DLR/2018	Subsurface geothermal gradient and internal structure of the planet. Identification of seismic risk at the location. Weather station to monitor weather conditions.
ExoMars	ESA/ Roscosmos with ASI, CNES, DLR, NASA, UKSA and Spain / 2020	Rover with 1.5m drill with instruments to search for bio-signatures, subsurface hydrated materials and very shallow ice.
Mars 2020	NASA with CNES, ASI, Norway and Spain/ 2020	Oxygen processing demonstration, catching samples for later return to Earth.
EMM Hope	UAE Space Agency / 2020	Synoptic weather views moving through all times of day
HX-1	China / 2020	Orbit, landing and roving mission. Investigate topographical and geological features, physical fields and internal structure, atmosphere, ionosphere, climate and environment.
Mars Orbiter Mission-2	ISRO / 2022	Orbiter to study the surface and sub-surface features, mineralogy composition and upper atmospheric processes.

Mars Moons eXploration	JAXA with CNES, NASA and other agencies / 2024	Sample return from one of the two moons to progress our understanding of planetary system formation and primordial material transport.

The study of Mars as an integrated system is so scientifically compelling that it will continue with future missions implementing geophysical and atmospheric network, providing in-situ studies of diverse site [21].

5 Individual characteristics of the developed robotic systems in relation to future mission demands

Robotic systems for exploration missions on planetary surfaces need to be robust, dust and temperature resistant, shall be redundant and able to cope with different soil conditions as well as steep slopes of craters and hills.

The systems should also be able to be operated with communication delays, which are up to 2s between Earth and Moon, and around 3-21 min between Earth and Mars.

The presented robotic systems of DFKI are able to cover future mission needs as described below.

5.1 Discovery of craters on Moon or Mars

The discovery of craters on celestial bodies can give information about the history, development and geological character of the respective planet. In order to explore craters, the tasks of used exploration systems range from observation of the area, generating a map of the area up to soil sampling. For such missions a robotic system has to be able to cover the necessary functions and shall be able to move into a crater and to return to the rim of crater.

The DFKI systems Scorpion, ARAMIES, SpaceClimber, CREX, CESAR, Charlie and Coyote III include the skill to move into the crater and also to climb the slope in order to return. All systems have a tool, or can be equipped with, to generate a 3D map of the surrounding. Once assembled with a camera also observation of the area is possible. The system CESAR is already equipped with a soil sample system and thus is able to collect samples as a single system.

5.2 Discovery of the surface on Moon or Mars

One of the main objectives of the study of planetary surfaces is to further develop an understanding of the basic physical processes, the morphology and evolution of planetary surfaces in our solar system.

Robotic systems offer one possibility to discover the surface. Tasks to be performed are soil sampling, mapping of the area and analysis of the air´s composition.

The robotic systems Charlie, Mantis, Artemis, Asguard v4, Coyote III, YEMO 1.1, and SherpaTT are able to generate a map of the area and also to walk or drive on uneven terrain.

YEMO 1.1 and Asguard v4 as well as CREX are already tested in cave explorations and therefore are deployable for such exploration scenarios.

Robotic systems for collecting soil samples are Artemis and CESAR. But since the robotic systems are able to work with each other in a team or one system can extended its functionality by connecting of PLIs via the EMI, also the robotic systems like Mantis, Coyote III as well as Sherpa and SherpaTT are able to collect samples. By extending the functionality of the robotic systems with different PLIs via the EMI, the systems can perform required tasks like, e.g., to analyse the composition of the air by a gas sensor module.

Due to the fact of communication delays between Earth and Moon or Mars, the robotic systems should be able to act autonomously. The mentioned systems are able to handle at least semi-autonom.

One special case is the exploration of the ice layer on Europa, the moon within Jupiter´s orbit. The communication delay between Earth and Europa is around 33-53 min, thus it is necessary that robotic systems on such a celestial body are able to discover autonomously. DFKI developed the Teredo Iceshuttle and AUV Leng, which are foreseen for autonomous exploration.

5.3 Build up an infrastructure on Moon or Mars

Human beings are looking for alternatives for living places apart from Earth. Possible areas are Moon or Mars, even if cosmic and solar radiations destroy the tissue and especially the DNA of living beings.

It needs a well-developed infrastructure and habitats for the purpose of living on Moon or Mars, whereas Mars is more likely to be considered because of its earthlike geological nature.

Robotic systems are developed and still in development in order to support to build up an infrastructure on Mars. Necessary features for robotic systems are the ability to handle and move on uneven terrain, to manipulate with different tools and to communicate with other systems or astronauts.

A cooperation between different robotic systems, the MRS, is a highly efficient way to build up an infrastructure. Actually SherpaTT and Coyote III can work with each other while using PLIs and a BaseCamp to enhance the functionality within the team.

The team can be extended by the use of Charlie, Mantis, Asguard v4, CREX and YEMO 1.1. Once a system is equipped with the EMI, it is possible to extend its functionality by a special PLI.

In this way it is possible to perform different mission scenarios which can include to build up a habitat, collecting samples within a sample return mission, exploration of the surrounding, maintenance and repair.

Furthermore the robotic systems are more effective by the competence to cooperate with astronauts. YEMO 1.1 is already proven to collaborate with human beings.

6 Conclusions

The previous sections provided an overview of a wide variety of robotic systems, integrated and tested at DFKI RIC, to analyze their potential for future space exploration. The aspired next steps for robotic space exploration on Moon and Mars are highlighted according to the latest global space exploration road map. While the evolution of system development ranges back for more than a decade, the needs which arise for upcoming exploration goals are still valid. In the coming time frame the exploration of the surface and environment is the main goal for robotic systems. In later stages, the cooperation between humans and robots are foreseen. Here, the Moon is coming back into the focus as steppingstone for a manned Mars mission. Both for Moon and Mars, robots are needed to be as agile as possible, to reach interesting scientific spots, such as crater walls and/or lava tubes and to provide a certain degree of autonomy in order to cope with the increasing complexity of upcoming missions. While all presented robots are able to operate as single system, the ability to work in a team is presented and promises a wide area of application. This ranges from spacious surface exploration in a robotic team to infrastructure preparation and installation within a human robot collaboration. Besides the exploration of Moon and Mars, bodies that are more distant are gaining interest, such as the icy Jupiter moon Europa. While the requirements for the exploration vehicle are completely different the operational needs show a high correlation in terms of need for a high level of autonomy.

The presented systems provide a wide operational range with various fields of application. They have shown their capabilities during extensive terrestrial laboratory and field tests and provide a high potential to be further developed for space exploration in order to meet the upcoming mission goals.

Acknowledgements

The authors would like to say thanks to the teams of the projects SCORPION, ARAMIES, SpaceClimber, RIMRES, iStruct, LIMES, SpaceBot, ESA Lunar Robotics Challenge, TransTerrA, FASTER, Moonwalk and EurEx.

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