Light-Weight Mechatronics and Sensorics for Robotic Exploration: a DLR Perspective

B. Schäfer, B. Rebele, M. Schedl, M. Görner, A. Wedler, R. Krenn, A. Seeni, G. Hirzinger
German Aerospace Center (DLR), Institute of Robotics and Mechatronics
Oberpfaffenhofen, D-82234 Wessling, Germany
bernd.schaefer@dlr.de

Abstract

Mobility and manipulability are dominant functions to be addressed to any planetary autonomous in-situ exploration. These capabilities will drive the design of the robotic elements to support these functions and to guarantee for mission success. Light-weight and powerful components and intelligent systems are therefore a prerequisite. DLR's Robotics and Mechatronics Institute since many years already has been following these major issues by developing highly integrated robots and many different kind of mechatronic systems, not only for space applications. This paper addresses DLR's most important robotic developments to be used for planetary mobile exploration, and tries to give a vision for their potential use in more advanced long-term future exploration missions.

1. Introduction

Future missions to moon and mars demand robots and rovers to operate in highly challenging environments. Apart from developing systems in safety and reliability perspective, it is also important to have minimal weight and low power consumption components for robots. Technology advancement and development in concurrent engineering has given rise to light-weight as well as high performance systems at DLR. These systems designed with special geometries are light-weight and highly efficient.

Rovers operating in polar areas and in craters, due to very reduced sunlight, need to save power and exhibit low thermal losses to the environment. Hence, actuating systems for mobility need to have low thermal losses and better torque levels to suit such mission requirements. DLR's in-house developed Robodrive (Robotic Optimized ServoDrive) has those phenomenal characteristics and is flexible enough to be used in multi-mission scenarios. Such a light-weight actuator achieves high torque levels with less energy requirement, and it also suits the demands of usage in Light Weight Robots (LWR). The LWR is a manipulating system that has an outstanding payload to total mass ratio. It is integrated with light gears, sensors, powerful motors, and weight-optimized brakes. These robots are modular, intelligent, and are of advanced flexibility compared to their present-day industrial robots. LWR is capable to perform high dynamic and flexible operations, and thus it is well suited to be used as a strong manipulative means to support scientific and exploration tasks in surface sampling missions.

This paper presents the available light-weight technologies by discussing the novel technical and performance characteristics. It also proposes some conceptual designs of their usage in a mobile platform (rovers). Moreover, the paper discusses the significance of this DLR advanced technology for future space exploration and addresses scenarios for both mobile and manipulative systems for planetary surface exploration. Finally, we describe the current design and implementation status of the light-weight actuators and sensors into two types of mobile systems, a wheeled planetary rover and a six-legged crawler, and the combination with a manipulative anthropomorphic system.

2. Motivation

DLR's Institute of Robotics and Mechatronics (RM) since many years already, has been developing highly integrated robots and many different kind of mechatronics systems, not only for space applications, but also for on-ground, industrial and medical areas. Both, the novel light-weight robot arm of generation number 3 (III), and the 4-finger hand of generation number 2 (II), world-wide belong to the most advanced mechatronic systems. They integrate modernst actuatorics, sensorics and communications techniques within a highly complex but modularly built-up system [1-3].

Based upon these promising developments, very early we were convinced that these systems are very well suited for numerous applications in mobile and manipulative operations for planetary surface exploration missions: Light-weight anthropomorphic robots for any kind of manipulation tasks, 4-finger hand for safe and very skilled gripping and manipulative operations. And moreover, we are optimistic that for mobile systems the use of our differential bevel gear concepts as demonstrated successfully within the finger actuators and medical robot applications, will lead to a breakthrough in designing compact and light-weight rover wheel drives and multi-legged walkers.

First results on mobile systems drive design have shown the applicability of the underlying basic actuator concepts for legged walkers (see chapter 5), and for a combined rover wheel actuator for both wheel driving and steering (see chapter 4).

3. Basic Technologies

The main scientific-technological focus of the institute is the multidisciplinary (virtual) design, computer-aided optimisation, and realisation of mechatronic systems and man-machine interfaces. We thus aim at the development of intelligently controlled mechanisms (in particular robots, airplanes, vehicles). These typically exhibit some kind of autonomy, but also should allow for human interference at any time, e.g., based on shared control (shared autonomy including teleoperation).

Mechatronics, as the fundamental technological basis of our institute, for us not only means the utmost integration of mechanics, electronics and information technologies in one functional unit, but also the holistic, computer-aided 3D-simulation and design optimisation: concurrent engineering. Therefore we aim at the parallel design and simulation of all dynamical and physical effects and their interactions, e.g., multibody dynamics, spatial integration of electronic components into 3D-CAD design, simulation of electronic circuits and their heat transfer characteristics, as well as design and simulated verification of control and feedback algorithms to be realised in embedded computer chips. For critical aerospace and vehicle applications we develop new control engineering techniques and tools for modelling, simulation, and control design if available products do not fulfil our needs or the needs of our strategic partners.

Two of our outstanding achievements are the advanced ultra-light and minimal-energy robot arms and the multifingered hands (Figure 1). These technology developments serve as a prerequisite for future “robonauts” (Figure 2) and have yielded extra-ordinary results. Three generations of torque-controlled, compliant and “soft” arms and articulated hands have been realized in the robotics lab in the past years. The arms are kinematically redundant (i.e. 7 degrees of freedom, DOF). With the third generation, which received design awards on several occasions, DLR is approaching the limits of what is technically feasible today.

Figure 1. The new mechatronic robot and hand generation of DLR

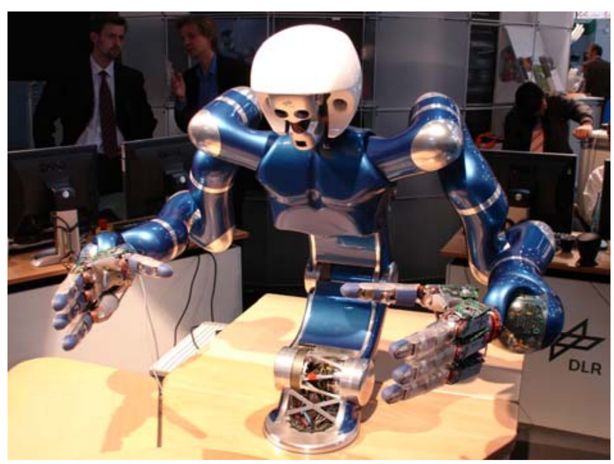

Figure 2. JUSTIN, the DLR humanoid torso with 43 torque controlled joints, sensor head (equipped with miniature stereo camera, laser range scanner, laser line projector)

A new motor concept developed via advanced concurrent engineering techniques reduced weight and power losses by 50%. Thus the new arms with their weight of around 13kg and yet high motion speed, their load capacity of more than 20kg, their high dynamic speed and the minimal energy consumption of around 150W are presumably the most advanced robot arms even at an international level.

But equally important, the institute has developed (and experimentally verified) the first unified (passivity-based) theoretical solution for impedance and position control of flexible-joint robots on both joint and Cartesian level. Two of the joints and their control schemes are the basis of the ROKVISS experiment, currently operated at the International Space Station, ISS, with begin in January 2005.

In a similar way the newest four-fingered hands out of DLR's lab with their nearly 100 sensors, 13 integrated actuators and several hundred mechanical and electronic components are among the most complex robot hands ever built. They are fully modular (i.e., exchangeable in seconds) and have tiny 6-DOF force-torque sensors integrated in the fingertip [4-5].

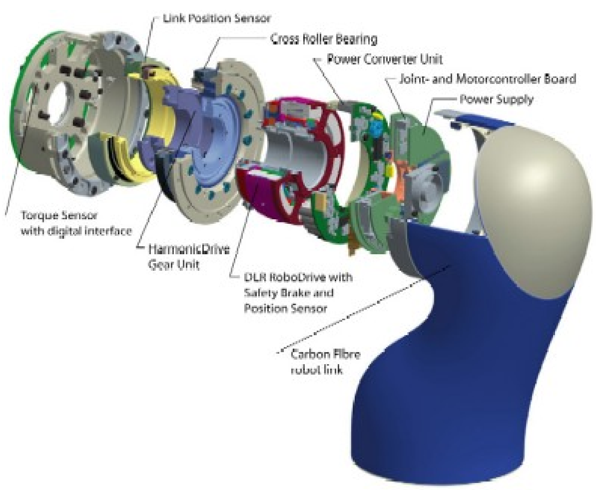

Figure 3. Robotic joint, consisting of weight and power optimized RoboDrive motor, harmonic drive gear, output torque sensor, position sensor on motor and output side

Basis for the light-weight robot joints as well as for the smart finger joints is the new high-energy motor drive, called RoboDrive, developed during the past years in our institute (Figure 3). Based upon required modifications, this drive concept together with the integrated sensor package may be taken into account as an interesting candidate drive concept for the ExoMars rover. Since the joint drive requirements in space robotics and planetary vehicles are different from many other terrestrial applications (especially the demand for low weight and low power losses), we tried to develop an optimised electric motor with respect to the criteria, using the latest results in concurrent engineering. All (multi-) physical effects and their interactions had to be modelled and simulated "in parallel" (Figures 4 and 5).

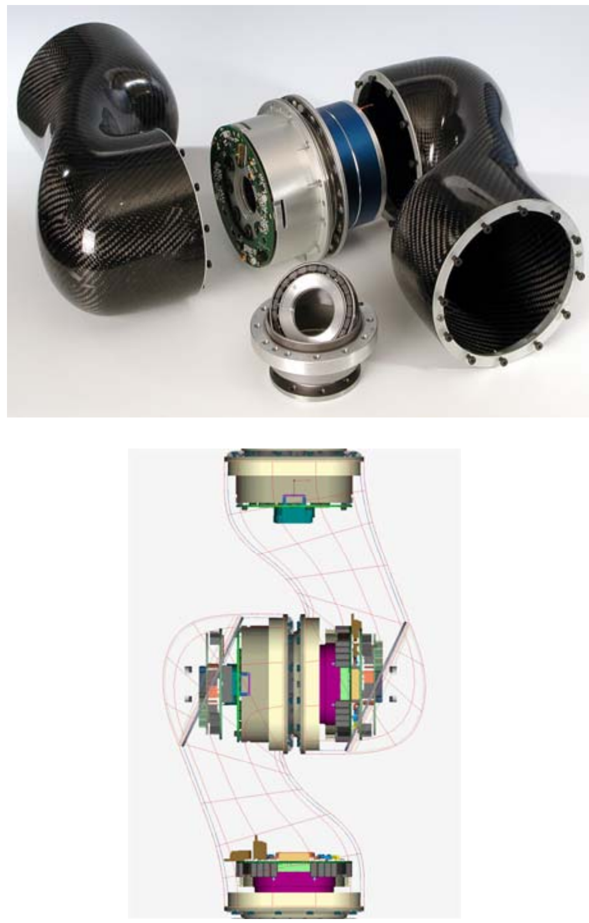

Figure 4. Robotic joint, combining two robotic links: decomposed system (top), CAD drawing of actuator integrated between two links (bottom)

For achieving excellent controllability, the torque characteristics should be linear without distortions and higher harmonics. On the other hand some parameters can only be optimised via trade-offs with others, e.g., between minimal power loss and motor weight, minimal diameter and torque, etc. Finite element technologies were used to model diverse parameter influences on motor performance such as iron thickness.

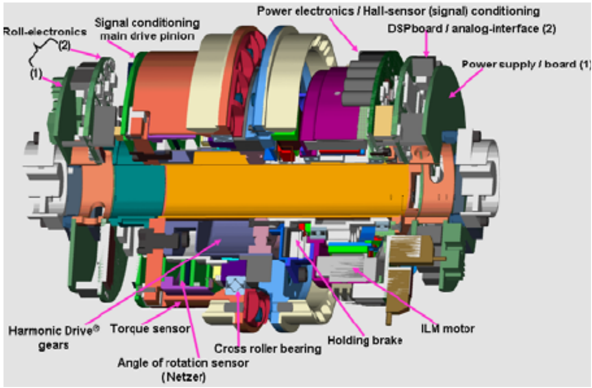

Figure 5. LWR-3 joint: high integration density

All these dependencies were modelled analytically and verified by means of prototype realisations. The result was a motor design yielding all relevant characteristics like copper cross section, iron geometry and a number of coil windings, but in particular a hardly believable 50% reduction in weight and power loss compared to the best commercially available motors we had used so far. Another very satisfying result was that the performance as calculated from the virtual design differed from the real one by only 3%.

In summary, 6 motor types are available meanwhile and they are more and more in demand, not only for new robotic systems but, e.g., for applications in advanced vehicle technology (brake-by-wire, steer-by-wire). Together with specially adapted Harmonic Drives gear type, piezo-electric brakes, and the integrated power and signal electronics, the drive units can be accommodated in very small housings. Moreover, the drives are equipped with a number of sensors like torque sensors and position sensors on both, the gearbox input and output side. Therefore, the motor drives are also well prepared for the application of sophisticated vehicle control strategies.

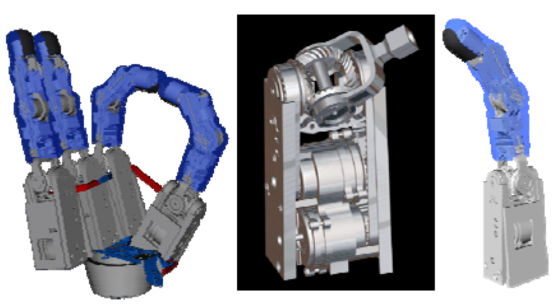

Figure 6. 4-finger hand (left), differential bevel gear stage (middle) used for finger base 2 dof motion, and one finger with 3 dof (right)

4. Mobility with wheels (rovers)

Wheels are the commonly used systems for many terrestrial and planetary robotic vehicles. Wheels provide necessary motion for the vehicle along with other structures associated with locomotion subsystem such as rocker, bogie, chassis, joints, actuators, controllers, sensors, electronics, and steering mechanism. Wheeled rovers can be categorized based on the number of wheels i.e. drive units it possesses, such as four-, five- or six-wheeled. Eight-wheeled heavy rovers such as the Lunokhod were developed in early days and are no longer being developed. For the current ExoMars mission under development, a 6-wheeled rover is favourised, as has been already realized and successfully operated by NASA for their former Martian Sojourner and the two MER rovers now.

Because of their large and long-term experience with the use of differential bevel gear stages, e.g. in the finger base 2-dof motion (Figure 6), DLR has proposed an equivalent actuator concept for wheel driving and steering. The DLR concept is based on the combination of the steering and the driving units via a coupling bevel gear, used already in many applications developed at DLR as well as for KUKA robots in the hand axis and automotive applications that use bevel gears (i.e. differential drives). The main idea of the drive and steering units' combination is to use two axes independently, but both motors supporting each of the two dof (Figures 7 and 8). Due to the bevel gear behaviour, the two units are able to combine their power depending on the need of each dof. This results in lower power consumption and therefore smaller and lighter units as well as higher dynamics.

The low reduction ratio will increase lifetime dramatically as the total number of motor revolutions is very low. Low reduction also reduces complexity and risks as there is no additional planetary gear. Control of bevel gear drives and both axes, respectively, is state of the art. It is also possible to apply different control strategies to the steering and wheel drive, e.g. position control for steering and torque control for driving.

Bevel gear drives are widely used in robotic applications. This concept also achieves a lower centre of mass which results in more stability and climbing capability of the rover because of implementing both units in the hub. Another advantage is seen in the thermal characteristics for the cold Martian environment. Due to the compact housing and close combination of both drive units, all the thermal power loss is well used for heating. The number of additional

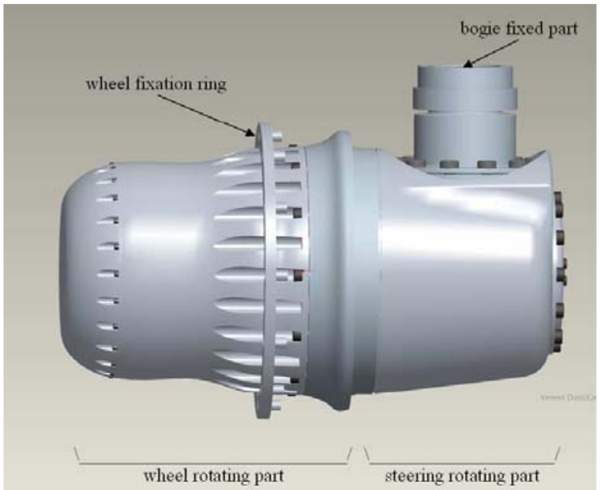

Figure 7. Wheel driving and steering actuator: combined unit overview

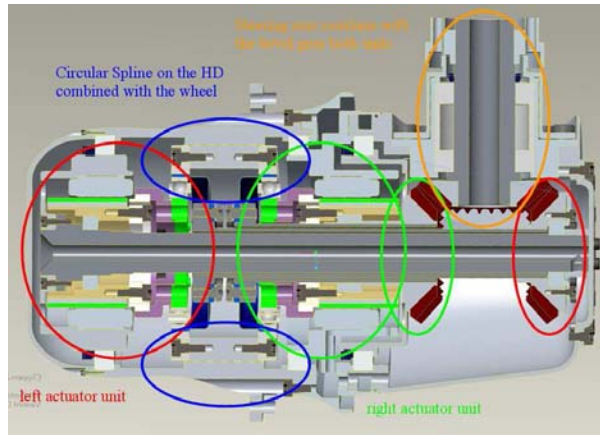

Figure 8. Combined driving and steering unit: Schematic functional parts

heating equipment can be reduced. Both motors will work thermally balanced, so a single cold unit (e.g. the steering actuator when driving a straight path) can be avoided. By the possibility of applying the torques of both motors to assist only one dof, higher peak torques can be applied to the wheel or steering function as in non bevel gear applications (Figures 9 and 10).

The DLR walker is a hexapod (6-legged) robot recently developed at our institute (Figure 11) [6]. It currently serves as a test-bed for control and autonomy of walking systems. The legs of the robot are the fingers which were originally developed for DLR Hand-II [4].

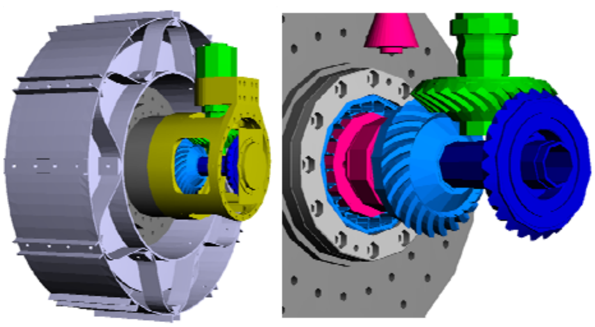

Figure 9. Combined wheel actuator: attached to wheel hub (left), details of differential bevel gear (right)

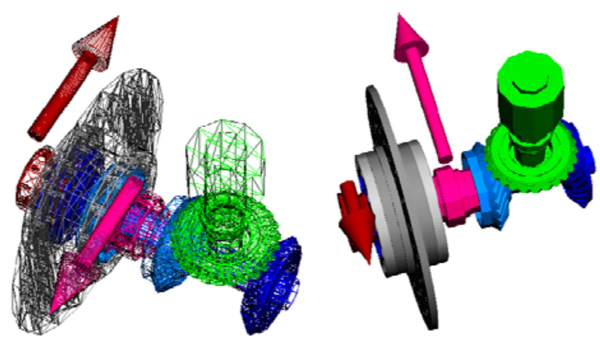

Figure 10. Combined wheel actuator: views taken from kinematic animation, (left) grid model view, (right) shaded surface model view; the two arrows correspond to the output angular rate selected for each of the two motors

5. Mobility with legs

Biological designs and neurobiological controls inspire robot development and have given rise to several robots. Biology offers working examples of robust and sustainable motion behavior. Realized biology inspired designs known as "legged walkers" are consisting of various numbers of legs: there exist 4-legged, 6-legged and 8-legged walkers.

These legs/fingers consist of three independent actuated joints that enable omni-directional walking. The base-joint actuating system in each leg consists of brushless DC motors, tooth belts, harmonic drive gears, and bevel gears. The base-joint is connected to the main body. It is of differential bevel gear type and movable in two dof. The actuating system in the medial

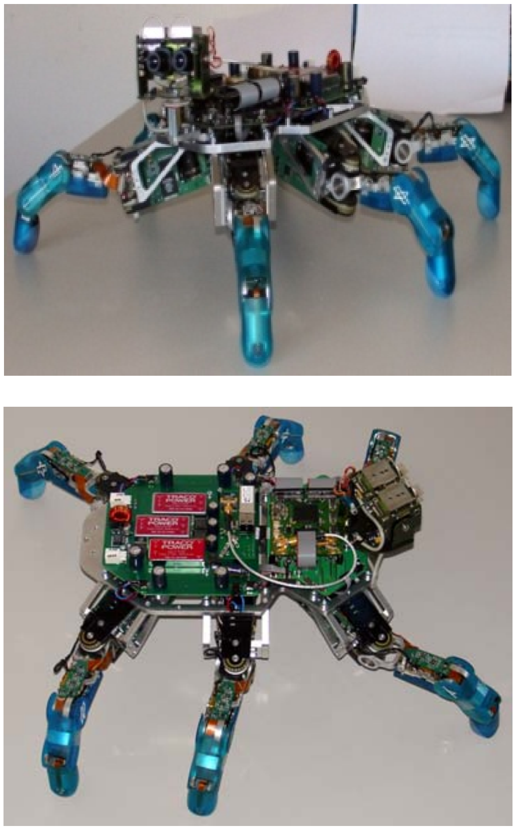

Figure 11. DLR 6-legged walker: (top) in specific walking gait equipped with stereo camera for autonomous navigation, (bottom) showing electronics and actuated joints

joint has relatively less power than the base joint and is designed to meet the conditions in the base joint when the leg is in stretched configuration. The third joint near the tip is passive and coupled to medial joint actuating system. In total, the entire system comprises 18 actuated joints.

The joints are integrated with sensors to provide accurate information of the position and conditions during operation. Each leg has three joint-position sensors, three joint-torque sensors, one force-torque sensor, three motor-torque sensors, and six temperature sensors. The leg tip has a force-torque sensor that measures force and torque in all three directions.

Different walking modes can be applied to obtain various kind of gaits, mostly inspired by biological creatures such as insects. The most known are of periodical character: (1) tripod gait (is the fastest for hexapods), (2) tetrapod gait (is a wave-like gait from back to forth where always four legs have ground contact), (3) wave gait (is the slowest and most stable for hexapods, since only one leg is without ground contact; each of the succeeding non-contacting legs follows a wave-like motion that starts from back and progresses to the front on one side, then doing the same on the other side), (4) additionally there are free gaits for quadrupods and higher, that do not follow a periodic scheme (mostly used in unstructured terrain). The latter, obviously, are of interesting importance for planetary surface walking modes, due to the inherent unstructured environments.

6. Mobility with Hybrids

The wheeled, tracked (not treated here), and legged locomotion systems discussed before have their own advantages and disadvantages. For example, while wheels are capable of higher speeds on a flat terrain than tracks or legs, it is relatively less capable of traversing obstacles than the other two. Hybrid robots possess two locomotion modes in the same vehicle and offer the advantages of both. One very promising type of a hybrid concept, namely the wheeled-leg hybrid, is discussed in this section.

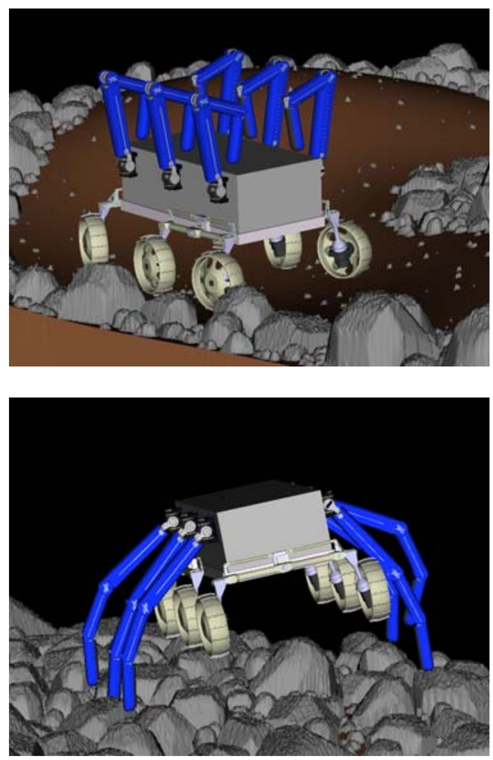

Figure 12. DLR hybrid mobility concept in “wheeled” mode (top) and “walking” mode

Wheeled-leg hybrids have the advantage of higher mobility of walkers combined with the energy efficiency of wheels. The system as a whole can be designed to be highly modular, reusable, redundant, reconfigurable and with adequate margins.

One such example is the DLR's so-called Scout system that has a two-in-one hybrid design concept: a six-wheeled rover that carries a six-legged crawler (Figure 12). Wheels are used to roll on smooth terrain, whilst legs are used to move on extreme terrain. This hybrid concept can be used with unprecedented mobility capabilities; however, they are not under development for space exploration yet.

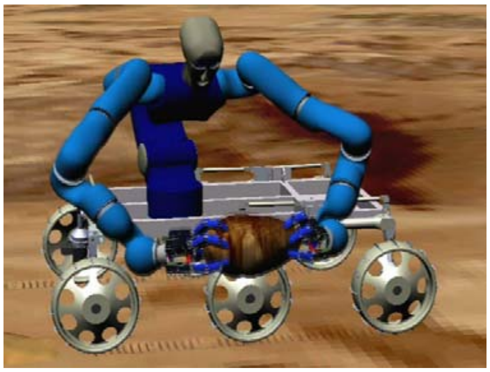

Figure 13. Rovonaut = Robonaut on Rover, DLR's vision of a multi-fingered robonaut on planetary surface: derived from 2-arm JUSTIN configuration (see Figure 2), accomodated on a typical 6-wheeled rover type, such as ExoMars

7. The Rovonaut

Robot experts are confidential that a future vision for planetary exploration may look like the Rovonaut sketched in Figure 13: a mobile two-arm humanoid-like torso that collects soil samples and analyses them in-situ. Moreover, it can be expected that also vision information will play a dominant role while transmitting video images in real-time and with high bandwidth to Earth. Thus, to some extent, allowing a telepresent imagination for numerous people on Earth in adequate stereo projection halls, as if they were on Mars, for example.

8. Conclusions

Several of the presented advanced robotic elements (e.g. new motor drives, force/torque sensors) have already demonstrated their technological maturity by being used in long-term space experiments such as ROKVISS (almost three years already, outside of ISS). Their proved reliability and fail-safe in Low Earth Orbits has been one of the dominant issues, that has to hold also for their use in extremely hostile environment like on planetary surfaces. Here, testing in more extreme conditions is the next step to promote these systems for their intended use on planets.

Light-weight constructions for actuators, increase of intelligence by multiple sensors added to the systems (anthropomorphic robots, multiple fingers, rover drives), and all of these systems paired and provided with advanced and excellent controllability favorize their use in space exploration robotical missions.

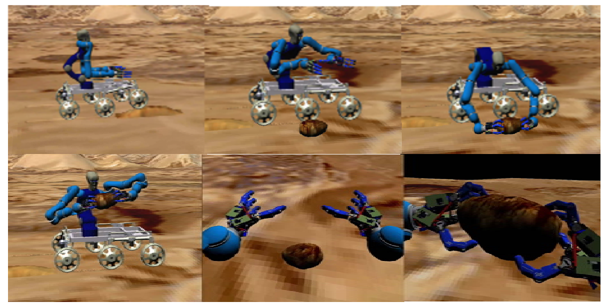

Figure 14. Rovonaut: Different scenes (taken from animation) for demonstrating surface exploration, sample collection and inspection

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