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Heterogeneous, multi-tier wheel ground contact simulation for planetary exploration

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ABSTRACT

Today's growing scientific interest in extraterrestrial bodies increases the necessity of extended mobility on these bodies. Thus, planetary exploration systems are facing new challenges in terms of mission planning, obstacle and soil traversability. In order to fit the tight schedules of space missions and to cover a large variety of environmental conditions, experimental test setups are complemented by numerical simulation models used as virtual prototypes. In this context we present an integrated simulation environment which allows for using different available contact models, ranging from simple but real-time capable approximations based on rigid-body modeling techniques up to very accurate solutions based on Discrete Element Method (DEM). For this work, a one-point Bekker based approach and the so-called Soil Contact Model (SCM), which is a multi-point extension of the BEKKER-WONG method taking soil deformation into account, are used. These two contact models are applied for homogeneous models with only one type of contact model for all wheels as well as for a heterogeneous multi-tiered model with different contact models for the wheels. It will be shown that the multi-tiered approach enhances the simulation result accuracy compared to the results of a homogeneous model with a low level of detail while speeding up the simulation in comparison to a homogeneous higher tier model.

Keywords: Wheel-Ground Interaction, Terramechanics, Soil Contact, Planetary Exploration.

1 INTRODUCTION

In order to further understand the formation of planets and our solar system, planetary science requires extended mobility for the exploration of extraterrestrial bodies. Therefore, the locomotion sub-systems enabling planetary exploration are facing new challenges in terms of durability, mission planning, obstacle and soil traversability. Testing in the actual environmental conditions is often very expensive and time-consuming or not even possible. Additionally, environmental conditions on the site of operation are often uncertain and not well-known beforehand. Thus, in order to fit the tight schedules of space missions and to cover a large variety of environmental conditions, experimental test setups are complemented by numerical simulation models used as virtual prototypes.

In this context we present an integrated simulation environment for the heterogeneous simulation of the wheel ground contact using tiered contact models, specially designed for planetary rovers. These models range from simple but real-time capable approximations based on rigid-body modeling techniques, over penetration and soil deformation approaches, to very accurate but slow particle methods. Having these different techniques available in one environment allows us to directly compare results and to use them in conjunction with each other. We will show how this approach can on one hand be used to improve the simulation accuracy of faster simulation techniques and on the other hand improve the simulation speed of more accurate techniques. The different tiers will be explained in detail, tangible comparisons are given and their respective applications for current planetary exploration missions, as well as their limits are discussed. In this context we also discuss a future verification of our simulation models.

The comparisons of single homogeneous and multi-tiered heterogeneous wheel ground contact will be carried out using our in-house Soil Contact Model (SCM). This previously verified Model is still capable of being used in the efficient computation times of multi-body dynamics and is thus used as the highest tier. In conjunction with SCM, a lower tier, single point contact model is used in order to speed-up full system simulations and thereby to support applications reaching from control design to actual mission planning. The most detailed DEM models are taken into consideration for future enrichment of lower tier models as well as for the usage in the multi-tier environment. The particle-based models are still found to be too computational expensive in order to efficiently use them in large scale, full system simulation.
Hence, this article is aimed to be a first feasibility study for multi-tiered wheel-ground contact, as well as to exemplify its advantages and raise questions in this field.

2 THE DLR ROVER SIMULATION TOOLKIT FOR MODELICA

Modelica is a multi-physics, object oriented modeling language. Base objects are defined by equations and interfaces, which are then assembled into larger, more complex objects, which again might be part of an even larger component. In this way very large and complex multi-physics systems, spanning multiple domains, such as mechanical and electrical, can be modeled consistently and simulated subsequently.
The DLR Rover Simulation Toolkit is a Modelica library covering all relevant physical subsystems of a planetary rover, such as drive-trains, sensors and electrical systems, with a special focus on locomotion in general and the wheel-ground contact in particular. Using Modelica allows us to utilize a large number of custom and commercially available libraries. The toolkit is designed

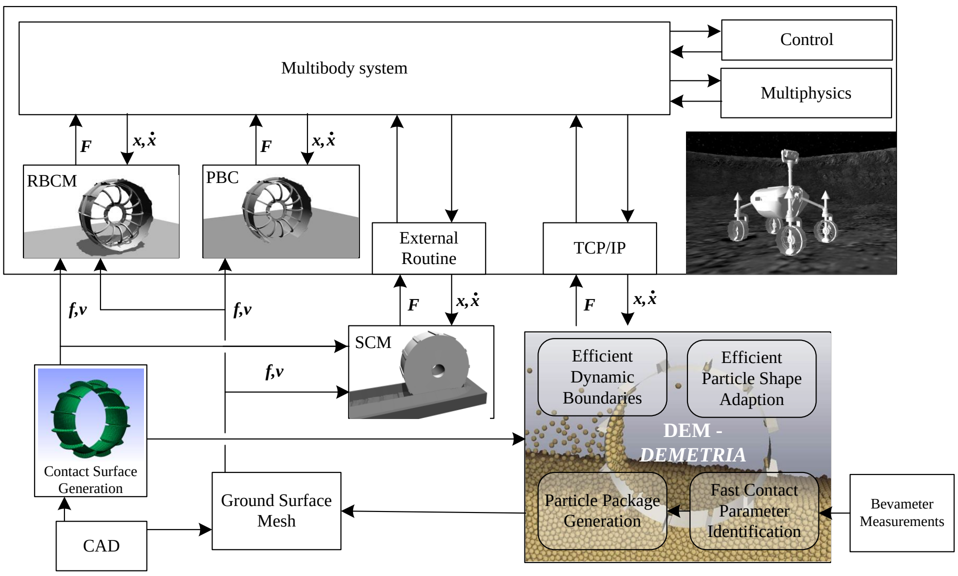

Figure 1. Structure chart of the overall simulation framework, showing the connections between its different parts.

to be essentially modular. All parts are replaceable by either different simulation models or HIL systems, with a standardized interface. Thus, it provides an ideal environment for the following investigations. The structure and adaptability of the framework is illustrated in Fig 1, showing the setup with focus on ground contact simulation component. The Mulibody system (MBS) simulates the movement of the objects according to applied torques and forces. On the one hand this system is influenced by the simulation of the drive-train and attached systems, on the other hand by the ground contact. As shown, the ground contact models all use a common interface to the MBS. The MBS communicates the current position and orientation of the wheels, including derivatives, to the ground contact simulation, which responds with resulting forces and torques.

2.1 Rigid Body Contact

The simplest simulations of multi-body dynamics are typically based on rigid bodies only. Therein a rigid body is defined as an idealized, perfectly non-deformable object, independent of the external forces acting upon it. Connections, joints and contacts always maintain their imposed constraints and hard impacts between objects use impulse transfers to avoid any penetration. While neglecting many effects of real world objects, the results are still sufficiently accurate for many applications. The big advantage of this approach lies in the small required simulation time: with modern desktop computers even complex scenarios can be simulated in real-time, thus this technique is favored in animation and gaming industry [1] [2] [3].

2.2 Penetration-based single point Penalty Models

More accurate results can be achieved by incorporating the deformability of real bodies. Depending on the simulation focus, joints or contact and impact points are modeled by adding virtual spring damper elements. For simple contacts only the penetration depth is taken into account. Especially critical for the real-time capability are multiple such virtual spring damper elements in a serial configuration and stiff contacts, as required for the accurate simulation of many real world materials [3]. The rigid body and penetration-based approaches are compared in Figure 2. Both approaches feature single point contact detection between a contact sphere of constant radius and a CAD surface, but can be adapted to surface-surface contacts. Effects like grouser-induced effects and soil displacement are not covered by these models, as they are not directly dedicated to terramechanics. Thus, they are mainly used for real-time applications and first estimates in early mission phases. Furthermore, the rigid body approaches are suitable for the simulation of hard contacts between wheels and stones. In order to cover the forces and torques, as well as

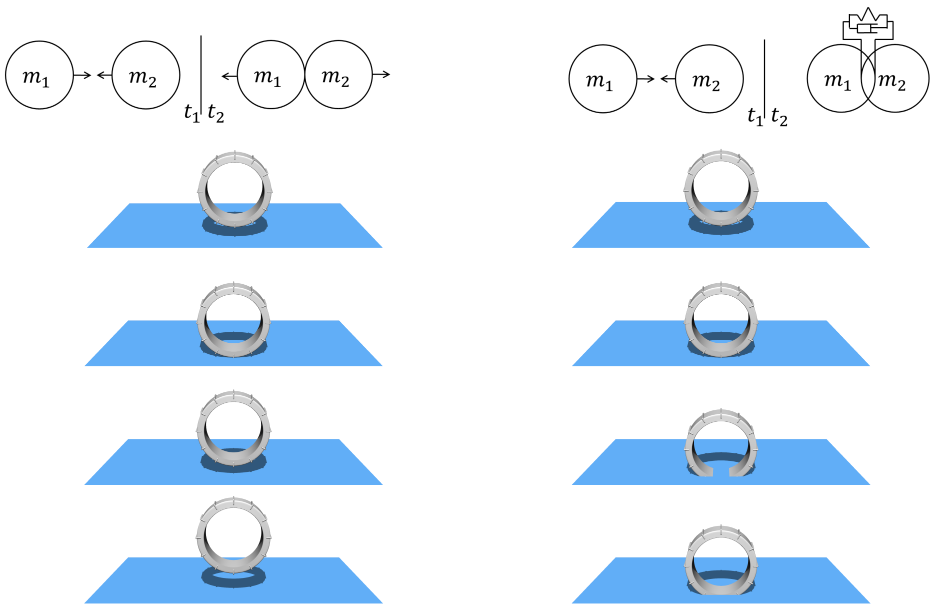

Figure 2. Rigid-Body model and penetration model for Wheel-Ground contact simulations - Left side: impulse transfer, right side: virtual spring damper elements; top: abstract depiction, below: example time series of a dropping and bouncing wheel

the sinkage behaviour of locomotion in soft, sandy soils, the well known BEKKER-WONG theory is applied in our framework. Therefore, several contact points can be taken into account to cover the contact between cylindrical wheels and non-convex surfaces. However the forces and torques are calculated with a single evaluation of the contact equations by averaging the position as well as the contact normal over all contact points. The extended BEKKER-WONG terramechanics model for the simulation of off-road locomotion is parametrized by seven parameters. These val-

ues characterize a specific soil and can be measured empirically using a specialized device called 'Bevameter'. We performed many empirical tests and possesed an extensive collection of parameter sets for different soils. The model is best known for its role in the design of the Lunar Roving Vehicle [4], but has found popularity in the development of planetary exploration rovers.
The model doesn't immediately prompt an implementation, but additional assumptions are necessary for a numerical simulation. Our implementation is based on the pressure-sinkage relationship, proposed by BEKKER as follows:

$$p = \left(\frac{k_c}{b} + k_\phi\right) z^n$$

(p: pressure, z: sinkage b: smaller dimension of contact patch, n, k_c, k_ϕ: BEKKER's soil parameters [5])
This may then be used in the calculation of the shear stress according to MOHR-COULOMB with extensions by JANOSI-HANAMOTO:

$$\tau = \tau_{\max}(1 - e^{-j/K}) = (c + \sigma \tan\phi)(1 - e^{-j/K}); \quad \sigma \equiv p$$

(σ: normal stress, τ: shear stress, ϕ: angle of repose, j: shear displacement, c: cohesion, K: shear deformation parameter)
Finally a multi-body simulation is used to determine the contact area between the locomotion system and the ground. Integrating the normal and shear stress over the contact area yields the resulting contact forces [6] [5]. Furthermore, we use a custom extension of this model to incorporate the effects of grousers based on RANKINE's passive earth pressure [7]. However the soil displacement by the wheel is not covered.
The model is suitable wherever fast simulations covering the basic effects of terramechanics are required.

2.3 Soil Contact Model - SCM

Up to this point the soil did not actually deform. However one of the most important effects for the simulation of planetary rovers is the plastic deformation of soil caused by the wheels. In our simulation framework we use the SCM (Soil Contact Model) algorithm for the simulation of soft soil contact forces and plastic deformation of the soil. SCM is a in-house developed, highly specialized, three dimensional, novel extension of the well known BEKKER-WONG method [8, 9]. The main features of SCM are:

- Surface contact between arbitrarily shaped objects,
- soil forces and sinkage calculated for every discretization node based on the BEKKER-WONG theory,
- plastic soil deformation covered by deformable surfaces,
- soil displacement by empirical flow field and erosion algorithm.

Analogue to the previously introduced models, SCM is based on surface contacts for both wheel and soil. In contrast to the single point contact models, which use the soil surface only for contact detection, SCM calculates the soil deformation and reaction forces at every single node in the contact patch. Therefore, only the nodes of the wheel grid are used to form a discrete BEKKER theory model.
The sinkage and normal pressure are calculated based on BEKKER's theory [5] by weighting the pressure distribution based on the centrality distribution over the contact area [9]. In order to cover plastic soil deformation and thus rutting, as visualized in Figure 3, the portion of soil within the footprint is disposed to the nearest-neighbor nodes outside the contact area. Thereafter the displaced soil is settled by an erosion algorithm iteratively. Thus, the maximum angle of repose as

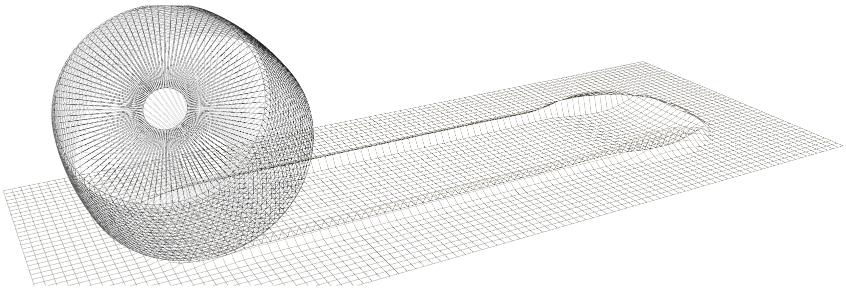

Figure 3. SCM for Wheel-Ground contact simulations including terrrain deformation and rutting

well as landslides induced around the wheels can be covered by SCM's plastic soil deformation. Using this approach, SCM enables to cover the main effects of terramechanics and soil deformation, namely bulldozing, rutting and multipass, in the environment of multi-body dynamics in an efficient way. Therein multipass and rutting are covered mainly geometrically. While the volume of disposed soil and its strength are influenced by a plasticity parameter, the soil parameters themselves remain unchanged. SCM has been successfully used in the simulation of planetary rovers [9] and the evaluation of its control using multi-body dynamics [10]. A first verification of the model was carried out in [9] for models of pressure sinkage tests, as well as full-system scale tests. Further validation is currently performed using the DLR-RMC single wheel test facility.

2.4 Discrete Element Method - DEMETRIA

The most detailed models are based on particle methods, i.e. the Discrete Element Method (DEM). These methods allow to model regolith directly as granular material without the need of empirical relations. However even for modern powerful computers, simulations using the real grain size

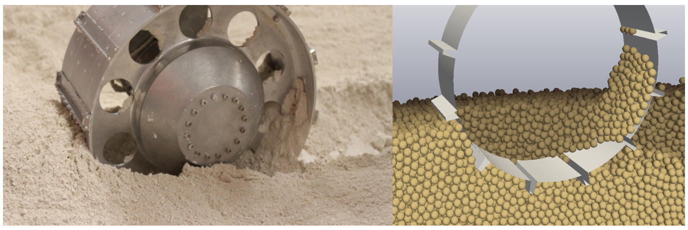

Figure 4. Wheel-Soil interaction in the laboratory (left) and particle-based Wheel-Soil Interaction (right) comparing principle effects of soil deformation in terramechanics [11]

are still not possible. Thus, the DLR-SR particle dynamics framework "DEMETRIA" (Discrete Element Method Enabled Terramechanics Interaction framework), based on the particle simulator Pasimodo, is incooperating systematic particle scaling and a priori parameter estimation. The framework's main features and advantages are explained in [12] and [13].
DEMETRIA was successfully applied to simulation of planetary rover wheels, exemplifying wheel-optimization potential [11]. Additionally, it was applied to InSight's [14] subsurface locomotion system: The HP^3-Mole [15] was simulated using co-simulation of particle and the MBS mechanism model [13] and influences of the outer shape on the performance were shown [16]. The particle-based soil models have been verified and validated using several kinds of material tests, usually used for characterization of soils. In addition to that the HP^3-Mole's co-simulation results are validated against deep penetration tests. The DEM wheel models have been checked for their qualitative behaviour in worst-case soils as exemplified in Figure 4 and are currently being validated using the DLR-RMC single wheel test facility.
However due to the high demand on computation time and power, DEM is not suitable for the

simulations of long trajectories at full vehicle level. Thus, these models are mainly used in order to investigate and understand the low-level effects of the interaction and thereby to enrich more efficient models. Hence the particle-based models will not be used for further investigations in this article, but are considered for future heterogeneous wheel-ground contact studies.

3 MULTI-TIERED WHEEL-GROUND CONTACT

In this section it will be shown, how the availability of diverse simulation techniques in a unified environment can be exploited to improve both the simulation speed and results. In order to characterize the soil, BEKKER's parameters derived for the DLR-RMC soil RMCS-13 using the DLR-RMC Bevameter and identification approach [17] will be used. The used simulant is based on calcium carbonate, which represents a worst-case soft soil for wheeled rovers, currently used in test campaigns at DLR-RMC. Utilized in a loose configuration the simulant is almost impassable due to excessive sinkage. Nevertheless the soil is highly compressible and can be prepared in different conditions in order to represent different kinds of planetary regoliths.

3.1 Approach

Coupling fast and slow models can drastically improve simulation times compared to homogeneous higher tier models with admissible influence on the results. Therefore, each wheel's contact model needs to cover the main effects of the interaction. The leading wheels of a planetary rover are usually driving through loose, uncompacted soils. Thus, their model needs to not only cover the current sinkage and reaction forces, but also the soil displacement causing additional resistance due to bulldozing, as well as the generation of ruts. These ruts will lower the trailing wheel's driving resistance and at the same time apply higher lateral guidance forces. In order to cover the rutting, SCM is used for the rover's leading wheels, whereas the trailing wheels are modeled one tier lower as single point BEKKER in order to study the approachs feasibility. The other models presented in section 2 will not be used for further investigation in this article, but are considered for future research in the field of heterogeneous wheel ground contact. Figure 5 shows the associated

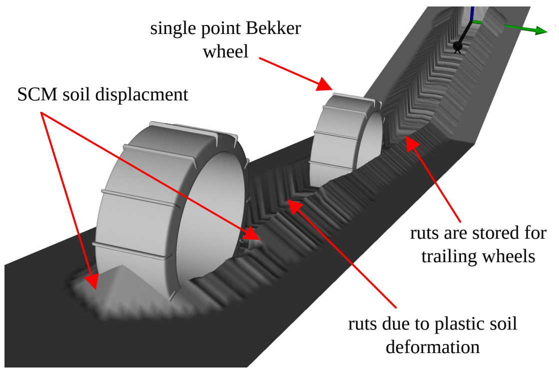

Figure 5. Multi-tiered heterogenous wheel soil contact

effects of the proposed heterogenous multi-tier contact using SCM's deformed soil for the contact detection of the trailing wheels. Thereby the BEKKER simulated wheel's results are enhanced by the trailing SCM wheel's presence, such that the overall motion behaviour is reaches a similar accuracy as the full rover using only SCM. The influence of the used soil simulant's compressibility on the soil parameters for the trailing wheels is neglected in this first study. Thus, the same soil parameters are used for both SCM and BEKKER contact model.

In addition to this approach, simpler wheel-soil models can be improved by offline simulations of higher tier models, such as DEM. By gaining a better understanding of the underlying processes, many of which would be extremely hard or even impossible to analyze in real world tests. As an example SCM's soil deformation can be checked and enhanced by the farther detailed DEM models.

3.2 Virtual Test Setup

In order to compare homo- and heterogeneous ground contact simulations, a simulation scenario for the evaluation of the tractive performance of planetary rovers is used. The rover is driving along a linear trajectory in a plane of soft soil, sufficiently long to reach a quasi-stationary state of the wheel ground interaction. Thereafter the rover is facing a 20° slope and climbs upwards, ensuring that a stationary state is reached again. This scenario was chosen, as the 20° sloped terrain is a common test setup for the locomotion capabilities of planetary rovers. The rover itself is modeled as a single track system with two wheels, modeling the symmetry of a four wheeled rover. In Table 1 the parameters of the simulation domain and the full rover are given. In addition to these parameters, the BEKKER model features parameters, which are not only influenced by the soil condition, but also by the soil's load history and the actual dynamics of the wheel. As there is no widely accepted method to choose these parameters, their identification is done based on empirical knowledge gathered from measurements. In order to check the consistency and the applicability as

Table 1. Parameters of the simulation setup and soil simulant

Parameter	
wheel diameter d_w	250 mm
wheel width b_w	125 mm
grouser height h_Gr	10 mm
number of grousers n_Gr	12
full rover mass m	100 kg
angular velocity of the wheel ω_w	$1\,\frac{\mathrm{rad}}{\mathrm{s}}$
total size of the domain	$4000 \times 400 \times 728\,\mathrm{mm}^3$
k_c	$7075\,\frac{\mathrm{N}}{\mathrm{m}}^{n+1}$
k_ϕ	$29\,850\,\frac{\mathrm{N}}{\mathrm{m}}^{n+2}$
n	0,83
angle of internal friction ϕ	38°

well as the potential speed up of the heterogeneous multi-tiered wheel ground contact, each rover a homogeneous simulation for each contact model is performed first. Therein it can also be checked whether the usage of one higher tiered contact significantly improves the simulation accuracy of the large-scale models. Figure 6 shows the single-tiered homogeneous, as well as the multi-tiered, heterogeneous setups. The different setups are compared using the following objectives:

- real-time factor r_rt
- tractive forces F_y and torques M_y
- quasi-stationary translational velocity v_abs
- sinkage $s_z^\mathrm{f,r}$ of the individual wheels

To allow for improved comparability, the results will be normalized using SCM's results as a reference. Thereby normalized values are noted as $(..)_0$ and allow to directly compare the signals in terms of their deviations. The sinkage is calculated as absolute sinkage for all wheels. Explicit EULER integration scheme is utilized for all simulations carried out in this work. The solver's time step size is kept constant at the highest possible, but lowest required for all the models in order to omit influences on the simulation speed and accuracy due to the solver's step size control.

4 RESULTS

In the following section we will discuss the impacts of the proposed multi-tiered technique on both the accuracy of the simulation results with respect to the higher, single-tiered model, as well as the

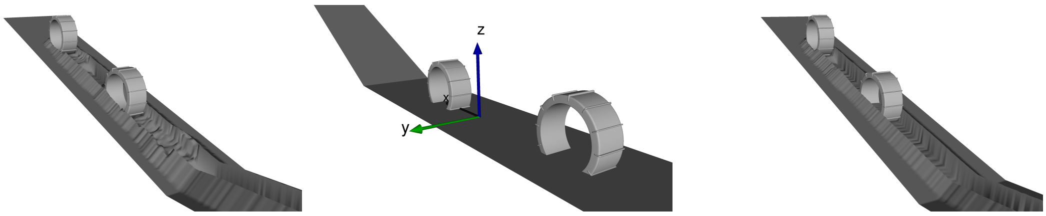

Figure 6. Virtual testscenario to evaluate the tractive performance of different rovers: SCM-SCM (left), BEKKER contact-BEKKER contact (middle), Heterogeneous SCM-BEKKER contact (right)

demand in computation time.

The tractive forces and torques as well as the wheel load in z-direction are used as respective results to compare the accuracy. Together with the individual wheel sinkages and the effective translational speed of the wheel, these values are usual outputs of tractive performance tests for planetary rovers.

The computational performance is rated by the real-time factor which is defined as $r_{\mathrm{rt}} := \frac{\mathrm{d}t_{\mathrm{sim}}}{\mathrm{d}t_{\mathrm{cpu}}}$, whereby t_{sim} is the simulated time and t_{cpu} the total used CPU-time.

4.1 Accuracy of the multi-tiered approach

By applying the common approach of single-tiered contacts it can be shown that the wheel loads differ for both homogeneous setups as certain important effects of soil deformation are not covered by the single-tier BEKKER model. Compared to the latter, the heterogeneous wheel ground contact is able to enhance the results for both front and rear wheel. As the leading wheel (Fig.7) in the mixed-tier simulations is identical to the one in the reference model and thus the comparison is trivial, we will mainly focus on the rear wheels' comparison. By coverage of the soil deformation by the leading SCM-wheel the tractive performance of the multi-tiered model is increased towards the SCM-SCM level. This is especially evident in Figure 8 after the leading wheel reached the slope at $s_x = 0{,}95\,\mathrm{m}$ and after the rover reached the stationary state on the slope. Nevertheless the

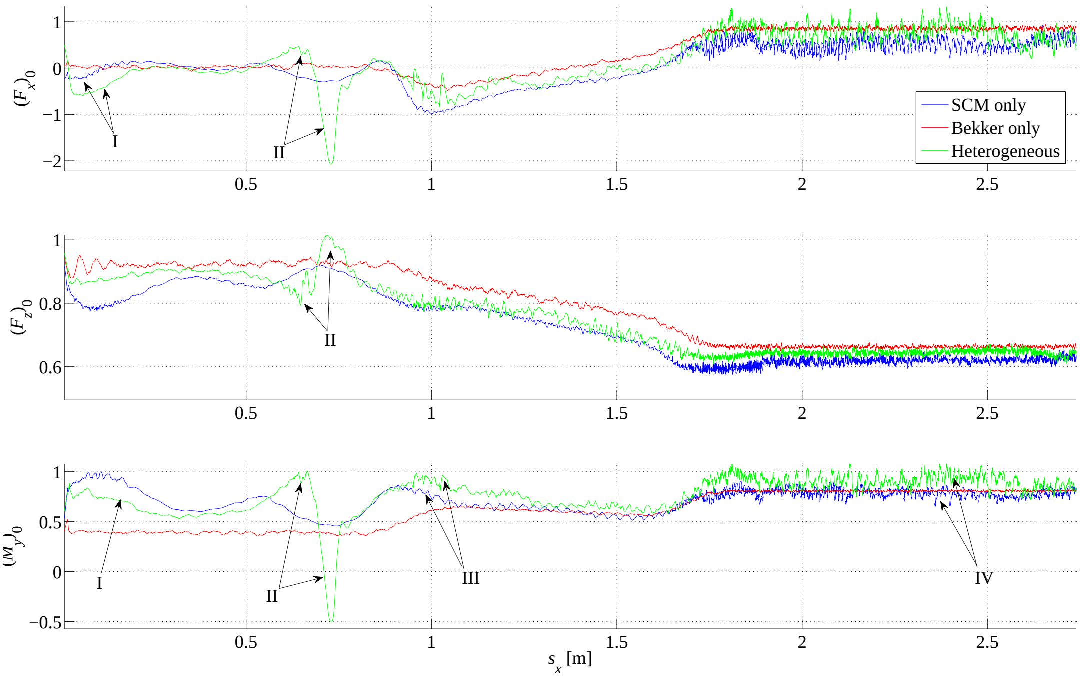

Figure 7. Loads on the front wheel

results are always closer to the reference as the homogeneous BEKKER contact model is. However the approach still shows differences in the dynamic behaviour compared to the reference model. The main differences are marked in Figures 7 and 8 with I-IV. At point I the disparity is caused by the deviation in the sinkage of front and rear wheel. As can be seen in Figure 9 the rear wheel sinkage s_z^r for the homogeneous BEKKER model as well as the heterogeneous approach are at $\approx 67\%$ of the reference model. As both SCM and BEKKER contact feature the same soil parameter, the decreased sinkage causes lower forces and torques accordingly. At point II the

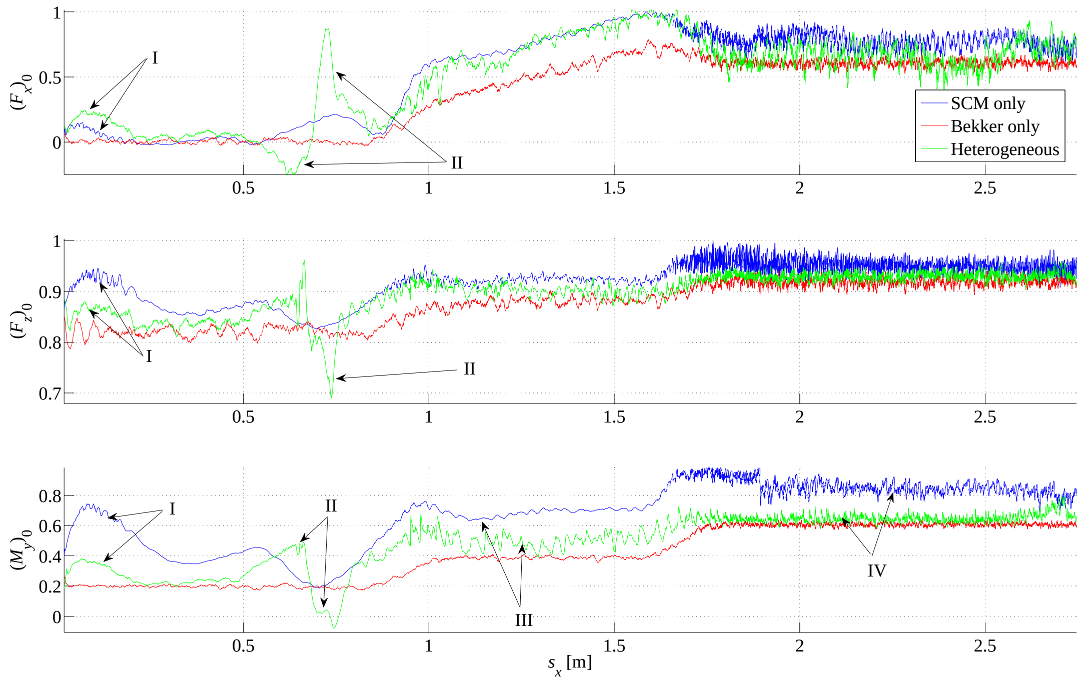

Figure 8. Loads on the rear wheel

difference in the multi-tier behaviour is directly induced by the approach itself. Figure 10 shows the results of the multi-tiered simulation on the top and the reference model on the bottom. In the pure SCM scenario the front wheel generated a rut in the soil, whereby during the initial sinkage process, material is displaced not only to the front and sides of the wheel, but also to the rear. As the trailing SCM wheel approaches the piled soil, the bulldozing force is increased until the wheel drops into the rut of the leading wheel. Using the multi-tiered model, the trailing wheel does not feature soil deformation and thus the piled soil is not displaced. However the displaced soil is used in contact detection and causes increased forces on the trailing wheel compared to the reference scenario, as well as a lift of the wheel itself (Fig. 9 middle). Due to this lift, the dynamic impact when dropping into the rut is increased as well which causes higher sinkage. Due to differences in sinkage and thus weight distribution, the deviation observed in III and IV occurs. These differences also lead to disparities in rut formation in SCM which in turn causes deviations at the front wheel, too.

4.2 Analysis of the computational effort

Regarding the computational performance of the simulation, Figure 11 shows that the homogeneous BEKKER model executes faster than real-time. As expected SCM features the lowest real-time factor, as it is the most complex of the models and the only one carrying out several iterations per time-step. In contrast to that the speed-up of the multi-tiered model is not as high as originally expected. While the homogeneous BEKKER model yields a real-time factor of 0,52, the multi-tiered model yields $r_{\mathrm{rt}} = 5{,}15$ and the SCM reference model yields in a factor of 6,44. During first investigations on this issue, it was found that the plastically deformable surface supplied by SCM

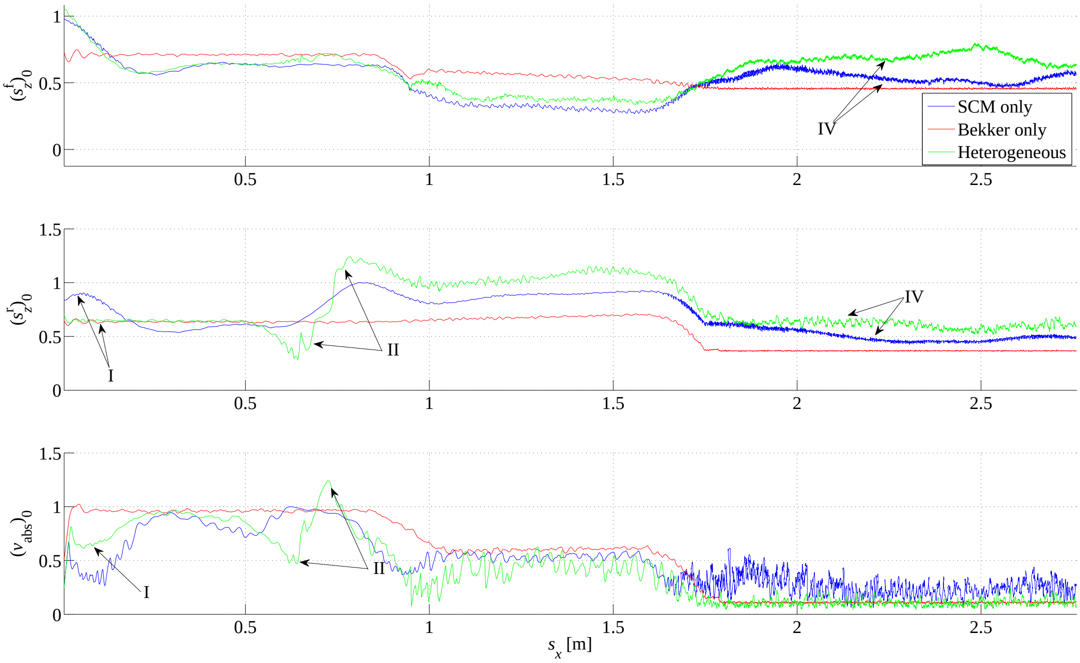

Figure 9. Sinkage of both, front and rear wheel as well as rover velocity

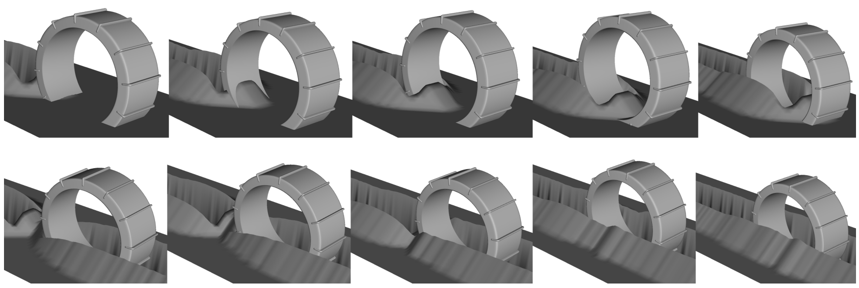

Figure 10. Effects of the front wheel rut and displaced soil on the real wheel in the BEKKER model (top) and SCM (bottom)

causes higher computational effort, than the BEKKER model running on a rigid surface. In order to check the influence, the homogeneous BEKKER model was executed on a plastically deformable surface supplied by SCM. It was found that the real-time factors are: $r_{\mathrm{rt}}^{\mathrm{flex}} > 5 \cdot r_{\mathrm{rt}}^{\mathrm{rigid}}$. The lower than estimated run-time speed is caused by the synchronized communication between Modelica and the visualization if the SCM supplied surface is used. If the connection is not synchronized

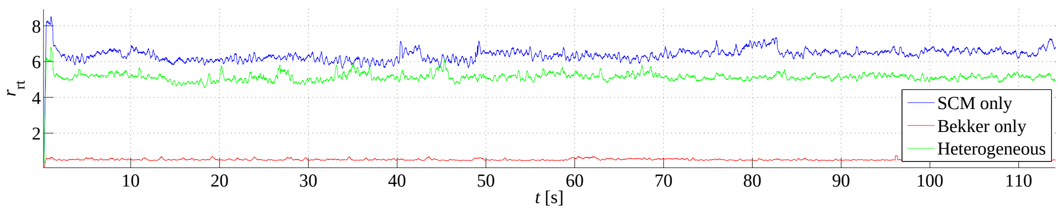

Figure 11. real-time factor r_{rt} for all setups

the multi-tiered model's real-time factor decreases to roughly 70% of the above mentioned value, which is within the expected range. Additionally, the homogeneous BEKKER contact model is sped-up as well, but in contrast SCM's execution time stays constant. However as it enables a more robust contact detection, the synchronization option is kept in favor of the simulation results. Summing up this first feasibility study for multi-tiered wheel ground contact, it can be stated

that the usage of heterogeneous wheel ground contact simulations improves computational performance compared to full higher-tier simulations on one hand and enhances the level of detail compared to lower tier simulations on the other hand.
As SCM is already verified by previous analysis, it is used as a reference model within this work, however it is still not entirely validated and shows effects that are not compliant with reality for the used type of regolith, e.g. the bulldozing is overpredicted for calcium carbonite based soils. Such effects will be focused on in a currently ongoing in-depth validation campaign of wheel soil models at DLR-SR.

5 CONCLUSION

In the article we showed the integration of wheel ground contact models of different level of detail in a unified simulation framework to allow for the simulation of the various tasks in planetary exploration. Due to the integration of these models in one framework, multi-tiered heterogeneous wheel ground contact modeling is possible in a unified manner.
By usage of our BEKKER and SCM contact model implementations we exemplified this approach in order to achieve a speed up of the simulation while still maintaining nearly the same level of accuracy for the simulation of planetary rover locomotion. Additionally, drawbacks of the approach were shown. In terms of the computation time, the observed speed up was lower than expected. Possible reasons for this were investigated and it was shown that by neglecting synchronization the expected speed-up can be reached.
As calcium carbonite based sands feature excessive compressability, a next step will be the investigation of multi-pass effects in precompressed ruts in compressible simulants. Additionally, further validation of the single models as well as investigations on lowering the computational effort due to the plastically deformable surface will be performed. Moreover in order to allow a deeper insight in the potential speed up, rovers with increasing number of wheels, featuring leading wheels' SCM contact and lower-tiered contacts for the trailing wheels, will be compared in future work. It is expected that the benefit of the increased accuracy of the soil interaction models is decreasing with a higher number of the multipasses.
Moreover, validated models, e.g. knowledge about deformation fields from DEM can be used to enhance the soil relocation algorithm in SCM.

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