Planetary Rover Mobility Performance Simulation Tool

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Abstract. Demonstrating, by reliable simulations, the mobility performance of a planetary wheeled rover system under all different kind of driving conditions, is an indispensable and essential asset for all kind of rover development phases. The underlying simulation method will be described, its capabilities demonstrated, and the validation process be discussed based on available but limited testing. First correlation results with experiments obtained from testbed runs will be presented for the current development of ESA's ExoMars rover. The simulation tool makes efficiently use of a multibody system dynamics approach for the rover chassis and locomotion system, in conjunction with efficient contact dynamics description for the important interaction between the flexible wheels and the rigid and soft soil characteristics.

INTRODUCTION

The demonstration of rover mobility performance is extremely necessary to guarantee for mission success, not only for the development phase of the flight model rover. In ground-based testbeds, the unknown essential model parameters have to be experimentally extracted by numerous tests, while making use of modern and fast identification routines (off- and on-line). These tests have to be performed under very different specific requirements, considering gradeability, driveability, uphill, downhill, and sidewards driving, overcoming obstacles, driving in sandy and fluffy surface soils, or in a more rocky terrain, or mixtures of all this. Also, injection of emergency cases like broken wheel (refer to NASA Mars Exploration Rovers, MER), is an important issue to be analysed by simulation.

At final completion of flight model rover development it is not guaranteed that mobility performance will meet the real planetary mobility characteristics. The reason is that mobility performance can be tested only in testbeds, where the underlying model parameters have been governed by intensive testing, or improper basic ones replaced by modified wheel-surface contact models. To be very close to planetary soil conditions, testbed terrain will have to be provided with soil simulants to best knowledge. Analysing Martian driving behaviour (MER rovers) will give us a first estimate of soil characteristics. Nevertheless, identical soil conditions never can be established on ground. As a consequence, the simulation tool has to be validated against the conditions found in testbeds. Once this tool has been validated based on conditions given on ground, the step forward to simulate actual planetary surface conditions for wheel-soil contacts is therefore very straightforward. Reliability in rover mobility performance under planetary surface conditions is therefore highly increased.

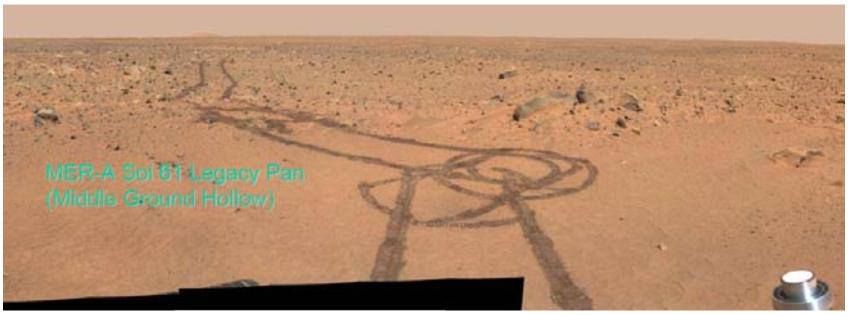

Fig. 1. Opportunity (MER-B) wheel tracks: by Navcam (left) and by Pancam observation (right) [1]

DLR's Institute of Robotics and Mechatronics has a long experience in modelling and simulation of vehicle dynamics based on multibody system approach involving rigid and elastic parts of chassis and locomotion subsystem. Moreover, for off-terrain driveability, such as aircraft landing in rough terrain outside runways, we have already started to model properly contact dynamics between wheels and soil. We have applied and extended these first approaches within the ExoMars project, where DLR is responsible for the modelling and simulation of the overall dynamics behaviour of the whole vehicle, specifically of the interaction between the wheels and all kind of planetary surface conditions. The simulation tool development has neared its final completion now. This paper describes briefly the important need for combining a multibody dynamics system tool [2] with an efficient model approach for the wheel-soil contact dynamics, for any kind of terrain consistency, be it rigid, soft or a combination of both [3]. The capability of the 3DS (3 dimensional simulation) tool is presented, and first results concerning the validation and verification (V&V) process are given.

ASPECTS OF MOBILITY AND LOCOMOTION MODELLING AND SIMULATION

The interaction between the rover wheels and the uneven and very different surface terrain conditions will affect locomotion performance and rover stability strongly. Moreover, these terrain conditions are expected to change very often and possibly rapidly during motion, ranging from soft and sandy soil characteristics over soil types of medium characteristic like pebbles to very hard ones consisting of smaller and larger rock sizes. Valuable information and data on terrain characteristics and rover performance can be gathered from the two NASA MER rovers. Typical examples of wheel tracks on sandy and pebble terrain are depicted in **Fehler! Verweisquelle konnte nicht gefunden werden.** and **Fehler! Verweisquelle konnte nicht gefunden werden.**

Fig. 2. Opportunity (MER-B) wheel tracks taken by Navcam observation [1]

As an important consequence, the development process has to rely to a very large extent on accurate and reliable modelling and simulation work. In this context, 3D simulation of the complete rover and its interacting surface environment plays a key role in the development process. This has to be completed by performing numerous and versatile hardware tests in order to simulate, by the combination of hardware and software, the real conditions to be expected for the Flight Model.

Verification of the underlying mathematical models and their implementation in an efficient and powerful simulation tool is therefore a must to be performed during all project phases, and for all individual rover units to be modelled and simulated. Validation has to take place by comparing computer results with test results that are obtained in different test scenarios, starting from single wheel testing to the full rover model testing (system level testing). Mathematical model update (or even better models may have to be used) by parameter tuning is supposed to happen all the time, which turns Verification & Validation (V&V) to a very cumbersome and dominant task.

Only this combination of comprehensive testing and model adaptation, update, and efficient computer code generation will finally guarantee for the achievement of a highly confidential rover Flight Model. Moreover, this methodology allows to reduce the burden of building several (or too many) development rover models through all the project phases. However, the models to be developed and used, of course, try to account for certain known and dominant effects that are to be expected for the complete rover dynamics, its locomotion behaviour and operational performance. These are mainly:

- modelling the rover chassis by multiple rigid bodies,
- adding some kind of spring and damping properties to hinges (if necessary)
- modelling of flexibility in wheel
- modelling of contact dynamics (Polygon Contact Model, PCM, and Soft Soil Contact Model, SCM) for hard (or rigid) and soft soil characteristics

- modelling special wheel-soil properties like bulldozing and multipass effects
- modelling of soft soil properties when impacted during rover passes like wheel tracks, soft soil displacement, deposition and erosion (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

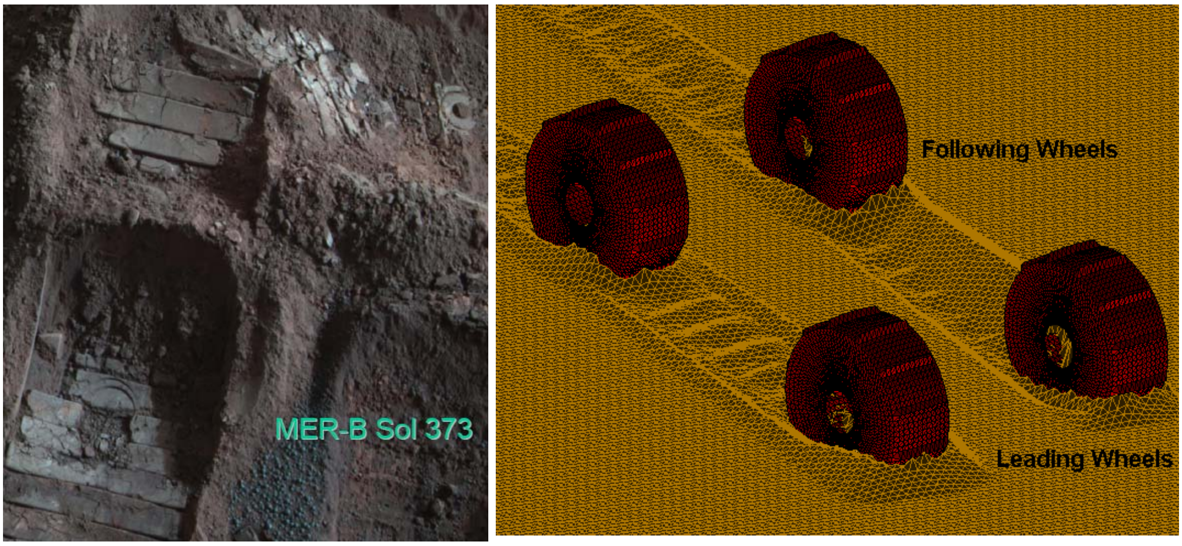

Fig. 3. The reality (left): zoom to Opportunity (MER-B) wheel tracks taken by Pancam observation [1]; and a first simulation approach (right) [3]: showing soft soil properties during rover multipasses (here presented without chassis set-up for better visualisation), i.e. wheel traces, soil displacement, soil deposition and soil erosion

DEMONSTRATION OF THE 3D SIMULATION CAPABILITIES

In Fig. 4 examples for two major applications of PCM and SCM for planetary rover simulations are presented: (1) the rover is moving on rigid terrain over arbitrarily shaped rocks of different sizes, modelled by the PCM method, and (2) the rover is moving on ideally soft terrain upwards on an inclined plane with increasing slope angle, until it gets stuck, modelled by the SCM method. The SCM simulations allow the possibility to assume completely loose and incompressible soil with hundred percent of soil displacement according to the sinkage volume of the wheels. In this case the multipass effect in terms of force reduction is negligible since the soil displaced from the leading wheels flows back into the track, and therefore the wheels following inline have to roll against a similar drawbar pull as the leading ones. Moreover, bulldozing effects are also of major importance for calculating driving force resistances. This impressive behaviour is clearly presented in Fig. 4 (right). The driving performance for a combination of rigid and soft terrain is shown in Fig. 5.

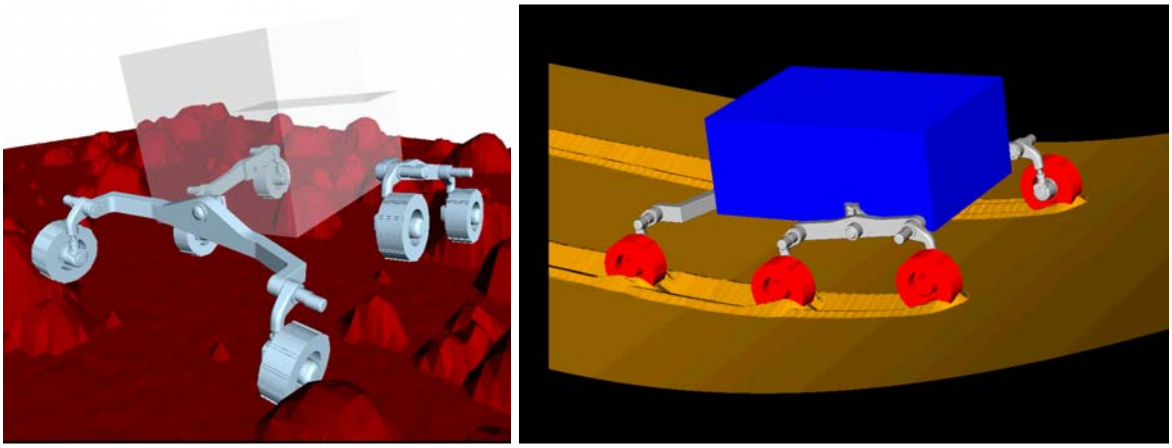

Fig. 4. Simulation of rover driveability on rigid terrain with rocks (left), and on soft soil (right)

In more realistic cases, we are also able to model and simulate a partially compressible soil, whereas both parts of soil compression and of soil displacement can be adopted appropriately. The proper share has to be obtained out of numerous experimental testing. In these cases, the important multipass effect can be clearly detected within the results for compressible soil. As expected for these cases, it comes out that the rolling resistance for the following wheels is significantly lower than for the leading ones, caused by the reduced drawbar pull of the following wheels. Moreover, the expected wheel grouser influence on increased drawbar pull is also an important result of the underlying models that account for multiple contact points between wheels and terrain.

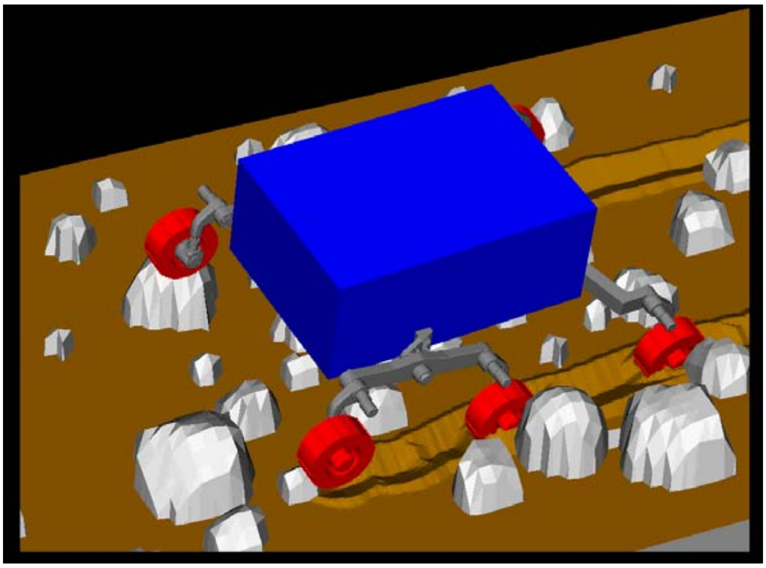

Fig. 5. Simulation of rover driveability on a combination of rigid terrain with rocks and soft soil

VALIDATION AND VERIFICATION ASPECTS

To adequately perform V&V, we have to distinguish between software tools and models or applications. In principle, V&V is required for both: software tools and MBS (rover) models. The first step is to prove that the software tools are able to describe the behaviour of interest. Simpack is an off-the-shelf MBS software tool and need not to be validated. Therefore, only the wheel-soil contact modules SCM and PCM have to be validated. The SCM deals with soft soil whereas the PCM covers contact dynamics of rigid bodies. These three software tools are shown in the 3D MBS Simulation block of Fig. 6. Together they form a complete model and the simulation environment can be used for various applications and models, respectively. Typical models are

- Benchmark simulation and simplified test setup
- Single wheel test setup, for both rigid wheel and flexible wheel
- Rover models, such as BB (Breadboard Models), DM (Development Models), EQM (Enhanced Qualification Model), FM (Flight Model).

Validated software tools are a basic requirement but do not guarantee for a validated rover model. We have to assure that the software tools allow for modelling of the overall motion behaviour of planetary rovers. Therefore, the next step is to prove that the simulation package is capable of predicting the behaviour of a planetary rover. This is done by means of the first available BB model (in the present case this is the BB1 model of ExoMars Phase B1) and correlating the test and simulation results respectively. Another important step is to prove that the modelling is performed correctly, and the software tools are used properly, respectively. We have to ensure that we build the right rover model and that we use the right model parameters.

It can be assumed that all ExoMars rover models (BB1, DM, EQM, FM) show a similar motion behaviour. For each rover model a validation by comparing with preceding and validated models and a plausibility consideration, respectively, allow a validation prior to the availability of any hardware items for testing. Where applicable, a final V&V will be achieved by correlation of test data and simulation results.

Fig. 6. gives an overview of the entire V&V process. The single blocks contain the modules that are necessary to perform V&V in the right way. Four main blocks have been identified:

- Testing in Testbed
- External Interfaces

- 3DS Simulation
- Static tests.

The main issues here are dedicated to the soil properties, i.e. soft and hard soil, and to the wheel and chassis properties, i.e. single wheel and entire rover testing.

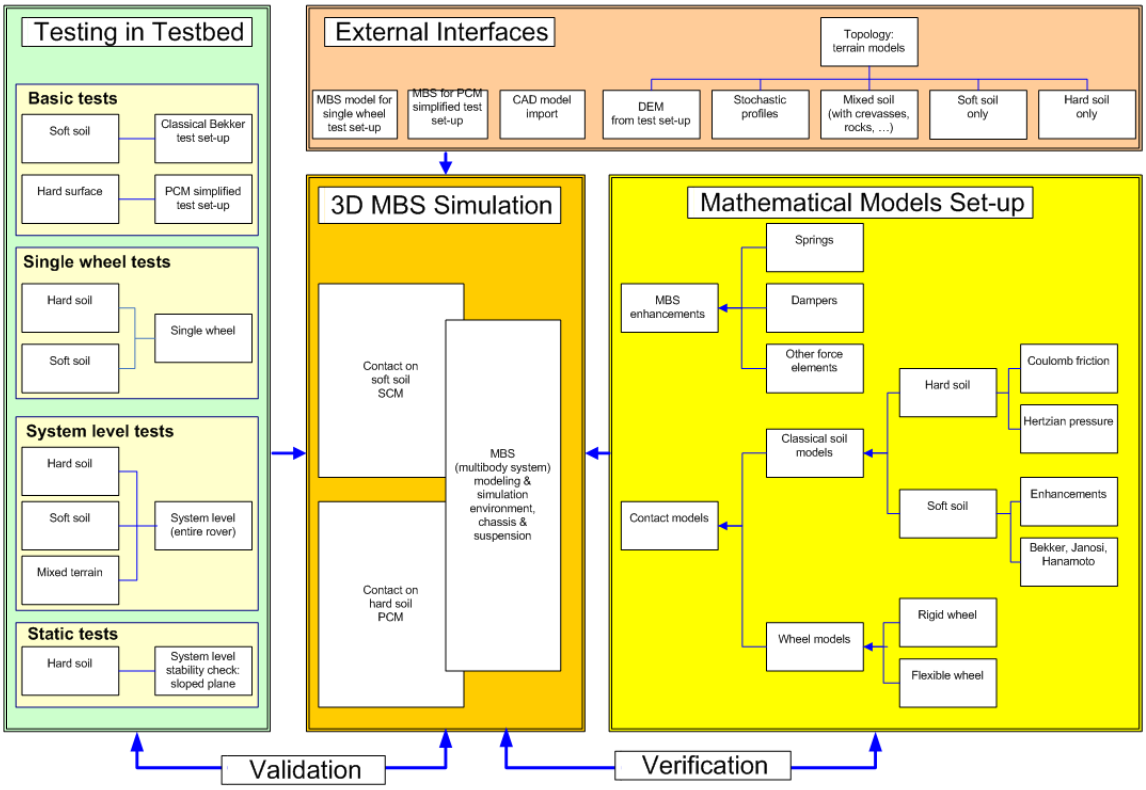

Fig. 6. V&V overall architecture

The block **External Interfaces** is concerned with initialization issues in order to start the modelling and simulation blocks. It comprises, first, the generation of the test setup, the terrain geometric shape or the body structure. It has to be mentioned that this step deals with the terrain geometric shape alone and not with the soil properties of the terrain. This covers terrain models created by a digital elevation mapping (DEM) process from real terrain data given by the hardware testbed, or simulated terrains by means of Matlab/Simulink like. Typical examples are:

- Ideal model of test setup e.g. benchmark tests,
- DEM of real test setup e.g. including texture of rocks,
- Arbitrarily generated Martian terrain.

Another important topic is the CAD model import of the entire rover or sub-systems of it. Next, this block comprises the various aspects of defining the properties of different terrain models and the procedure to pass them to the 3D MBS simulation environment:

- Soft soil terrain, e.g. Bekker parameters
- Hard soil terrain, e.g. friction coefficient
- Mixed soil terrain.

Finally, this block includes all the external modules and corresponding interfaces e.g.

- Actuator,
- Actuator controller,
- Chassis controller,
- Path planning,

The block **Mathematical Models Setup** is the major block that deals with the wheel-soil contact models and the MBS enhancements. The important sub-block **Contact Models** covers the classical soil models and the wheels models. The soil models are concerned with hard soil, where Coulomb friction and Hertzian pressure play the dominant role, and with soft soil, that deal with

- the classical Bekker equations and their enhancements given by Janosi and Hanamoto [4],
- and other empirical enhancements of those models, if found necessary.

The block **3D MBS Simulation** is the dominant block that directly interferes with the **Testing in Testbed** block. Here, the entire simulation of the whole dynamics motion behaviour is to be run. It contains the SCM and the PCM simulation sub-blocks for soft and hard soil, and the entire MBS modelling and simulation environment that deals with the dynamics of the multiple bodies interactions of the chassis and suspension subsystems, including the wheels as a rigid or flexible system. Furthermore, this block contains the necessary numerical integration routines for solving the time behaviour of the underlying, strongly non-linear differential-algebraic equations behind.

It is this block that interferes on the other hand with the Mathematical Models Setup block, and hence the verification process between the two blocks has to take place. Before interfering with the Testing in Testbed block, the verification process will tell us whether the simulation results are plausible or not. It is not the aim of the verification process to tell us that we have achieved a good agreement/correlation with the experimental results. Verification is a process that deals with code implementation, based on the mathematical models, and with numerical uncertainties. It has to ensure that the code is implemented correctly and produces repeatable results (code verification), which can be tested in standardized problems with known or highly accurate solutions, or on different computer platforms. On the other hand, we are faced with quantifying the error of numerical simulations (calculation verification), which is typically accomplished by demonstrating the convergence for the particular model under consideration. Numerical errors cannot be completely removed. Therefore, as in code verification, test problems have to be established that quantify the numerical accuracy of the model. Applying the right numerical integration routines plays a major role in this context.

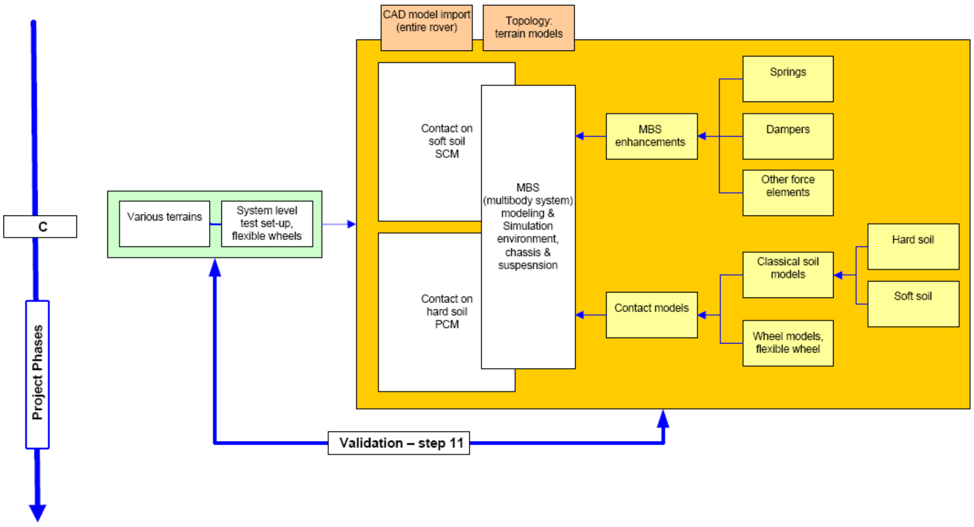

Fig. 7. Typical example for validation procedure: the final validation step (step #11)

Finally, the validation process has to be performed. This process takes place between the Testing in Testbed block and the 3D MBS Simulation block. This is the process of correlating the experimental results with the simulation results. Moreover, this process goes much farther and demands that the 3D MBS simulations are giving valid results (within certain limits, to be determined) for other realistic scenarios, that are similar to the ones used for validation and for which no test data are available. Importantly, this will be the case for flight rover motion behaviour on real Martian terrain. In case validation is not met, the process of validation has to be repeated multiple times. This procedure will also incorporate the verification process, since e.g. mathematical models may be updated or modified as well to meet the experimental results. Furthermore, the specific properties of the test setup may also be impacting the simulations results, which means that these properties have to be modelled in the right way as well.

In order to increase reliability in the validation task, the entire V&V process should follow a step-by-step approach. This means, we have to start from less complex validation scenarios, and proceed while adding more complexity to the system under consideration. Therefore, we have subdivided the V&V process into basic validation and enhancements thereof. Basic validation is achieved when it is proven that the minimum required accuracy is achieved for the benchmark tests and the validation scenarios. Not all the various validation steps are presented here: in total we have identified 11 steps with increasing complexity. As typical example, Fig. 7 shows the final validation step (step #11) covering the complete system level test set-up with the entire rover and the flexible wheels on arbitrary terrain type.

V&V FIRST RESULTS

Validation has been achieved for static stability purposes, where specifically the demonstration of stability on inclined planes under various rover yaw angles are of major interest. Fig. 8 shows the correlation results with experiments for flexible wheel modelling on a 15^o slope. Both, rigid and flexible wheels behaviour has been simulated, and only slight changes have been obtained while comparing both cases. The effect of this change results in a 0.5^o increased slope angle while accounting for flexibility in the wheels.

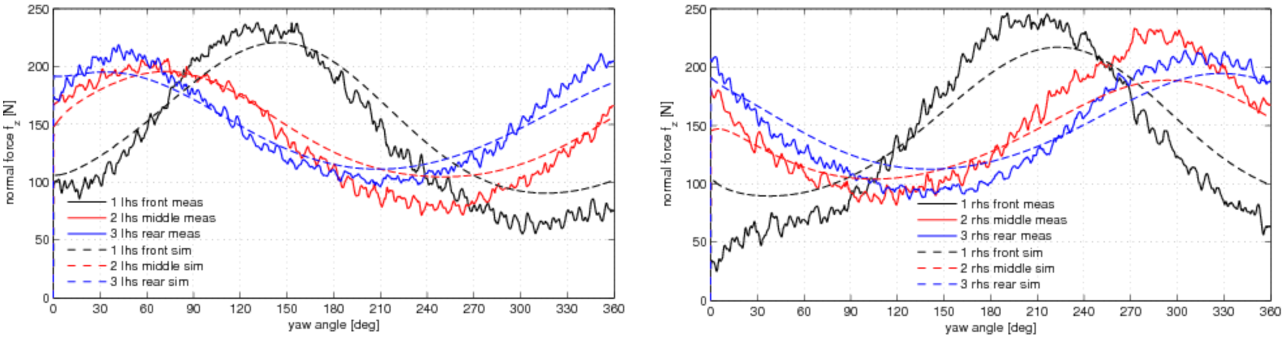

Fig. 8. Typical examples for correlation results of static stability on inclined plane, here for an inclination angle of 15^o: rover left hand side flexible wheels (lhs, left), and right hand side flexible wheels (rhs, right). Variational parameter (x-axis) is the yaw angle reaching from 0^o (rover straight forward in uphill direction) over 90^o (rover sidewards driving), to 180^o (rover straight forward in downhill direction), and finally back to the uphill direction (360^o). The plots show the wheel load forces that are normally directed towards the inclined plane.

Further simulations and comparison with experiments were performed demonstrating the static stability even for a 40^o slope. Pure simulations that have been performed for slope angles that reach beyond this slope angle limit of 40^o, even up to 44^o, show that stability is still maintained although one or two wheels may loose contact.

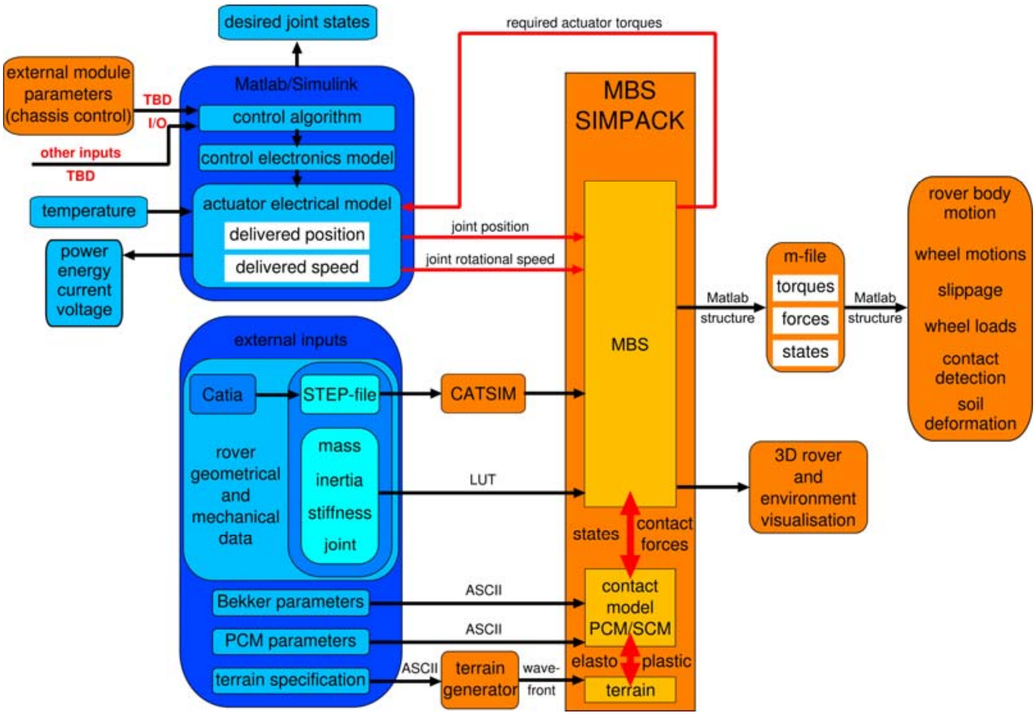

Fig. 9. Simulation architecture and interfaces

Besides static stability performance demonstration, the motion behaviour analyses of the entire rover, that represents a complex multi-body system interacting with hard and soft terrain, is still ongoing. For validation purposes, we are still lacking of profound experiments to be performed for various soil characteristics and operational trajectories. Although the simulation results obtained so far are very promising in terms of having achieved the right approaches for the interaction phenomena, there is still correlation work to be followed in order to match with the right contact parameters.

SIMULATION ARCHITECTURE

In Fig. 9. the full closed loop 3D MBS simulation architecture is depicted. The colour definition is as follows: orange for 3D MBS with additional inputs, and blue for all external modules and inputs. This architecture represents the complete closed loop vehicle simulation environment with a full mechanical MBS simulation module, all external modules in the loop and all required outputs for post-processing. The main blocks within this architecture are:

- MBS Simpack block
- MBS outputs
- external control modules
- external module parameter inputs.

External module parameters inputs like simple navigation tasks and other external inputs have to be defined within the control design. The export of the internal MBS model can be performed via the code export functionality to provide full MBS performance for external users. Synchronisation within the simulation between Simpack and all external modules is performed by the Simpack internal co-simulation tool.

ROVER OPERATIONAL CONTROL CENTER (ROCC): EFFICIENT USE OF 3DS TOOL

Once the 3DS tool is established in its full performance use, it is recommended most importantly and being worthwhile to use this tool for further applications, lying outside of the scope of merely using it for developing the final FM rover. It is therefore desirable to appropriately adapt the 3D simulation environment for its use as an operational tool supporting the actual ExoMars mission during its operational phases on Mars surface. This refers to several aspects that are found necessary in order achieve a successful operations planning and performance on Mars, covered by the ROCC:

- to prepare pre-simulations of rover trajectories for optimal trajectory finding
- to perform post-simulations of driven trajectories
- to help isolating failures in case of non-nominal trajectories driven by the Martian rover
- to extract the right Martian soil parameters from driven paths
- and finally, to increase reliability into the next trajectories to be determined by the ground operator.

CONCLUSIONS

The use of a multibody dynamics tool in conjunction with efficient contact dynamics models for the important interaction between the (flexible) wheels and the rigid and soft terrains is a prerequisite to fully understand and simulate the behaviour of rover driveability. Moreover, the need for conducting numerous experimental tests with single wheel and on system level is a must in order to validate the modelling and simulation approach. Once validated, the 3DS tool should be able to predict reliably the motion behaviour of the rover on Mars. It is by this reason an essential supporting tool to help the operators on ground to plan the daily Mars rover trajectories, and to analyse the driven paths by post-processing in order to detect and isolate possible non-compliances.

REFERENCES

[1] L. Richter, et al., “Strengths of soil deposits along MER traverses”, NASA/JPL MER Athena Science Team, 2006.

[2] A. Gibbesch, and B. Schäfer, “Modelling of planetary rovers by means of a dynamical system approach with respect to mobility requirements”, 10th European Conference of the ISTVS 2006, Budapest, Hungary, October 2006.

[3] R. Krenn, A. Gibbesch, and G. Hirzinger, “Contact Dynamics Simulation of Rover Locomotion”, i-SAIRAS 2008 - 9th International Symposium on Artificial Intelligence, Robotics and Automation in Space, Los Angeles, CA, USA, 25-29 Feb 2008.

[4] Z. Janosi, and B. Hanamoto, “Analytical Determination of Drawbar Pull as a Function of Slip for Tracked Vehicles in Deformable Soils”, 1st Int. Conference on Terrain-Vehicle Systems, Turin, Italy, 1961.