Proceedings of the XIV International Symposium on Dynamic Problems of Mechanics (DINAME 2011),
Fleury, A. T., Kurka, P. R. G. (Editors), ABCM, São Sebastião, SP, Brazil, March 13th - March 18th, 2011

Development Environment for Optimized Locomotion System of Planetary Rovers

Bernd Schäfer[1], Alexandre Carvalho Leite[2], and Bernhard Rebele[1]

[1] German Aerospace Center (DLR), Institute of Robotics and Mechatronics, Münchner Str. 20, D-82234 Wessling, Germany

[2] Currently at DLR, Germany, as Guest Scientist from Instituto Nacional de Pequisas Espaciais (INPE), São José dos Campos, SP, Brazil

Abstract: This paper addresses the first steps that have been undergone to set up the development environment w.r.t. optimization and to modelling and simulation of the overall dynamics of the rover driving behaviour under all critical surface terrains, like soft and hard soils, slippage, bulldozing effect and digging in soft soil. Optimization is based on MOPS (Multi-Objective Parameter Synthesis), that is capable of handling several objective functions such as mass reduction, motor power reduction, increase of traction forces, rover stability guarantee, and more. The tool interferes with Matlab/Simulink and with Modelica/Dymola for dynamics model implementation. For modelling and simulation of the overall rover dynamics and terramechanical behaviour in all kind of soils we apply a Matlab based tool that takes advantage of the multibody dynamics tool Simpack. First results of very promising rover optimizations 6 wheels are presented that improve ExoMars rover type wheel suspension systems. Performance of driveability behaviour in different soils is presented as well. The next steps are discussed in order to achieve the planned overall development environment.

Keywords: multibody dynamics, planetary rovers, optimization, terramechanics, simulation

NOMENCLATURE

J_{mass} = overall mass of a vehicle, kg
m_{parts} = mass of a mechanical part, kg
$J_{avpower}$ = average consumed power, W

Greek Symbols

Δt = simulation time, s
τ = torque provided by powered wheel, Nm
ω = wheel's angular velocity, rad/s.

Subscripts

parts	index of a mechanical part
wheels	index of a powered wheel

INTRODUCTION AND MOTIVATION

Mobile systems for planetary surface exploration of Moon, Mars and other celestial bodies are attracting more and more importance for the scientific community. Also, for the exploration of geologically interesting areas this holds true in preparation for future missions with much larger extent such as an envisaged sample return mission to Mars, or even for a manned mission. First un-manned wheeled rovers have been sent to Moon very early already, the two Lunochod rovers in 1970 and 1972, but with remote operations from Earth. In recent years, rovers have been sent to Mars (NASA Mars Pathfinder Sojourner with launch in 1996, and the twin rovers MER Opportunity und Spirit with launch in 2003) that operated with some kind of increased autonomy very successfully. Next, two rovers will be sent to Mars again, the NASA Mars Science Laboratory MSL to be launched in 2011, and ESA's ExoMars rover with expected launch date in 2018 (Fig. 1). All these Mars rovers have in common that they were operating or will be operating in a more or less moderate surface terrain, in equatorial regions, i.e. close to lower latitudes. In all these Mars missions 6-wheeled rovers have been employed.

The Mars missions were very successful and MER rover Opportunity still is exploring Mars terrain. Although the two show-pieces, the MER twin rovers, have been roving and exploring the surface for incredible 6 years now, the exploration area and their driven path lengths are relatively small compared to the long operations time of several years. For Spirit this yielded 7.7 km (dated from spring 2009 when the rover got stuck, until now), and for Opportunity 20.6 km (dated from 12 May 2010). Although craters with soft inclination were visited by the twin rovers as well, the rovers have been designed to operate in a more or less moderately structured surface terrain. Moreover, due to the limited rover intelligence on-board, daily driving and operations is strongly constrained to low speed and to small driven distance. In the mean, a distance of 100 m per Mars day has been reached.

The exploration of much larger surface areas at comparatively similar mission times is one of the major impacts to come up with an essentially increased scientific output compared to present rover missions. Moreover, the very high development and mission costs are justified much easier by exceeding the mission operations time and the planetary surface area to be explored, remarkably. Figure 2, however, gives an impression where scientists might want to go but engineers may get nightmares with wheeled rover technologies. To reach, at least, several of the goals mentioned before, novel approaches for mobile systems development together with their intelligent and autonomous motion guidance and control have to be followed and realized. Our main objectives are to increase rover driving speed, to increase the wheel-soil interacting forces which are transmitted from drive motors to the ground, and to add more autonomy while driving through larger planetary surface regions. All this includes increase of motor performance by using new light-weight motor technology, novel actuator design concepts for both driving and steering capabilities, reduction of the entire rover chassis and locomotion mass, advanced wheel suspension systems to distribute the wheel forces almost uniformly to all wheels, and to 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.

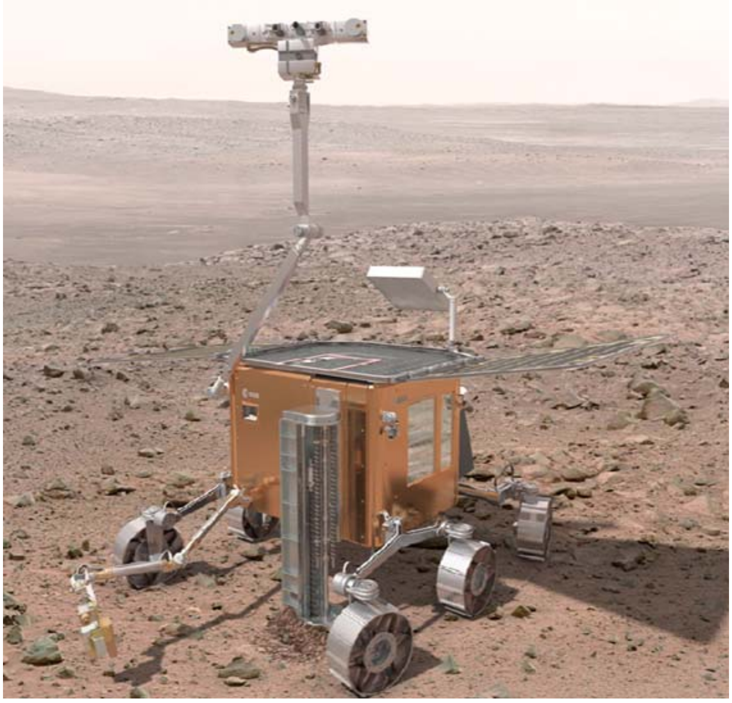


Figure 1 – ESA's ExoMars rover to be launched to Mars in 2018.

The expertise and achieved developments of the institute with respect to the goals stated above will be integrated into an overall development and design tool that optimizes a next generation planetary rover and which is used for design support. 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. 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, to given total mass, available energy resources, desired rover speeds and driving ranges.

Figure 2 – Planetary surface topologies: (top) scientist's dream site, a nightmare for rover design engineers; (bottom) a good compromise.

This paper will address the first steps that have been undergone to set up the development environment w.r.t. optimization and to modelling and simulation of the overall dynamics of the rover driving behaviour under all critical surface terrains, like soft and hard soils, slippage, bulldozing effect and digging in soft soil. Optimization is based on MOPS (Multi-Objective Parameter Synthesis), that is capable of handling several objective functions such as mass reduction, motor power reduction, increase of traction forces, rover stability guarantee, and more. The tool interfaces with Matlab/Simulink and with Modelica/Dymola for dynamics model implementation. For modelling and simulation of the overall rover dynamics and terramechanical behaviour in all kind of soils we apply a Matlab based tool that takes advantage of the multibody dynamics tool Simpack. First results of very promising rover optimizations for 4 and 6 wheels are presented that improve ExoMars rover type wheel suspension systems. Performance of driveability behaviour in different soils is presented as well and compared to certain test results obtained in a lab environment. The next steps are discussed in order to achieve the planned overall development environment.

DESIGN AND BOUNDARY CONDITIONS FOR OPTIMAL ROVER DESIGN

Several major constraints have to be considered that drive the design and development for optimal rovers. They arise from two main sets of requirements, i.e. mission and system requirements. For mission requirements, we mainly have to consider items like

- Target planet or moon: gravity, solar constant, radiation, temperature range
- Mission duration
- Surface topology, i.e. terrain: flat, soft/hard, sandy, gravel, rocky, cliffy, steep slopes, crater
- Latitude: equatorial, temperate zone, polar
- Payload: what size, power and mass

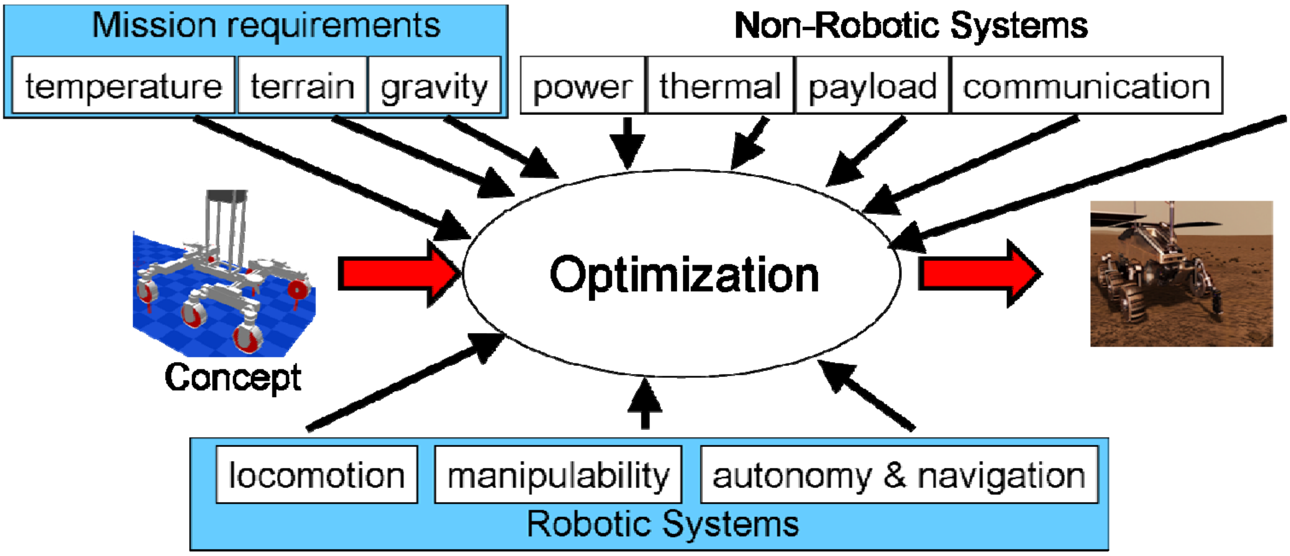


Figure 3 – Mission and system requirements that drive the optimal design of a wheeled rover.

For system requirements, the main items to regard are

- Mass and power limits
- Subsystems like
  - power (solar, battery, RTG Radio-isotopic generators)
  - thermal control (passive, active, RHU Radio-isotopic heating unit)
  - communication (with lander, orbiter, earth)
  - autonomy (rover-based cameras for navigation, orbiter-based cameras)
- Accomodation of payload on the rover
- Sample collection (from ground, subsurface, by drilling)
- Transport to lander
- Manipulability: robotic arm on rover, for grasping specific devices, various tools for sample acquisition and instrument deployment on planetary surface
- Locomotion concept: how many wheels, suspension kinematics, which wheels shall be actuated for driving and steering
- Technological Readiness (TR): what is the level of TR (the so-called TRL) for the various subsystems and components?

All these components and items have influence on rover sizing w.r.t. mass, power, and actuator dimensioning for driving and steering. They all impact on each other mutually. Figure 3 gives an overview how these components are expected to react with each other. Hence, it is very important to integrate all these mutual influences within a unique software environment that serves as the basis for a global design and development tool, and that covers modelling, optimization and simulation in one tool. Figure 4 addresses the complete development cycle for all the phases starting from conceptual work, going to first designs, performing validation between simulation and breadboard development by correlating testing with simulation results, and finally reaching the desired flight version.

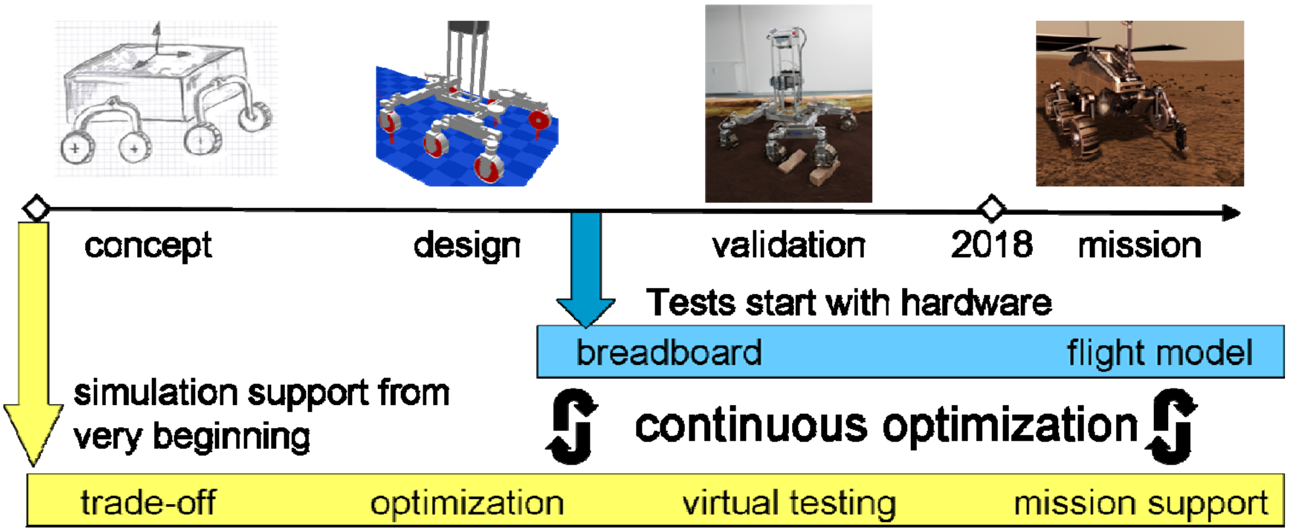


Figure 4 – Four steps of rover design, from conceptual work to flight version; to achieve confidence by combination of testing and simulation.

CONCEPTUAL ROVER DESIGN: MULTIBODY SYSTEM AND TERRAMECHANICS MODELING AND SIMULATION

To support the design optimization and to demonstrate the rover performance on both hard and soft soil terrain, we have set up a modeling and simulation tool that makes use of a multibody system (MBS) approach for the rover dynamics, SIMPACK software tool, and which interacts with very detailed and complex terramechanics models for the wheel-soil interaction (Krenn et al., 2008), being part of the MBS environment (Fig. 5). This methodology is used to rapidly set up a design concept on best engineering knowledge and experience gathered by past rover designs. Mobility performance simulations on various terrains then are obtained (Schäfer et al., 2010), and can give a first indication of how to drive the subsequent optimization process w.r.t. the proper selection of objective functions and to rover parameters to be chosen for optimization (Fig. 6).

Moreover, at the end, when the optimization process has been accomplished successfully, this MBS tool is used to demonstrate again the, hopefully, better performance of the optimized rover design compared to the conceptual, first approach. Although we also need MBS and terramechanics models within the optimization phase, those models have to be taken in a constraint or reduced manner in order not to oversize the overall optimization problem. In the optimization phase, we rather want to focus on the features that drive the optimization process, i.e. proper objective function selection, choice of the demanding rover design parameters, regarding the impacts from mission and system requirements. However, this all requires precise modeling as well, but on a lower level compared to the conceptual rover modeling and simulation phase. In the end, having different modeling and simulation approaches at hand, this very nice feature is expected to increase reliability and efficiency of the simulation runs, before going for manufacturing, breadboarding and testing of the rover hardware.

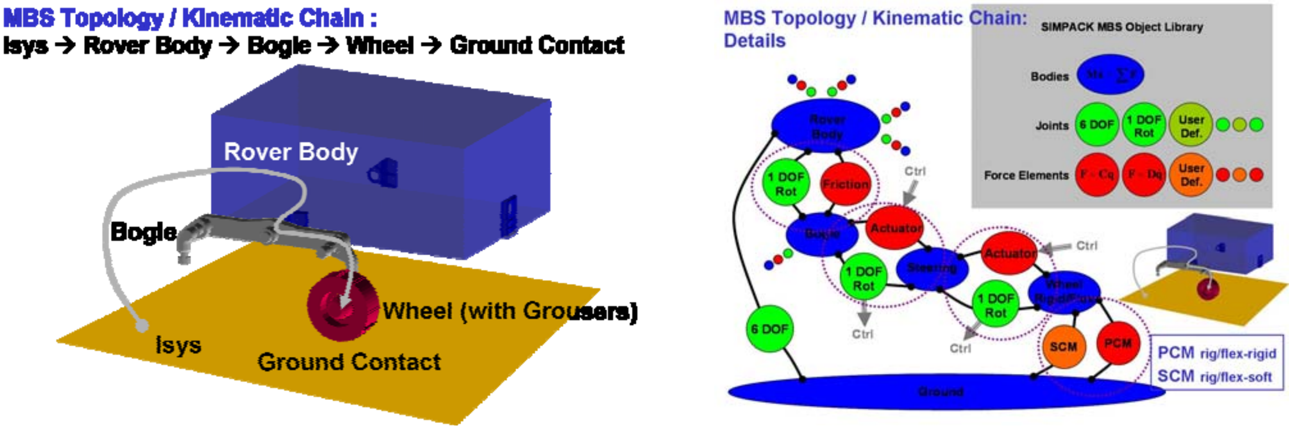


Figure 5 – Typical MBS topology approach: kinematic chain from inertial reference system to rover body, rover bogie (suspension), wheel and wheel-soil interaction. Various user defined force elements are to be applied for passive (spring, damper) and active (motorized, control) actuation between the elements. PCM (rigid soil) and SCM (soft soil) represent force elements that model the wheel-soil interaction.

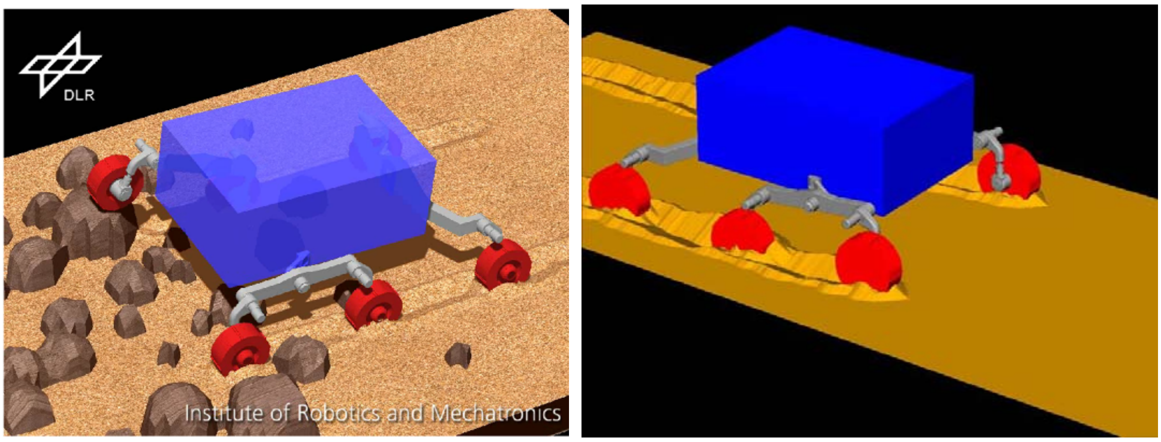


Figure 6 – Simulation results for a 6-wheeled planetary rover driving on soft soil (right) and mixed soil (left).

DESIGN OPTIMIZATION

Our design optimization methodology is separated in four different phases. First, a standard simulation model is set up with specific contact models for various terrain topologies. Then, objective functions and feasible regions are determined and selected properly. What follows, is a multi-case optimization and robust solution assessment. And finally the optimization tool is described and applied.

MBS model and wheel-soil contact models

To constrain the optimization problem we use a MBS approach with specific contact models. The kinematic structure is modeled with standard components (joints and rigid bodies) of MBS software (in this case Dymola®/Modelica), as shown in Fig. 7 (top). The contact model between each wheel and soil/obstacles deals with arbitrarily deformed terrains, rigid surfaces, soft surfaces and complex shaped rocks (Fig. 7, bottom).

Most of our modeling effort is in contact modeling, since this is very specific for all-terrain vehicles. The main idea of our contact model is to apply terramechanics theory (Fig. 7, bottom, (a)) on a laterally discretized wheel (Fig. 7, bottom, (b)) to compute some of the traction and resistance forces. Contact between the models and rocks is computed with the well-known Coulomb friction model, but the contact must be detected. For that purpose we use the collision detection techniques implemented in the SOLID® library (Fig. 7, bottom, (c)). Forces acting on the lateral of the wheel are highly dependant on the lateral shape of the wheel, the computation of these forces is based on vector calculus over a surface represented as a triangle soup (Fig. 7, bottom, (d)).

Note, that a multi-wheeled vehicle generates tracks which affect the sinkage of the following wheels. To compute this effect properly, the terrain is deformed for each contact patch on a simulation integration step (Fig. 7, bottom, (e)). A highly subdivided triangle-faceted mesh represents the deformed terrain.

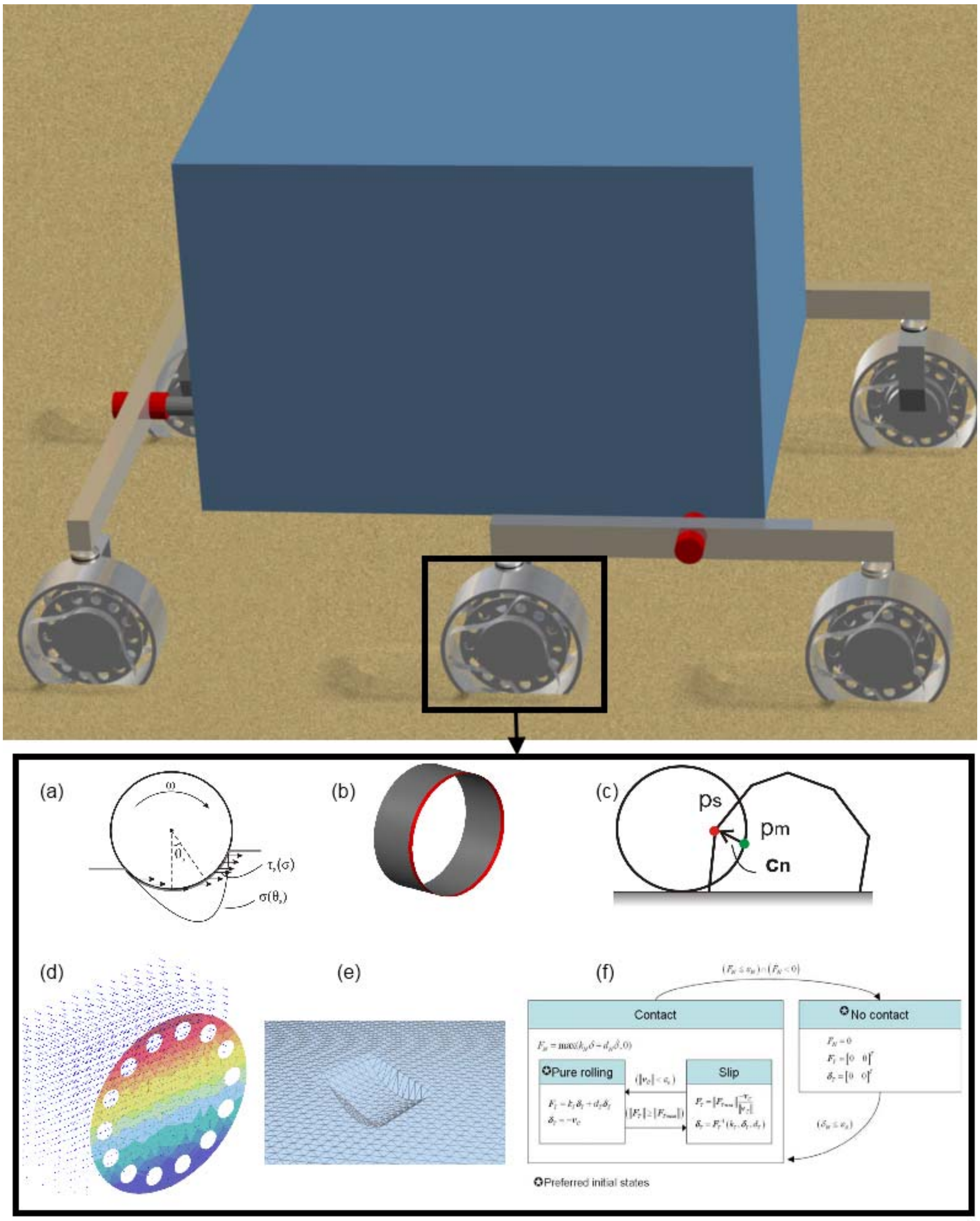


Figure 7 – Overview of multibody simulation model (top) and contact models (bottom): a) normal and tangential pressure distributed on a slice; b) clear-cut of a discrete slice; c) wheel-stone contact detection; d) pressure field acting on the bump-stop; e) deformed surface; f) states diagram of the contact model.

Moreover, the wheels are allowed to loose contact with the surface or with the rocks. Furthermore, rigid surfaces contacts are constrained to keep tangential forces inside the friction cone. This constraint embodies the transition between pure rolling and slipping behavior. To represent all these state transitions, there is a state machine which implements the state transitions and assures the proper change of the structure of the system of Differential Algebraic Equations in the simulation model (Fig. 7, bottom, (f)).

Objective functions and feasible region mapping

There are some characteristics of planetary exploration rovers which are well suited to achieve desired performance indices of trafficability, maneuverability, terrainability, automobility and mission requirements (Apostolopoulos, 2001) for conceptual definitions. Some of those characteristics are: slippery behavior, sinkage behavior, consumed power, weight and dynamic stability. They can be stated as metrics to achieve better performance in soft soil with irregular distribution of rocks. As an example, three objective functions, J, are being used in this work to quantify the performance of rovers. They are: overall mass,

$$J_{mass} = \sum_{parts} m_{parts} \tag{1}$$

average consumed power,

$$J_{avpower} = \sum_{wheels} \frac{1}{\Delta t} \int_0^{\Delta t} \left| \tau \cdot \omega \right|_{wheel} dt \tag{2}$$

and dynamic/static stability. The static stability margin is computed as the worst case stability margin between longitudinal and lateral static stability margins. The dynamic stability margin is very useful when the wheels are in contact with the uneven terrain, which is computed as in Papadopoulos and Rey (1996). Static stability measures are useful in soft terrain traveling, and the vehicle length and track are the most impacting design parameters. Dynamic stability is appropriate in rough terrain navigation; this is highly affected by vehicle suspension design parameters. Overall mass can be computed without the need of simulation, since it is a static objective function but with direct impact in all dynamic objective functions. Average consumed power is explicitly integrated in the simulation time domain and highly sensitive to terrain variations, control laws of the motion controllers, geometry and inertia parameters.

The design parameters are limited due to manufacturing constraints and system requirements; this defines the feasible parameter region. Figure 8 shows the mapping of the feasible parameter region into the feasible objective function region of a single wheel driving straight ahead on rigid or soft surface. The figure shows individual mapping of the ExoMars-type wheel on a range of radius/width configurations into its corresponding mass/power performance. Note that the intermediate parameter choices are mapped exactly in the intermediate feasible objective function region and that the contour of the feasible parameter region embodies exactly the feasible objective function region. In this case, the multi-objective optimization problem is a trade-off solution without the need of optimization algorithms, because it is not numerically intensive.

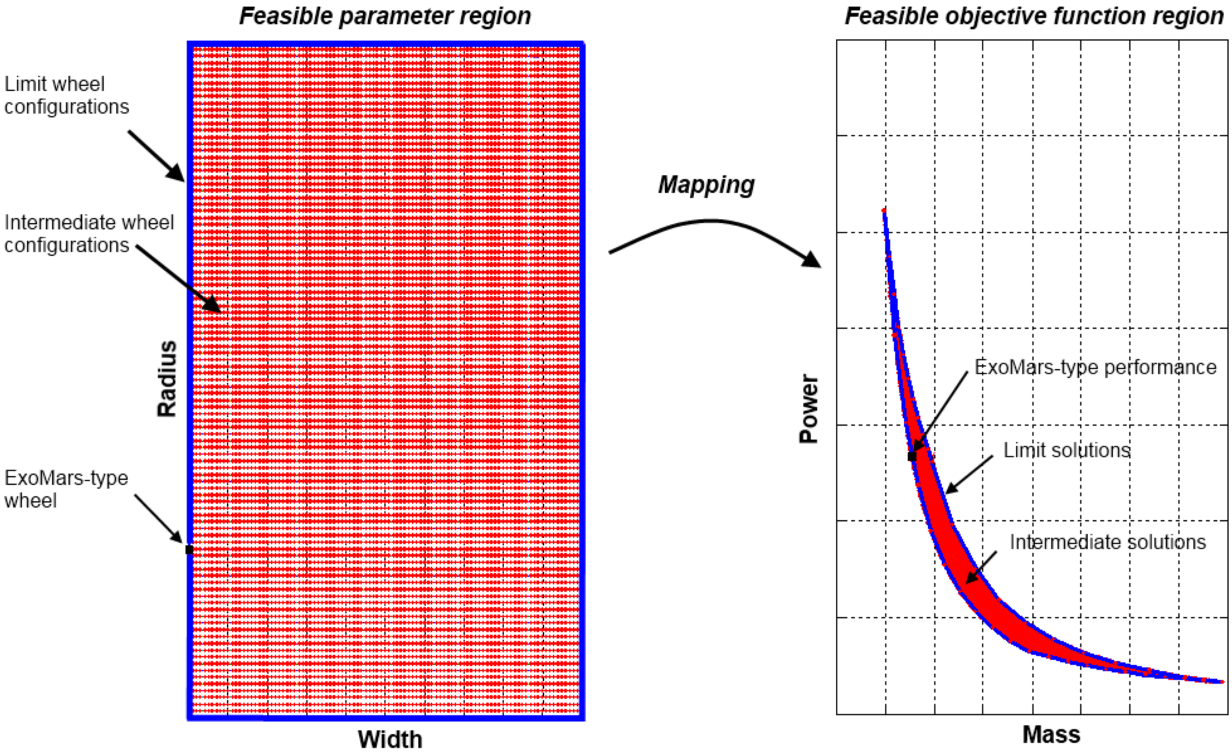


Figure 8 – Mapping of the feasible parameter region (here, wheel radius and wheel width) into the feasible objective function region for a single wheel.

It is interesting to use this insight to search optimal solutions for general multi-wheeled all-terrain vehicles. We applied the same mapping procedure on a two-wheeled bogie in the same simulation conditions. The results are that of Fig. 9.

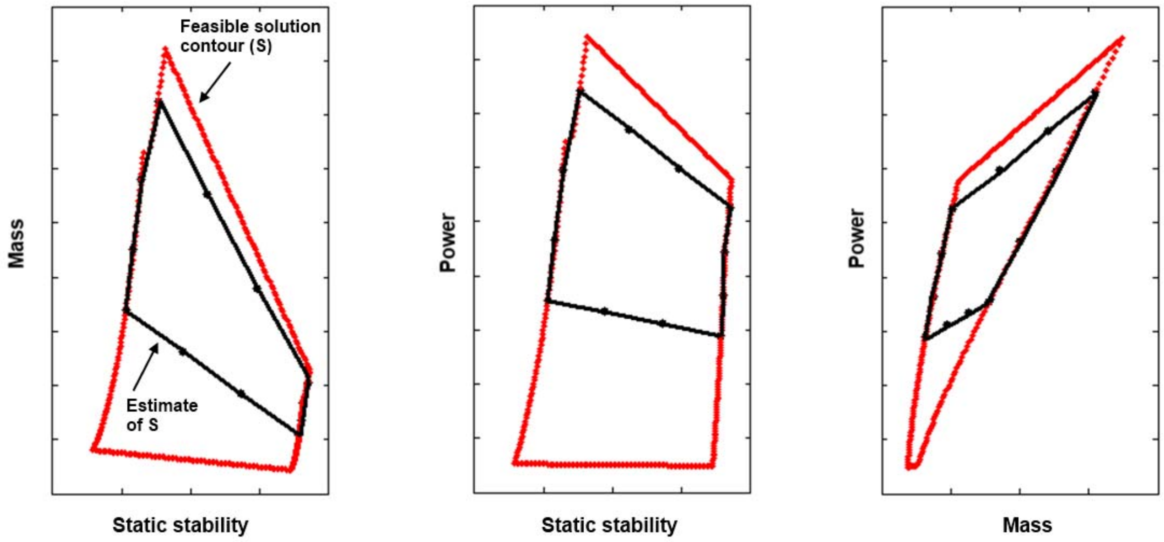


Figure 9 – Mapping of the feasible parameter region into the feasible objective function region for a two-wheeled bogie.

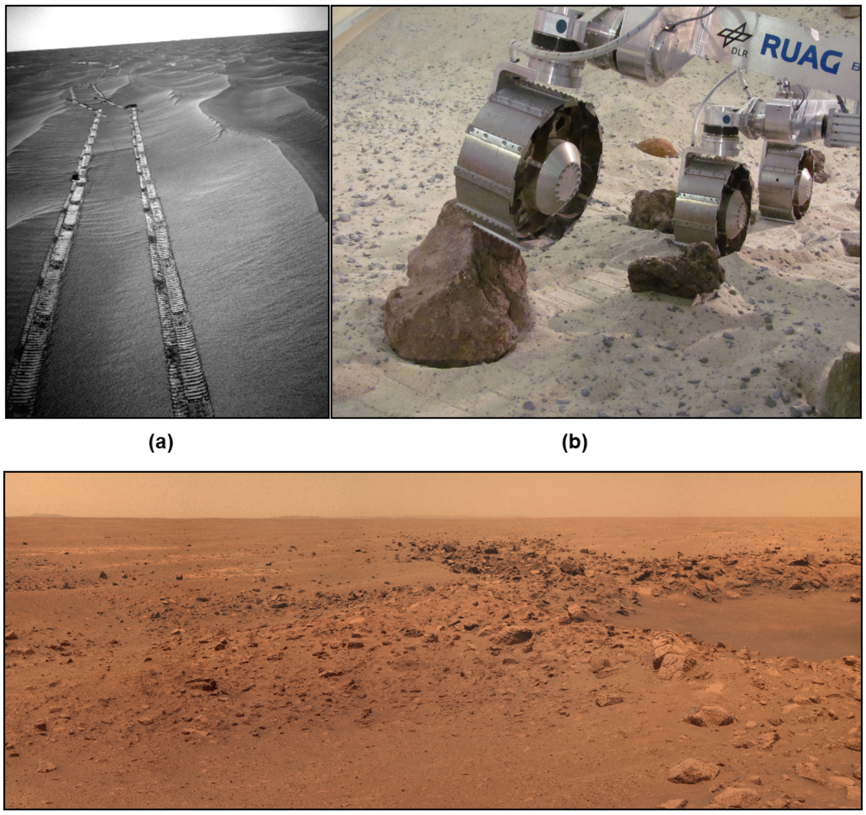
This new case introduces a new insight which can be extended (it was verified) for four and six wheels. The feasible objective region mapped from intermediate design parameters generates the feasible solution contour S. The contour S embodies the contour generated from the hypercubic feasible parameter region (no more a rectangle like in Fig. 9) of the bogie design parameters (length, surface area, distance between bogie and wheels, wheel radius and wheel width). This result can be directly applied to an optimization procedure, because the embodied contour is a reasonable estimate for the contour S, to which the optimal solutions belong. It was applied in the optimization process of a six-wheeled ExoMars-type rover, the convergence was improved and became four times faster than without previous knowledge of the estimate of S.

Multi-case optimization and robust solution

A planetary rover can achieve high performance indexes for some scenario (e.g. driving straight ahead on a rigid surface), but it can be quite unsatisfactory for other most representative scenarios (Fig. 10) with pure undulating terrain (dunes) or sandy environment with randomly spaced rocks. This is the main reason to adopt the multi-case optimization approach, where the optimal solution is found in order to agree with several simulation scenarios. It can be seen as an additional constraint to the optimization problem, because the terrain is one of the inputs of the MBS model.

Multiple cases approach allows the search of a robust solution. In other words, a robust vehicle with high capability of driving with improved performance in worst case scenarios and mission specific scenarios. Some of these cases are illustrated in Fig. 11. The four cases illustrated there are intended to provide suitable simulation inputs to the MBS model in order to find a robust optimal rover design. The assumption behind this approach is that the synthesized rover will achieve optimal performance in most of the real situations during its mission on another planet or asteroid. Additional parameter changes can generate other instances of scenarios. A specific scenario can be instantiated into several others with different terramechanics properties, friction coefficients, gravity, rock distributions, slope angle of the terrain, shapes of the rocks, etc. The more scenarios are available, the more constrained is the problem and more robust is the solution.

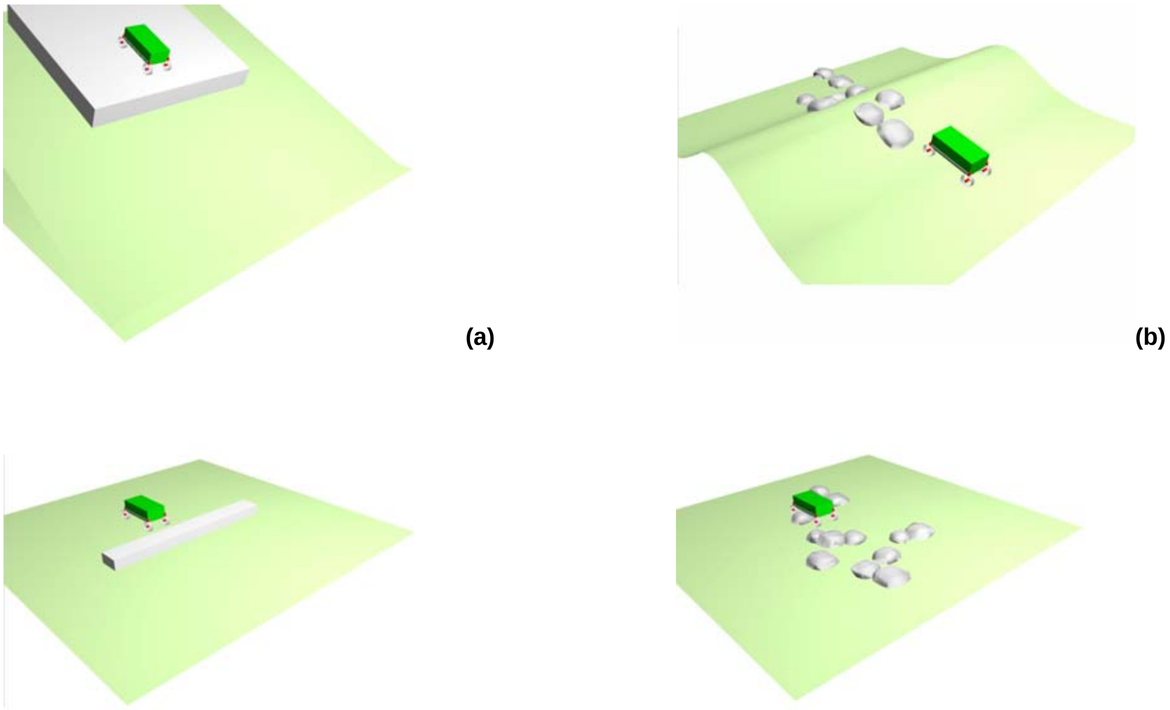
Sensitivity analysis can also be performed with respect to scenario parameters or design parameters, because the objective functions are functions of both sets of parameters. The multi-case optimization approach has two drawbacks. The first is that it requires more computation time, since one dynamic simulation of a specific planetary rover is required for each scenario. The second drawback is that unpredictable numerical instability is more likely to occur among several rover configurations and scenarios. When this situation takes place it ruins the optimization iteration, because there will be a wrong evaluation of the objective functions. To cope with the two drawbacks, a modeling effort is required, because the simulation must be numerically stable and computed fast by the numerical integrators. This is a challenge with the nonlinear/variable-structure simulation model used in this work. Some equations of the contact model are coupled with computational algorithms which cannot be reduced algebraically. These algorithms were implemented using the BLAS (Basic Linear Algebra Subprograms) to vector/matrix operations and take advantage of the specific characteristics of the application. For instance, mesh updates and subdivisions can take advantage of the fact that it represents a surface and not a general hull, memory and processing can be saved. Intersection area computation in collision detection was partially solved analytically which also reduces computational cost. Although future implementations using GPUs (Graphics Processing Unit) are planned to further reduce computation optimization time.



(a) (b)

(c)

Figure 10 – Real scenarios: a) and c) MER rovers (NASA, 2010), b) ExoMars testbed (DLR, 2010).



(a) (b)

(c) (d)

Figure 11 – Multi-cases: a) step-down/downhill; b) Gaussian terrain with stones; c) plane with step; d) plane with stones.

Optimization tool

The contact models, MBS models, optimization strategies and objective functions are components of an optimization tool under development. This tool can be used to synthesize optimal planetary exploration rovers regarding multiple objective functions. Figure 12 shows the sequential steps performed in our optimization tool.

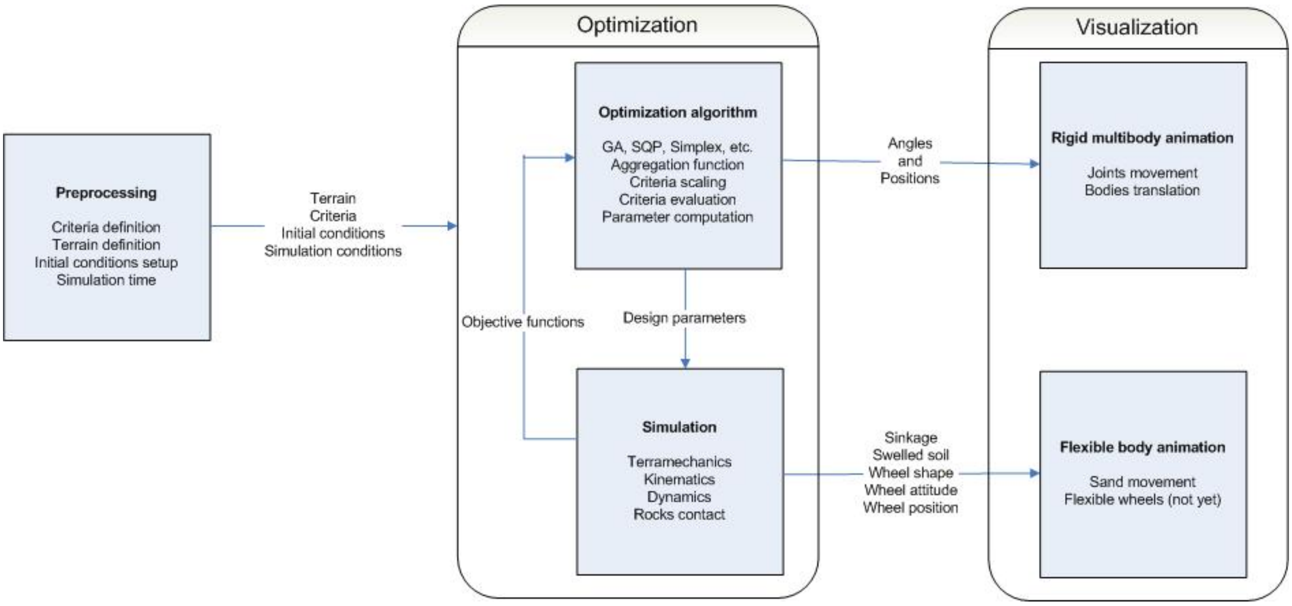


Figure 12 – Steps inside the optimization tool.

Initially, the scenarios (terrain definition, vehicle initial location, and suspension/wheels states and simulation time) and the objective functions are defined in the preprocessing phase. The next step is the optimization loop, one of the several optimization methods available in MOPS can be chosen. The optimizer changes the design parameters and runs each scenario simulation to evaluate numerically the objective functions. At the end of the optimization, the results can be not only plotted, but also shown as animations of the optimized planetary rover driving on several scenarios and compared with some predetermined configuration to depict improvements.

The softwares used to implement the whole tool and the dataflow between them is shown in Fig. 13. Note, that the tool can also be used as a modeling tool (through contact models available in Dymola environment). One can understand Dymola as the modeling and simulation environment, MATLAB/MOPS as the preprocessing, optimization and interface environment, and Blender as the rendering environment.

The inputs to the whole process are three:

1. A MBS model
2. Simulation scenarios
3. Desired objective functions to be optimized

The outputs of the whole process are:

1. A robust optimal planetary exploration rover
2. Graphs showing its performance (parallel coordinates, bar plots and time plots)
3. Animations showing performance and comparison with other designs

CONCLUSIONS AND FUTURE WORK

This work has focused on first steps optimize conceptual planetary rover designs w.r.t certain objective funtions. Optimization is based on a Multi-Objective Parameter Synthesis approach, that is capable of handling several objective functions such as mass reduction, motor power reduction, increase of traction forces, rover stability guarantee, and more. The optimization tool is still in development and the first version is not yet fully available. However, further improvement in the optimization capabilities, of the simulation models and new visualization options are well defined for future implementations. Further assets will also deal with various kinematics of the suspension system to find optimal solutions.

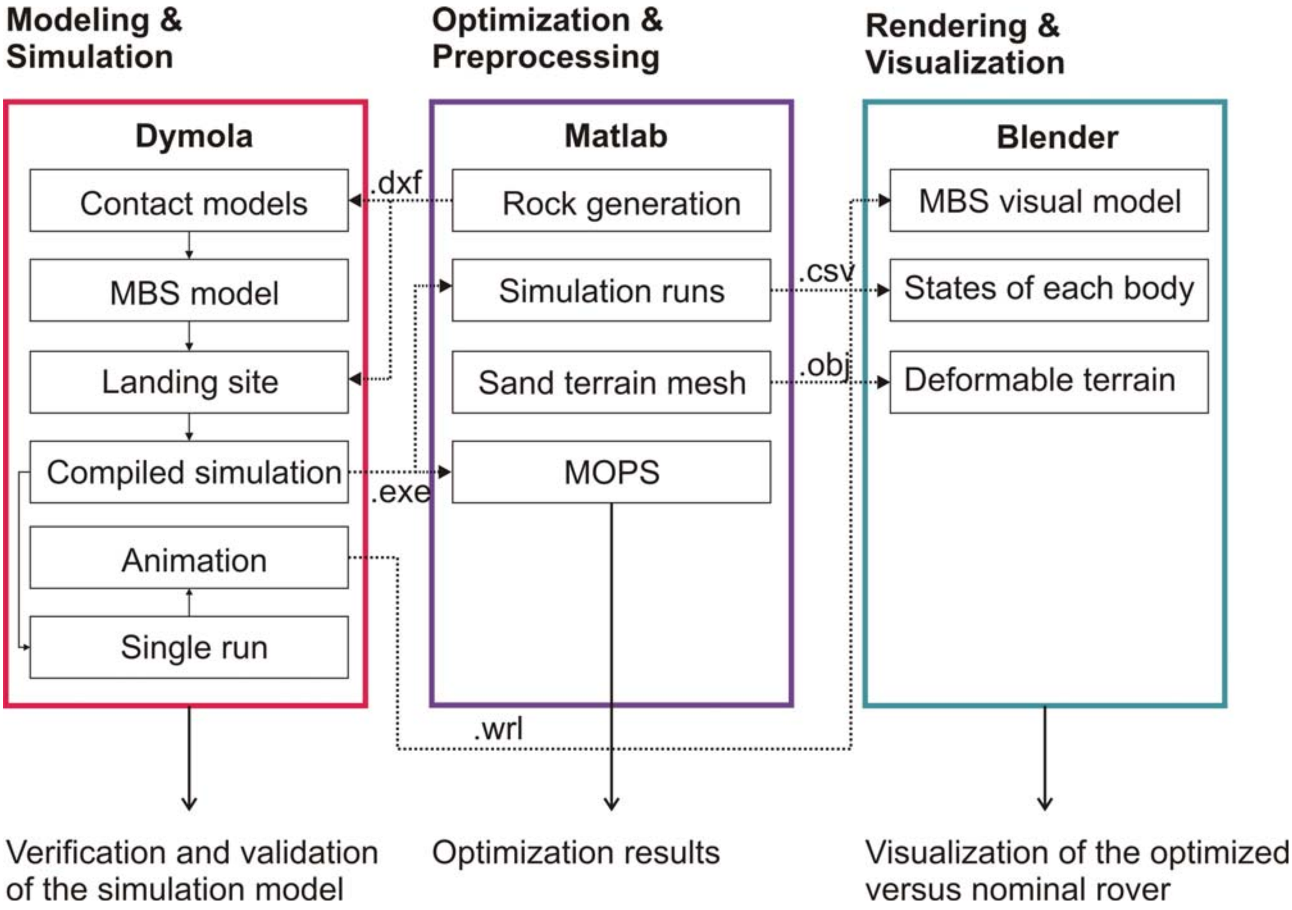


Figure 13 – Dataflow in the optimization tool.

ACKNOWLEDGMENTS

The authors wish to gratefully acknowledge the support by DAAD, the German Academic Exchange Service (Deutscher Akademischer Austauschdienst), to financially grant the stay of guest scientist Alexandre Carvalho Leite at the DLR Institute of Robotics and Mechatronics.

REFERENCES

Apostolopoulos, D. M., 2001, “Analytical Configuration of Wheeled Robotic Locomotion”, PhD Thesis, Carnegie Mellon University, Pennsylvania, USA.

DLR, 2010, “Mars-Rover im Prüfungsstress”, http://www.dlr.de/desktopdefault.aspx/tabid-6221/10233_read-27122/.

Krenn, R., Gibbesch, A. and Hirzinger, G., 2008, “Contact Dynamics Simulation of Rover Locomotion“, Proc. i-Sairas, 9th International Symposium on Artificial Intelligence, Robotics and Automation in Space, Los Angeles, CA, USA.

NASA, 2010, “National Space Science Data Center”, http://nssdc.gsfc.nasa.gov/.

Papadopoulos, E. G. and Rey, D. A., 1996, “A New Measure of Tipover Stability Margin for Mobile Manipulators”, In IEEE International Conference on Robotics and Automation (ICRA’96), Minneapolis, USA.

Schäfer, B., Gibbesch, A., Krenn, R. and Rebele B., 2010, ”Planetary Rover Mobility Simulation on Soft and Uneven Terrain“, J. Vehicle System Dynamics, Special Issue, Vol. 48, pp. 149-169.

RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.