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ON ADVANCED MOBILITY CONCEPTS FOR INTELLIGENT PLANETARY SURFACE EXPLORATION

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In order to increase the scientific output of a rover mission it is very necessary to explore much larger surface areas reliably in much less time. This is the main driver for a robotics institute to combine mechatronics functionalities to develop an intelligent mobile vehicle with an appropriate number of wheels, and having specific kinematics and locomotion suspension depending on the operational terrain of the rover to operate. Moreover, a shift from a traditional bogie and wheel design to more agile wheel-legged combined systems seems to be beneficial in order to reach the goals. DLR's Robotics and Mechatronics Center has a long tradition in developing advanced components in the field of light-weight motion actuation, intelligent and soft manipulation and skilled hands and tools, perception and cognition, and in increasing the autonomy of any kind of mechatronic systems. The whole design is supported and is based upon detailed modelling, optimization, and simulation tasks. We have developed efficient software tools to simulate the rover drive-ability performance on various terrain characteristics such as soft sandy and hard rocky terrains as well as on slopes, where wheel and grouser geometry plays a dominant role. Moreover, rover design supported by means of optimization tools from the very beginning is a must. Optimization aids can support the best engineering intuitions, that will optimize structural and geometric parameters, compare various kinematics suspension concepts, and make use of realistic cost functions like mass and consumed energy minimization, static stability, and more. For self-localization and safe navigation through unknown terrain we make use of fast 3D stereo algorithms that were successfully used in terrestrial mobile systems. The advanced rover design approach is applicable for lunar as well as Martian surface exploration purposes.

I. INTRODUCTION

The search for traces of past and present life, the characterization of planetary environment and the preparation of human exploration are three major topics that drive also a robotics and mechatronics institution to beneficially have a share in realizing those challenging goals.

So far, surface exploration by wheeled rovers on Earth's Moon (the two Lunokhods) and Mars (Nasa's Sojourner and the two MERs) have been followed since many years already very successfully, specifically concerning operations over long time. However, despite of this success, the explored surface area was very small, having in mind a total driving distance of about 8 km (Spirit) and 21 km (Opportunity) over 6 years of operation. Moreover, ESA will send its ExoMars rover in 2018 to Mars, and NASA its MSL rover probably this year. All these rovers are lacking sufficient on-board intelligence in order to overcome longer distances, driving much faster and deciding to a large extent autonomously on path planning for the best trajectory to follow. And this all without almost permanent supervision and intervention of human operators from ground,

Despite the support of scientific exploration tasks by robotics means, the building of future infrastructures for intelligent and wide-area lunar surface exploration and exploitation is a key application for any space robotics and mechatronics institution. This covers the set-up of robotic outposts as well as to provide mobility, manipulability and autonomy to any kind of explorative and exploitive systems. Moreover, providing capacities to autonomously pick up samples by manipulators accommodated on vehicles and equipped with special grippers or tools, and return them to a fixed landing station for processing, is a must in this future challenging scenario [1]. Additionally, we may think of direct or in-situ processing at the vehicle site as is envisaged now for the MSL mission. All this requires the development and integration of light-weight mechatronic components for reliable actuation and increased perception/cognition of environmental conditions. By this, we increase intelligence and autonomy of mobile and manipulative systems and reach the goal to explore much larger surface areas reliably and in much less time. These same key functionalities are also the main drivers to support the set-up of lunar outposts by robotic means in a safe way.

II. TOWARDS ADVANCED PLANETARY MOBILITY CONCEPTS

The main objectives here are to increase rover driving speed and driving safety over a large surface area. As already stated before, the knowledge of the interaction between wheels/legs and ground is of fundamental interest to solve this goal. Here, the increase of the wheel-soil interacting forces which are transmitted from driving, steering or leg-articulating motors to the ground is a big issue. This includes several tasks:

- Increase of motor performance by using new lightweight motor technology.
- Use of novel actuator design concepts for both driving and steering capabilities.
- Reduction of the entire rover chassis and locomotion mass.
- Design of advanced wheel suspension systems to distribute the wheel forces almost uniformly to all wheels.
- Guarantee for rover stability in all envisaged critical driving states ranging from smoothly inclined planes to steep slopes and even crevasses to be negotiated.

Moreover, advanced controller algorithms are required that take care of slippage between the wheels and soft and hard soils, and to reduce slip to a certain minimum. First attempts are already studied that deal with torque and slip control to be applied and tested in our planetary exploration lab. The influence of slip on odometry and hence precise navigation is of dominant importance and has to be considered appropriately.

The following chapters will outline the needs and the technologies being either under development or have already been demonstrated in terrestrial applications. The strategy to reach the goals is based on an institute's perspective that takes into account the recent findings.

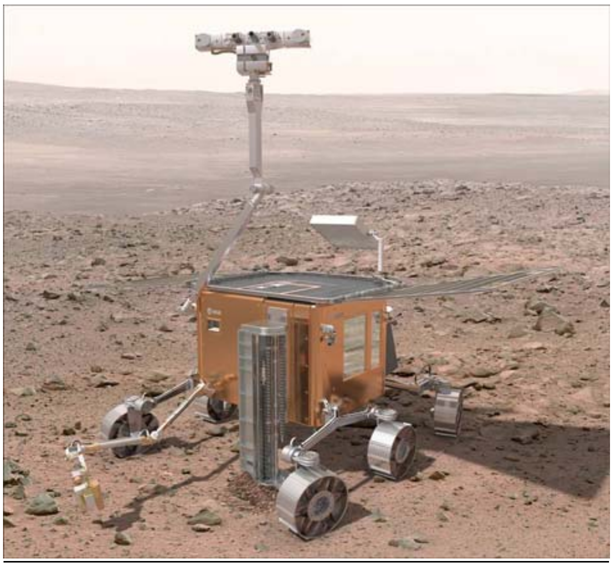

Fig. 1: ExoMars type rover, serving as an example to display the enabling technologies in order to design more advanced systems.

III. ENABLING TECHNOLOGIES

In Fig. 1, the originally envisaged ExoMars rover is presented that shall serve as an example for the various functionalities to be provided for any advanced mobile vehicle that will meet the challenging goals. By sure, the mobility function is the major driver for any kind of such an advanced vehicle. Starting with the interaction between vehicle and soil, this is the wheel in its traditional designs; but it also can be legs, or any kind of sophisticated wheel geometry with specialized grousers and more. All those approaches have to consider how to best transfer the actuating forces and torques to the soil in order to overcome the rough terrain efficiently and to speed up with driving, walking and else.

Further, the suspension system and its kinematic arrangement and attachments to the vehicle main body are of likewise importance. Existing bogie designs or sophisticated ones are the matter of investigation. The balance of forces uniformly applied to the various ground contacts while roving over rough terrains is, by sure, one of the prevailing requirements for any design approach. More advanced kinematics design will admit agile suspension geometries that allow to overcome extreme surfaces and steep terrain. By this, vehicle kinematics may be reconfigured, e.g. by legged/wheeled system kinematics, in order to safely negotiate rocky and steep terrains while lowering or raising the overall vehicle's center of mass (CoM), for example.

Efficient actuation and control of the joints in bogies, legs, and wheel driving, steering and deployment is a further prerequisite with respect to best travel through unstructured surface with reasonably fast speed and minimal energy consumption, and at the same time avoiding too high slippages that act conflictively.

All those elements serving for mobility interact with each other. To handle and to integrate them in an efficient way, the use of optimization methods seems mandatory to arrive at a best or somehow optimal solution. Therefore, the whole locomotion subsystem design is to be supported by and is based upon detailed modelling, optimization, and simulation tasks [2]. Efficient software tools were developed, building on commercially available basic software packages like Matlab/Simulink and Modelica/Dymola. This allows a precise and extensive simulation of the rover driveability performance on various terrain characteristics. They cover important features such as driving on soft sandy and hard rocky terrains as well as on slopes, where wheel and grouser geometry plays a dominant role. Moreover, rover optimization is performed to support the best engineering intuitions, that will optimize structural and geometric parameters, compare various kinematics suspension concepts, and make use of realistic cost functions like mass and consumed energy minimization, static stability maximization, structural elements stress and strain minimization, and more.

Increasing autonomy plays a fundamental role to achieve intelligent navigation and surface exploration, and hence almost faster driving performance. Here, the tasks of self-localization and safe navigation through unknown terrain are obligatory to be successful. This is done by a robust navigation system for rough terrain that is based on stereo vision [3]. The performance and the grade of quality depend to a large extent on the available computation power on the vehicle that otherwise influences rover design by mass and power consumption. Other visual (e.g. laser based systems for hazard detection and obstacle avoidance) and remote sensing capabilities (e.g. orbiter based imaging) may be added to support safe and fast navigation through unknown terrains.

IV. INNOVATIVE SOLUTIONS

Concepts of alternative actuation and realizations of safe navigation have been followed and will be described in this chapter. Advanced suspension kinematics and optimization based first results then are to presented in the following two chapters V and VI.

IV.I Actuation

DLR's Institute of Robotics and Mechatronics 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, and the 4-finger hand of generation number 2, world-wide belong to the most advanced mechatronic systems (Fig. 2, for a robotic joint). They integrate state-of-the-art actuatorics, sensorics and communications techniques within a highly complex but modularly built-up system [4-6]. Very recently, we have started to develop DexHand, a space qualifiable dexterous multi-fingered robotic hand in contract to ESA, that ESA is going to use for space applications [7]. Our innovative light-weight actuation and sensorics system together with an highly integrated electronics system are the primary features to achieve DexHand performance as required. Moreover, the basic actuation system has demonstrated its long-term space performance in the ISS-based ROKVISS experiment. The two-arm robot, attached to the external shell of the Russian ISS module, served for more than six years as a fantastic and reliable system to demonstrate the motion performance in extreme space environments. And very recently in 2011, we were able to receive this system back to Earth in order to investigate its technical state during the long term space sojourn.

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, and for a combined rover wheel actuator for both wheel driving and steering.

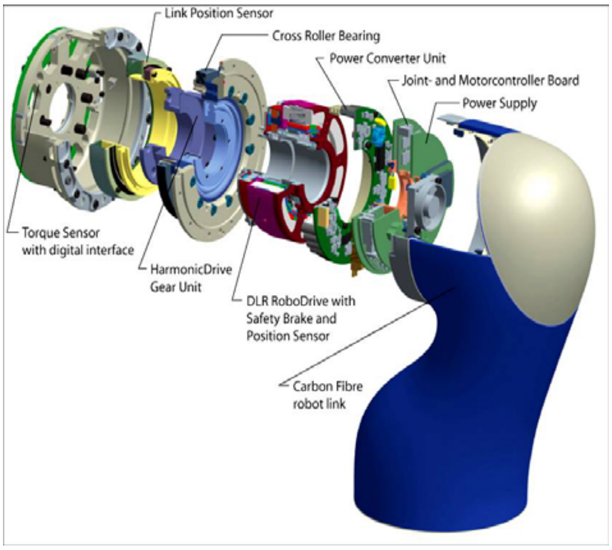

Fig. 2: Robotic joint, consisting of weight and power optimized RoboDrive motor, harmonic drive gear, output torque sensor, position sensor on motor and output side.

The new motor concept developed via advanced concurrent engineering techniques reduced weight and power losses by 50%. Basis for the light-weight robot joints as well as for the smart finger joints is this state-of-the-art high-energy brushless DC (direct current) motor drive, called RoboDrive, developed during the past years in our institute. Based upon required modifications, this drive concept together with the integrated sensor package will be taken into account as an interesting candidate drive concept for any mobile system. Since the joint drive requirements in space robotics and planetary vehicles are different from many other terrestrial applications, 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" [8].

In summary, several 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 (Fig. 2). Therefore, the motor drives are also well prepared for the application of sophisticated vehicle control strategies.

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 lunar and planetary 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 heating equipment can be reduced [9]. 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 (Fig. 3).

Some remarks should be added to the benefit of brushless over brushed motors, since the use of brushless DC motors in space applications receives increasing importance. For the two MER rovers (Mars Exploration Rover), NASA had built upon brushed motors yet. Their use in atmospheric environment, although with very low pressure, was somehow justified. However, even for the next rover missions (MSL, Mars Science Laboratory), NASA also builds upon brushless ones. It is well accepted that brushless DC motors have enormous advantages over brushed ones:

- Higher power densities.
- Higher peak torques, meaning acceptable overloads for short time.
- No mechanical friction contacts, except in housings: thus no brush wear and therefore enhanced reliability and lifetime without any maintenance.
- External stator (coil windings), internal rotor (permanent magnets): hence excellent heat dissipation by the external stator copper losses due to direct conductive heat path to the exterior.
- No shortcuts because of conductive debris in the commutator slots, since brushes/commutator transitions are lacking.

However, the use of more extensive power electronics and sensorics acts somewhat disadvantageously, but is no matter of severe concern.

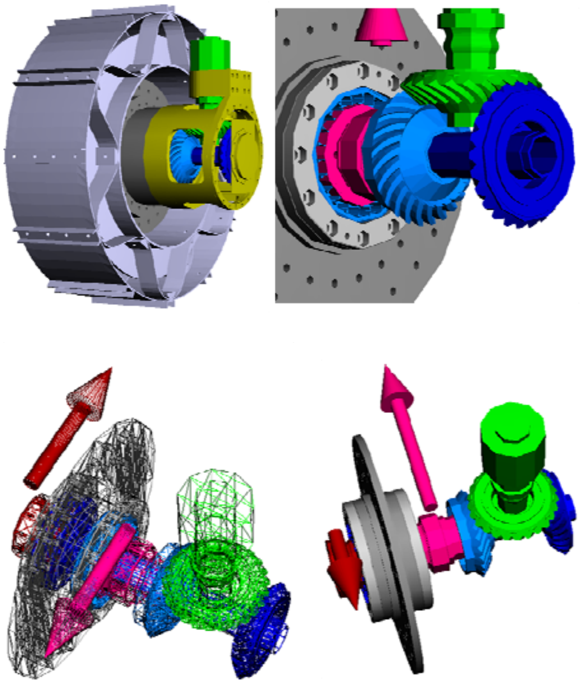

Fig. 3: Combined wheel driving and steering actuator. Top: attached to wheel hub (left), details of differential bevel gear (right). Bottom: views taken from kinematic animation, grid model view (left), shaded surface model view (right); the two arrows correspond to the output angular rate selected for each of the two motors.

IV.II Safe Navigation

Navigation is based on images from a stereo camera as primary sensor. The images are rectified and matched by stereo correlation or SGM (Semi-Global Matching) for computing a dense depth image (Figure 4). Correlation [10] is suitable in applications with low computing power, whereas SGM is useful for dense and more accurate results [11]. For reducing the computational burden of SGM, implementations on a graphics card [12] as well as on FPGAs (Field Programmable Gate Arrays) are possible [13]. Especially, FPGA implementations are particularly useful for mobile robots and space applications due to their low energy consumption and radiation tolerance.

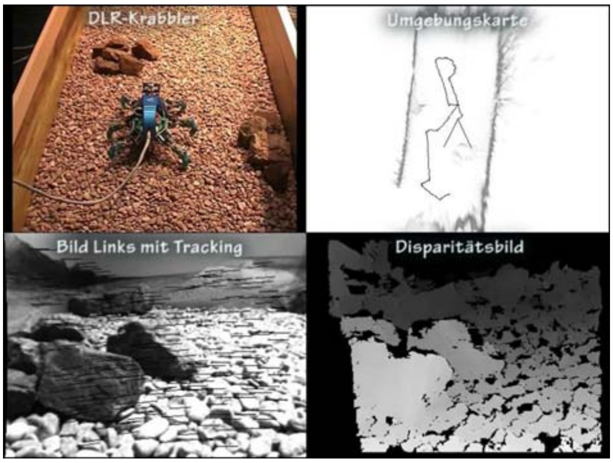

Fig. 4: Demonstration of autonomous driving based on image data processing (stereo camera on DLR's 6-legged crawler) with obstacle detection and avoidance.

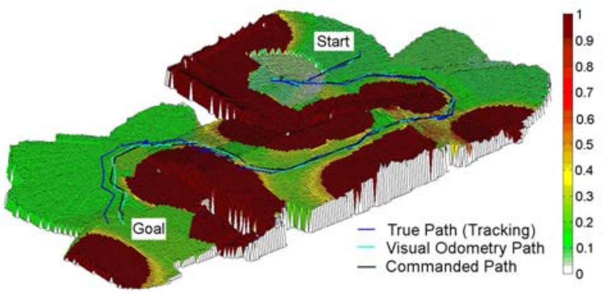

Fig. 5: Autonomous driving: simulation with start and goal destination in unknown and complexly shaped terrain, applying obstacle detection and avoidance (green: benign terrain; brown: detected obstacles resp. dangerous extreme terrain).

The visual odometry is computed based on the sequence of left stereo camera images and corresponding dense depth images [14]. The robustness is increased by fusing the visual odometry with IMU and odometry information [15]. This leads to registered depth images, which are combined into a 2.5D elevation model of the environment (Figure 5). The model is then analyzed for traversability and a D* light path planner is applied [3].

V. SOME ADVANCED KINEMATIC CONCEPTS

Wheeled, tracked (not treated here), and legged locomotion systems 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. The locomotion modes can be arranged separately (legs in parallel to wheels) or as a combination e.g. wheels mounted to legs.

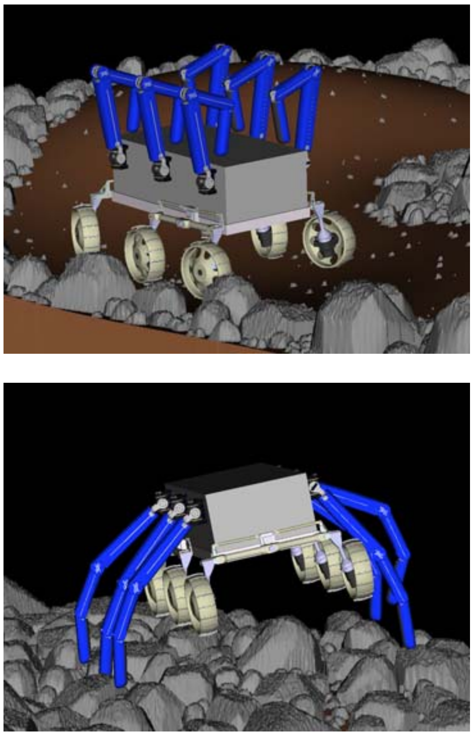

Fig. 6: DLR's hybrid mobility concept in "wheeled" mode (top) and "walking" mode (bottom).

One very promising type of a hybrid concept that we studied recently, namely the wheeled-leg hybrid, is shown in Fig. 6. Wheeled-legged hybrids have the advantage of higher mobility provided by 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.

The example of Fig. 6 is a two-in-one hybrid design concept: a six-wheeled rover that carries a six-legged crawler. 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, the system is just in a study phase and not under severe development for space exploration yet.

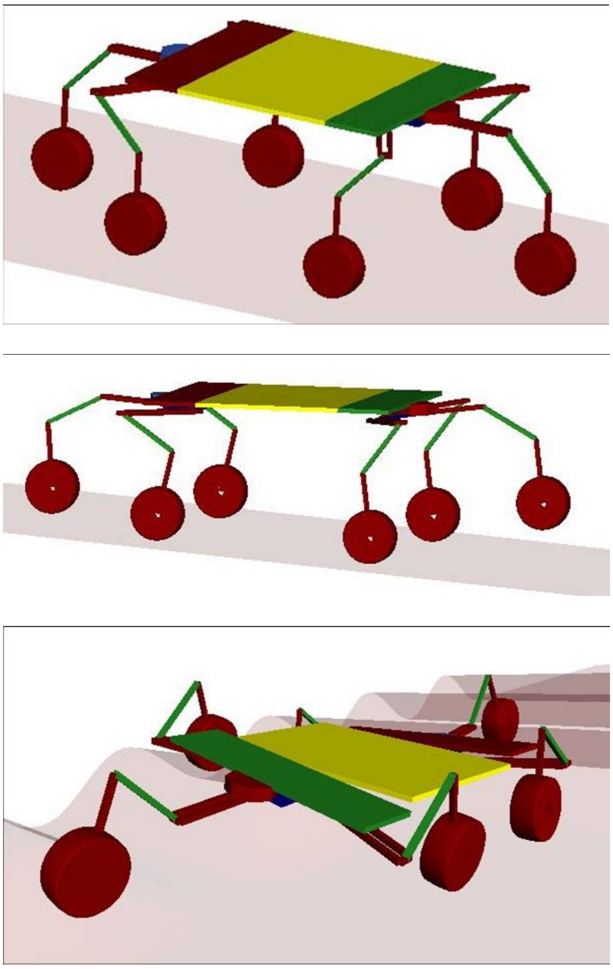

Fig. 7: Hybrid legged/wheeled concept: Large ground clearance with high CoM (top). One leg lifting/walking possible while using tangential (frictional) ground forces (middle). Passive suspension on rough terrain with low CoM (bottom).

Another very promising hybrid system combines articulated legs with wheels, somehow related to the Athlete system of NASA [16], but with totally different kinematics here (Fig. 7). It combines 3 legs at the front vehicle body and 3 legs at the rear side. Each 3 legs are suspended passively via a rotating connecting base plate to the main body. The central body is coupled via a differential gear in between of both, front and rear side. Each leg has 3 dofs. The connecting plate replaces somehow the functionality of a traditional bogie system, as in ExoMars or MER type rovers.

Several beneficial functionalities can be received by this kinematic arrangement:

- Leg lifting and walking by friction on ground, since we make use of a statically undetermined system.
- In benign terrains: legs kinematics can be blocked (motor switched off) in order to obtain an energy efficient driving mode.
- In complexly shaped terrains: the use of adaptive locomotion by using the articulated leg kinematics is of great benefit, e.g. by lowering or raising the CoM for increasing ground clearance (lifting) or by increasing the static stability behaviour (lowering).
- In very extreme terrains: walking over obstacles will be possible.

Since this is a very new design approach, further studies are underway now to optimize the kinematics itself and to work on control of such complex systems that is deemed being not an easy task.

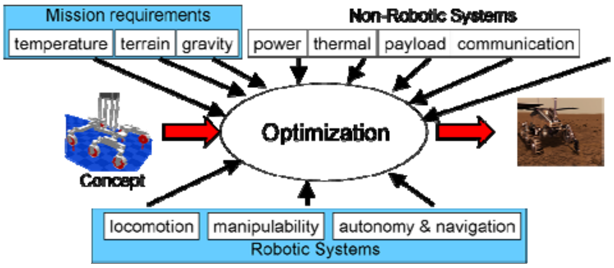

Fig. 8: Mission and systems requirements that drive the optimal design of a vehicle.

VI. OPTIMIZATION

The expertise and achieved developments of our institute with respect to the goals stated above have been integrated into an overall development and design tool that optimizes a next generation planetary rover (Fig. 8). Expertise is available in rover kinematics/dynamics optimization, in multibody dynamics and terramechanics, in energy management and minimization, and in design of advanced controller approaches (Fig. 9). The overall goal then will be the realization of a demonstrator rover that features new characteristics such as high mobility, energy efficiency, increased autonomy and long range driving capabilities at given total mass. In parallel, the development environment at its final stage will act as a design tool, and will very rapidly assist in optimized rover designs that fit to any type of terrain topology. And, moreover, that cope with given mission design specs such as given total mass, available energy resources, desired rover speeds and driving ranges [17].

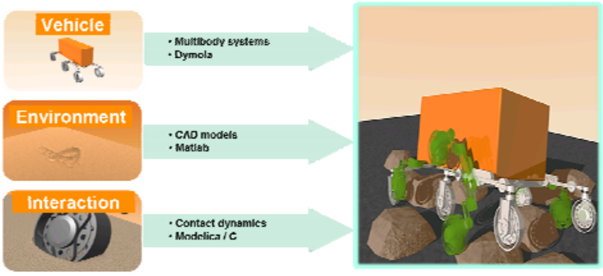

Fig. 9: Modelling of the various components: vehicle as a multibody system (by Dymola software tool), the terrain topology (environment, by Matlab tool), and the contact dynamics between wheel/leg and ground (by Modelica tool and C language).

The optimization environment uses MOPS, the Multi-Objective Parameter Synthesis tool that integrates with Matlab/Simulink. MOPS has the advantageous feature to optimize more than only one cost function (therefore named 'multi objectives') within one optimization run. The right choice of the objectives functions has been carefully investigated: mass, power, driven path distance, static stability, and structural elements strain and stress minimization are considered of dominant importance.

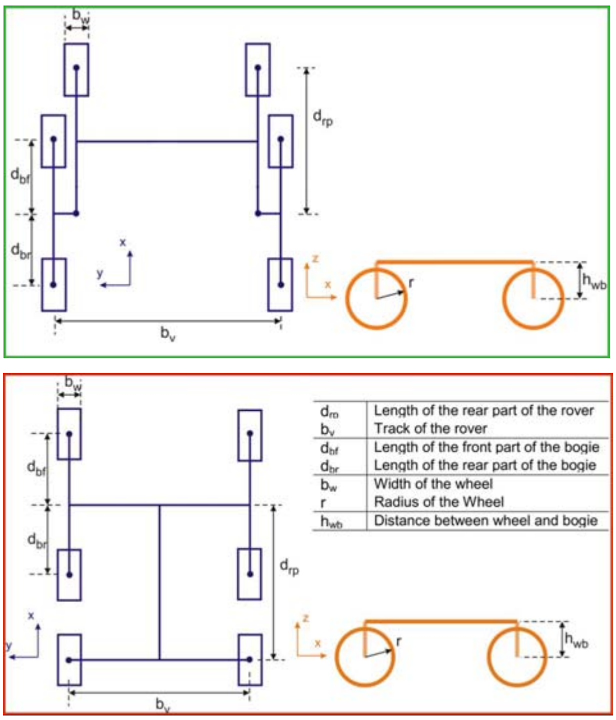

Fig. 10: Optimization example: suspension kinematics geometry optimization of MER (top) and ExoMars (bottom) type rovers.

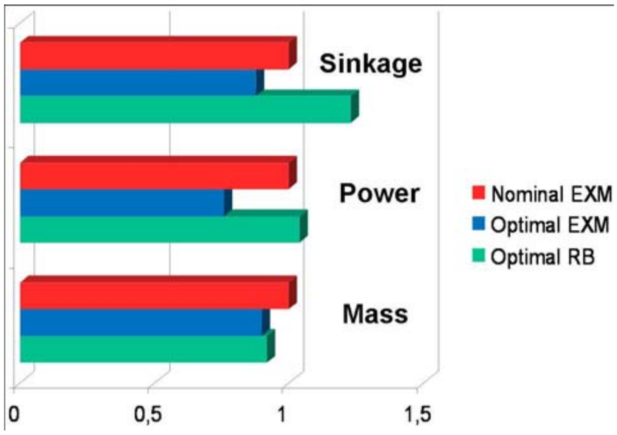

Fig. 11: Some results from optimization example: cost functions have been minimization of soft soil sinkage, wheel driving power consumption, and overall mass. EXM – ExoMars, RB – Rocker-Bogie (MER). The nominal values are taken for the existing ExoMars rover and are normalized to one.

Some results are shown in Fig. 11, where we regarded the existing ExoMars and MER rovers (suspension kinematics shown in Fig. 10), and investigated their potential for further optimization of locomotion parts. Some improvements could be obtained, although being of minor grade here, which otherwise shows the ingenuity of design engineers using their long standing experience and expertise only. However, when regarding much more advanced and hybrid vehicle systems to be designed in an efficient way, we would rather embark on a joint approach: applying the optimization tool from the very beginning and interacting with the expertise of experienced design engineers.

VII. CONCLUSIONS

This work has focused on advancing mobile systems for planetary surface exploration aiming at higher speeds and increased autonomy, while applying innovative engineering technologies for locomotion and navigation. Furthermore, it has been shown that optimization of locomotion subsystems is mandatory since the envisaged advanced vehicles will exhibit increased degrees of freedom, combining e.g. wheeled and legged mobility functions within one hybrid system. And, optimization is expected to deliver vehicle solutions that meet the requirements of faster driving or travelling and of more safely negotiating complexly shaped terrains. Next, design details and optimization of the presented hybrids will be further developed, and first experimental tests and designs on advanced controller approaches regarding torque and slip control are to be performed.

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