Verification and Validation Process on 3D Dynamics Simulation in Support of Planetary Rover Development

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Abstract. For planetary rover development, 3D dynamics modelling and simulation of the entire mobility performance is required. For this reason, powerful simulation modules have been developed and tested that interact very efficiently with each other. These modules cover (1) the locomotion subsystem based upon multibody system dynamics of the whole rover including suspension, driving and steering actuators and wheel sub-systems, and (2) the important wheel-soil contact dynamics that considers very smartly the interaction with the different soft and hard soil characteristics. To establish and to increase reliability in the underlying models and the simulation outcomes, verification and validation of the 3D simulation tool has to be performed. This paper describes this process, gives first results, and presents the simulation architecture developed to demonstrate the complete rover mobility performance. Moreover, the use of this architecture goes far beyond of using it as a mere development support tool. Rather, it is excellently prepared to be used for hardware-in-the-loop simulations for guidance, navigation and control activities, and hence for trajectory planning, and for pre- and post-processing of real trajectories on Mars.

INTRODUCTION AND MOTIVATION

The development of any planetary mobility system, specifically a wheeled system like the ExoMars rover, is an extremely ambitious task, particularly when considering often short time periods to cope with all of the engineering tasks. The demonstration of mobility performance in all potential terrain topologies and worst case scenarios is therefore mandatory for all the development phases, starting from Breadboard Model to the final Flight Model development. The interaction between the locomotion subsystem (rover wheels, e.g.) and the uneven and very different surface terrain conditions (termed as 'terramechanics') 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 are partly available and first results can be gathered from the two NASA MER rovers.

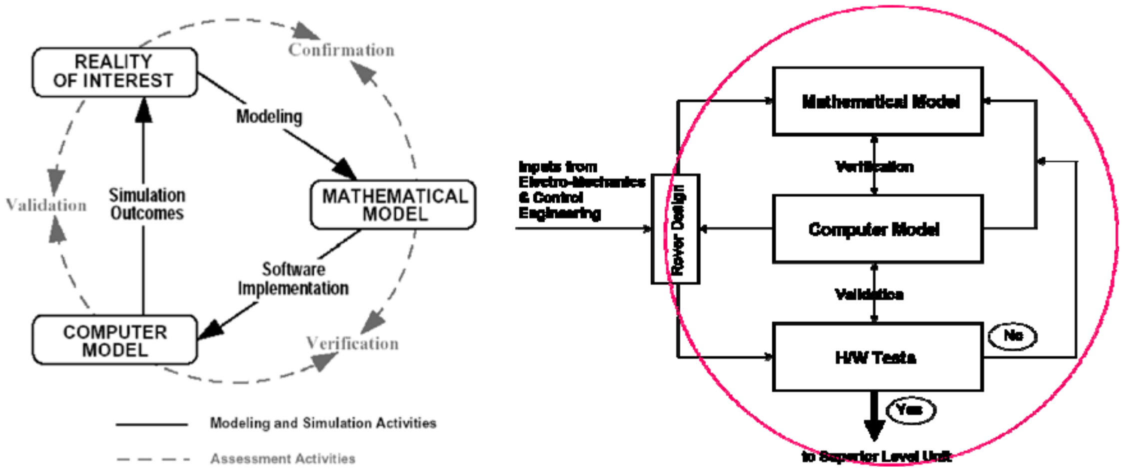

Fig. 1. Sargent cycle of model V&V process (left, [1]); V&V on component level (right)

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 mobile system and its interacting surface environment plays a key role in the development process. This has to be completed by performing numerous and versatile tests in order to evaluate, by the combination of hardware and software, the operational performance and the real conditions to be expected for the Flight Model. As a very typical example, the ExoMars rover development cycles are considered within this paper. The development predominantly will have to rely on precise mathematical models and their accurate and reliable integration within a 3D simulation environment. Furthermore, the close connection to the electrical and mechanical engineering development work has to be of high engagement and responsibility. A permanent mutual exchange of new engineering data is mandatory and has to be ensured in all phases [1-3]. In this context, the terms verification and validation (V&V) for modelling and simulation will draw a dominant role (Fig. 1, left). Fig. 1, right, gives the scheme showing the V&V process on component level.

The paper first treats the tasks to obtain sufficient reliability in the modelling and simulation part by adequately applying V&V processes in a step-by-step manner. Then, first results on V&V steps will be briefly given. Finally, the underlying simulation architecture is to be addressed and discussed in more detail.

VALIDATION AND VERIFICATION

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 (multibody system, [4]) 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 contact dynamics modules have to be validated, i.e. the modules that represent the interaction between the wheels and the soil. These contact modules are referred to as SCM (Soil Contact Model) and PCM (Polygon Contact Model) [5]. 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. 2. 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).

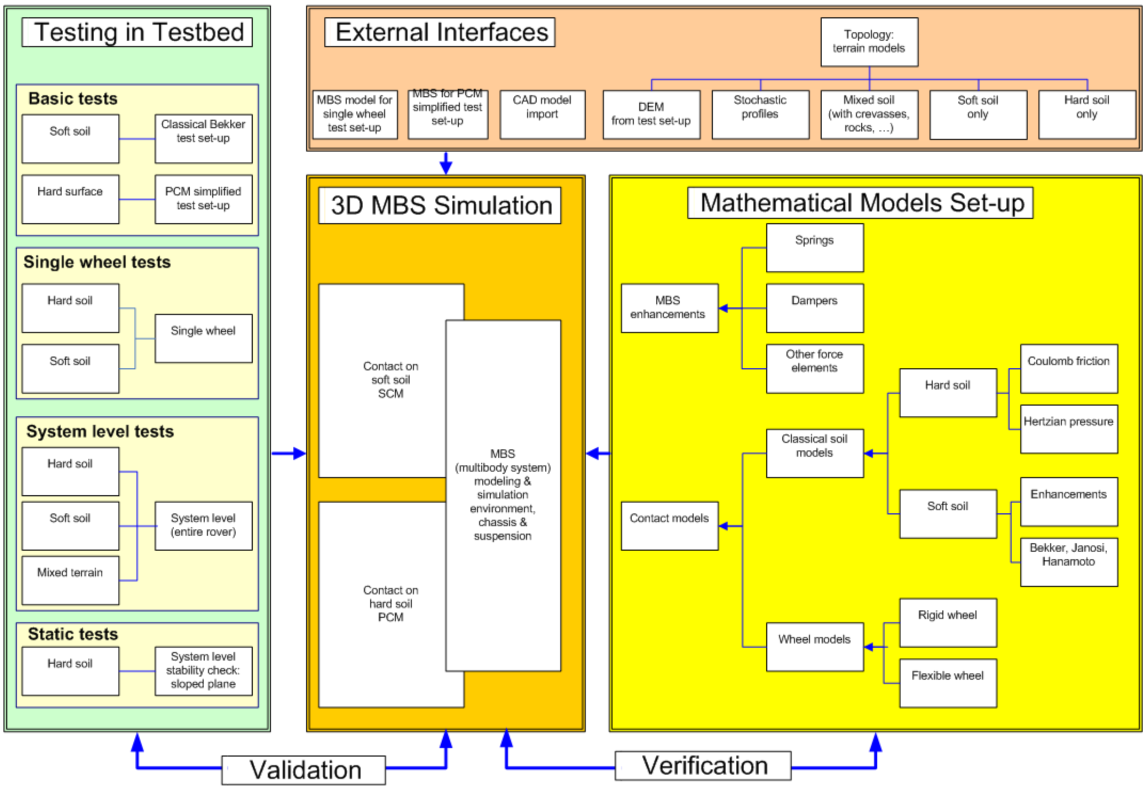

Fig. 2. V&V overall architecture

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. 2. 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.

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 [6],
- 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 [1-3]. 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.

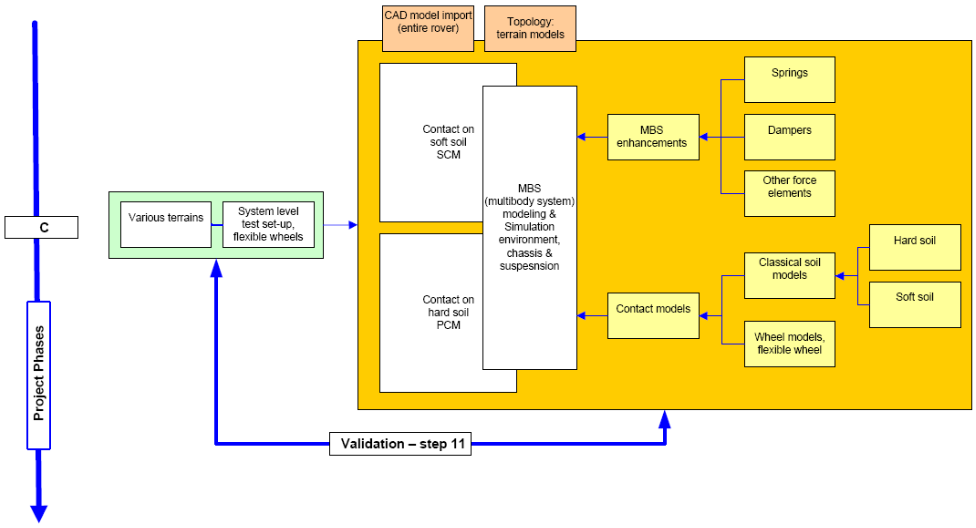

Fig. 3. Typical example for validation procedure: the final validation step (step #11)

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 in order 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. 3 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. 4 shows the correlation results with experiments for flexible wheel modelling on a 15° 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° increased slope angle while accounting for flexibility in the wheels.

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

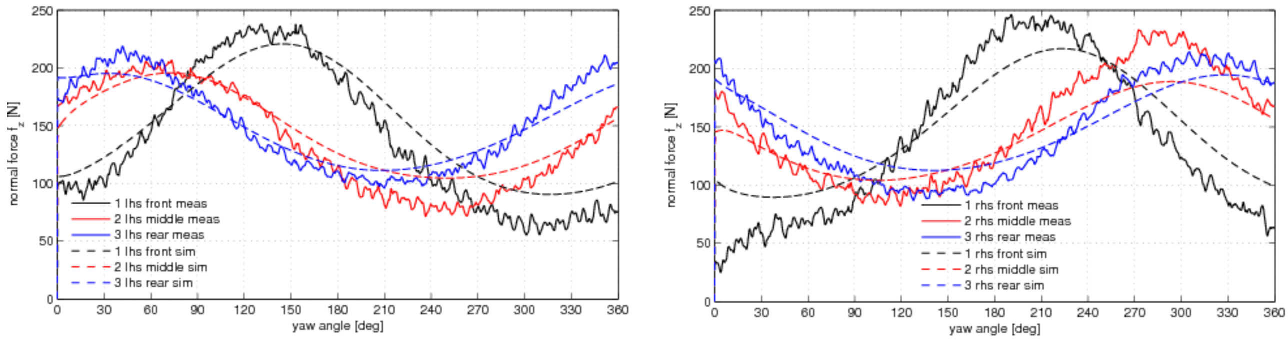

Fig. 4. Typical examples for correlation results of static stability on inclined plane, here for an inclination angle of 15°: rover left hand side flexible wheels (lhs, left), and right hand side flexible wheels (rhs, right). Variational parameter (x-axis) is the yaw angle reaching from 0° (rover straight forward in uphill direction) over 90° (rover sidewards driving), to 180° (rover straight forward in downhill direction), and finally back to the uphill direction (360°). The plots show the wheel load forces that are normally directed towards the inclined plane.

SIMULATION ARCHITECTURE

The underlying simulation architecture is described in the following. The first step is to model the ExoMars rover and to define the interface (settable parameters and dataflow, Fig. 5). Next, the properties and default parameters are set. Finally, Simpack allows exporting the 3D MBS dynamic model in form of an executable or a Matlab S-function. It shall allow running the dynamic model without the entire Simpack environment or as a stand alone application, respectively.

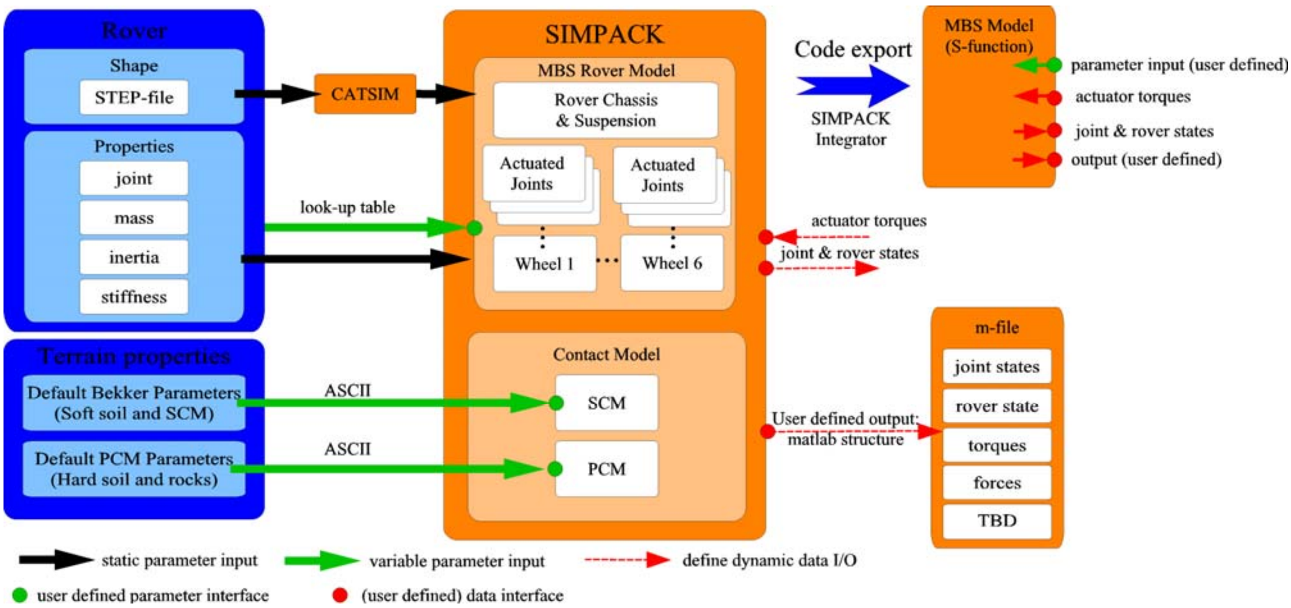

Fig. 5. MBS rover modelling and code export

The preferred option is to generate a Matlab S-function but creating an executable seems also a suitable solution. For simplicity only the term S-function shall be used in the following. The S-function can be easily integrated in the overall Matlab simulation environment. By creating the S-function the interface and the variable or I/O parameters respectively are fixed/frozen. No further modification to the S-function interface is possible. If additional properties shall be accessible or variable, e.g. a modification of the mass of a subassembly is required, code export is required and a new S-function has to be created. Different primary terrain descriptions can be included in the simulation environment (Fig. 6). Sources of primary data files are e.g. (1) data file based on image processing e.g. DEM and type, (2) Matlab data file created by terrain generator e.g. for arbitrary Martian terrain, or (3) user defined terrain (TBD). The primary data file shall contain (1) a digital elevation model formed from a regular rectilinear grid of height posts, or (2) a *t*errain type associated with each height post. The first step is to split the primary data file into sub-terrains, each sub-terrain consisting of elements of uniform terrain type. Next, the sub-terrain data file is converted into wavefront format. Finally, the final data file (wavefront file) of each sub-terrains and the associated terrain type will be stored in a data base.

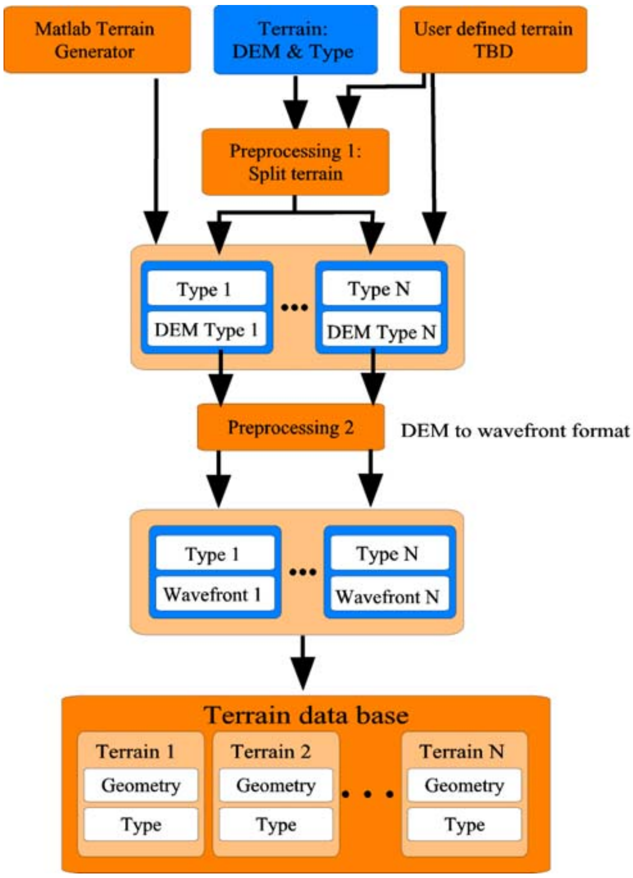

Fig. 6. Set-up of terrain data base

For each simulation run, the variable model and simulation parameters can be modified (Fig. 7). This allows evaluating different simulation scenarios and rover designs, e.g. by varying the CoM (Center of Mass) of the rover body.

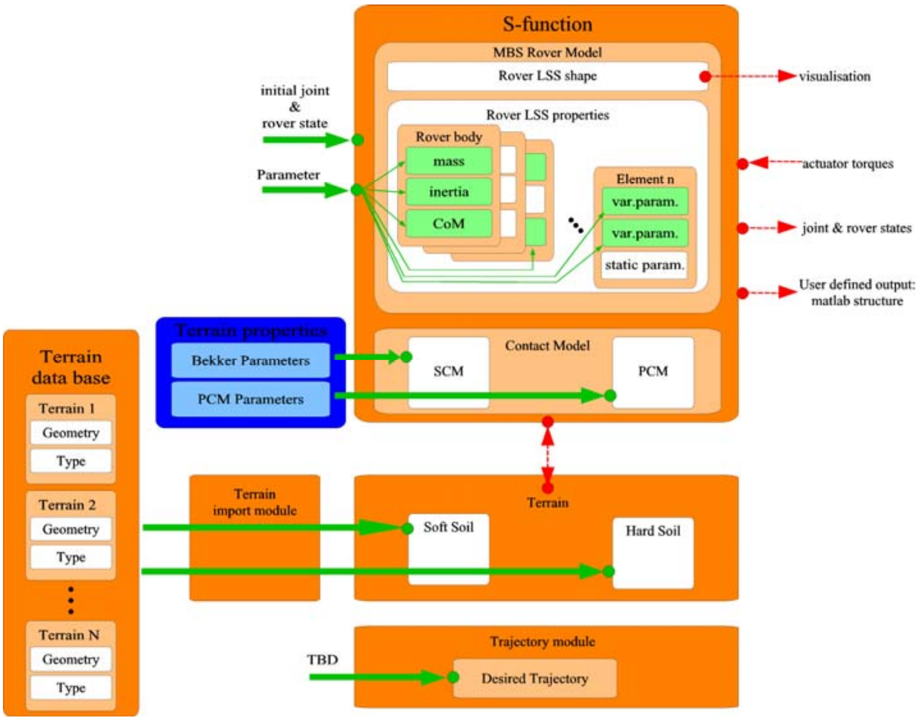

Fig. 7. Set-up of model parameters and model properties

At run-time (Fig. 8), the 3D rover dynamics model has to interact with the external modules and the terrain. Next, the MBS model has to provide all desired information for pre-processing and analysis.

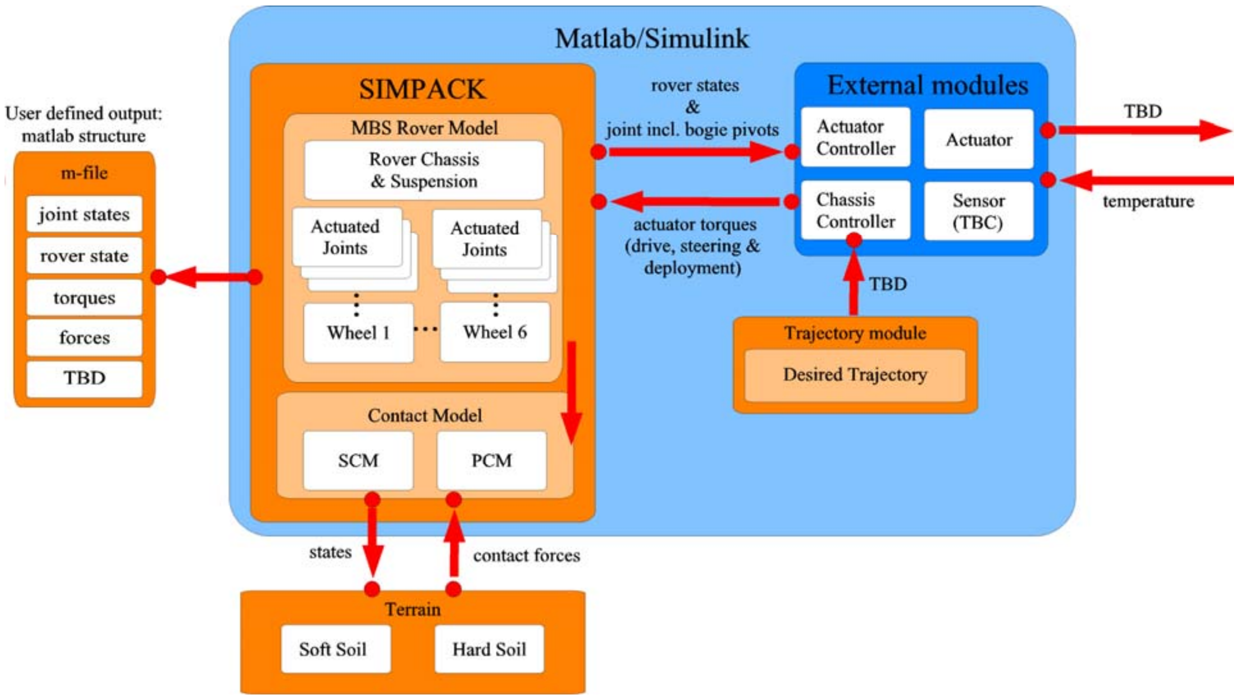

Fig. 8. Simulation at run-time and data flow

If code export will not perform satisfactorily or even successfully, a back-up simulation architecture is proposed that takes advantage of the so-called co-simulation method (Fig. 9). In this case, the full Simpack model is to be provided, and the external Matlab modules will be integrated via co-simulation.

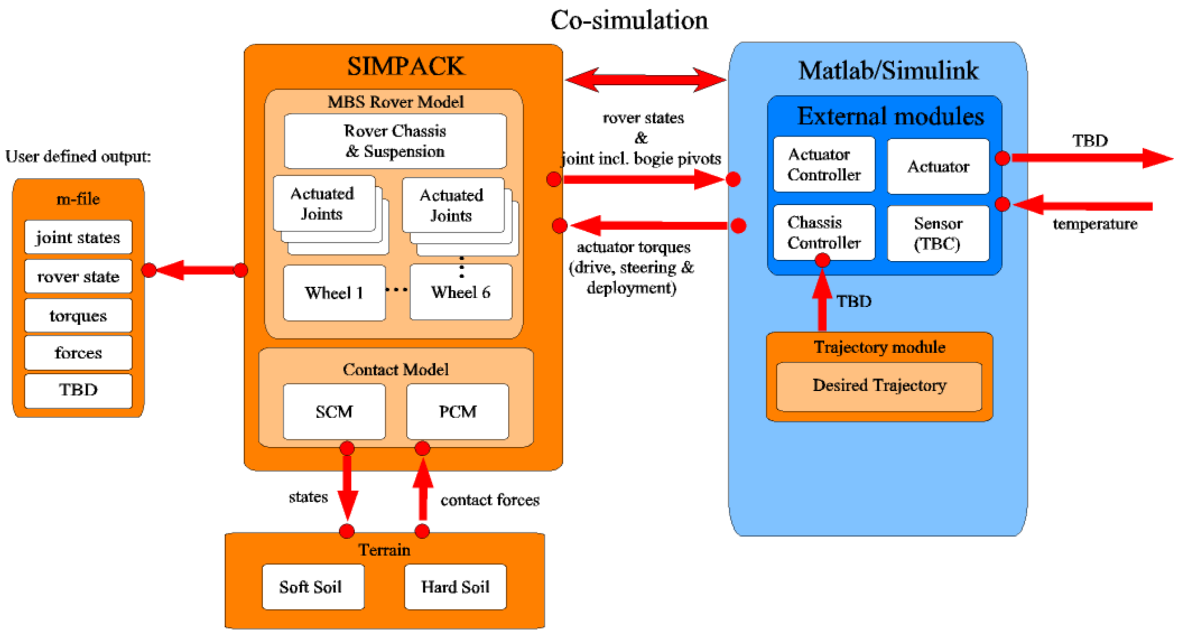

Fig. 9. Back-up solution: MBS simulation based on Simpack and co-simulation

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. 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.

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