Planetary Rover Mobility Performance Simulation Tool

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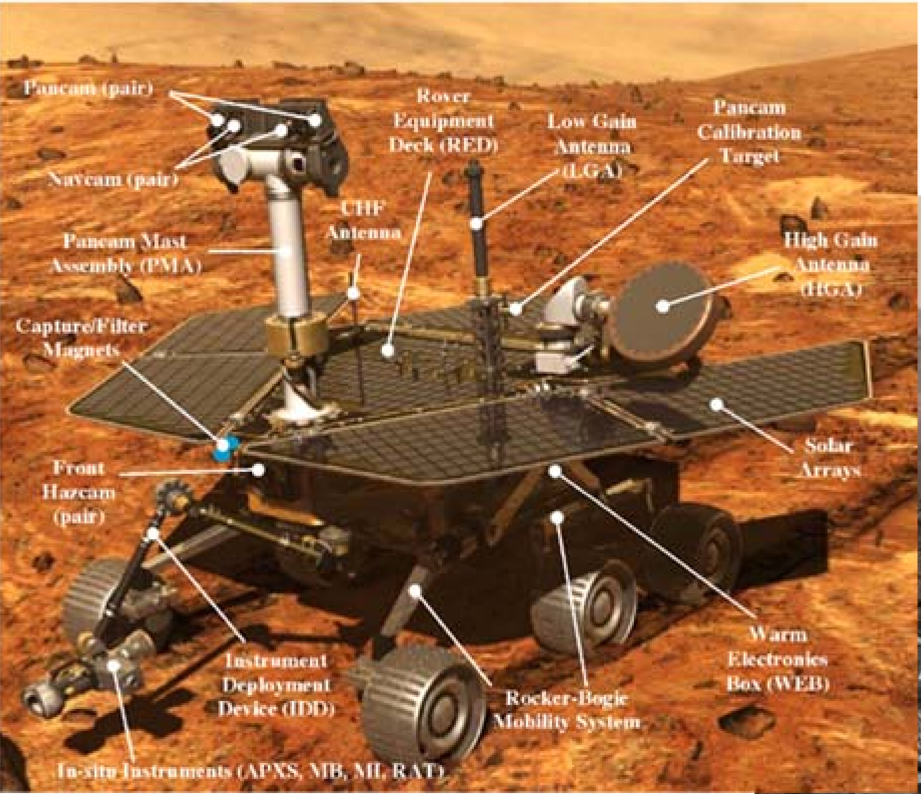
Contents

Background: Planetary Rovers, on Mars
NASA MER (Jan 2004) + ESA ExoMars (> 2013)



Suspension: 3 bogies

Suspension: rocker–bogie each side

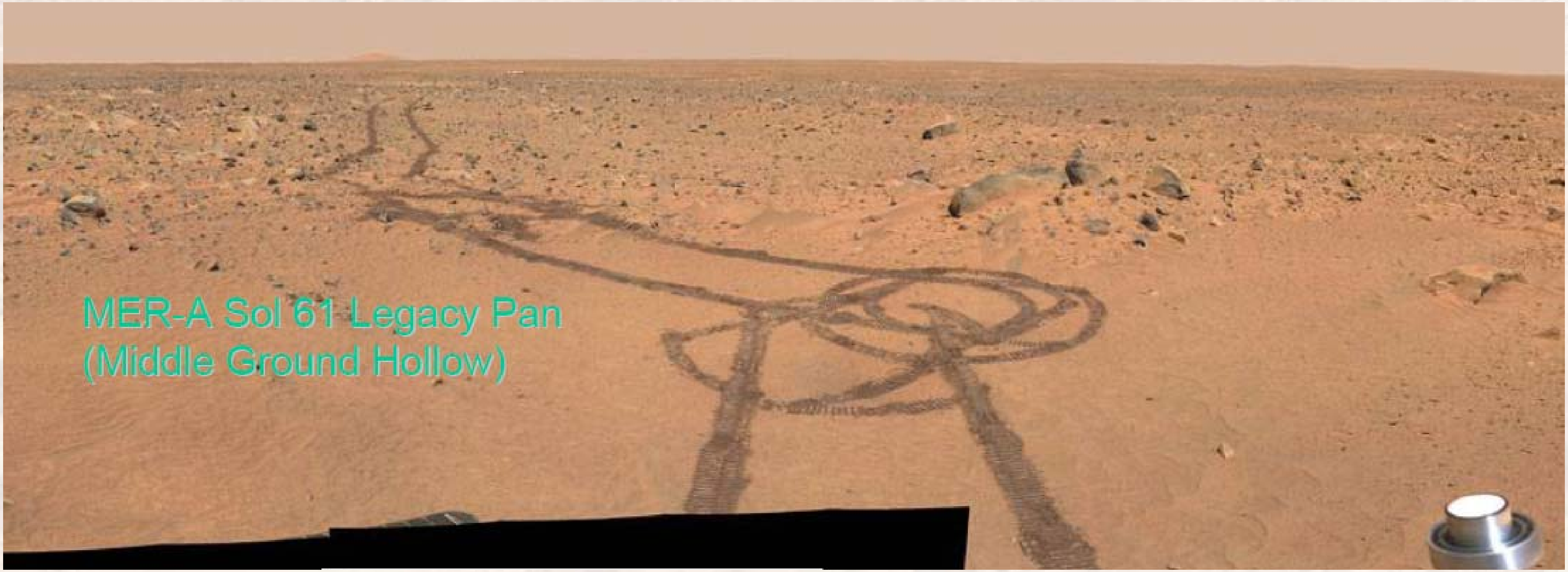
ESA's ExoMars: > 2013

total mass ~230 kg

all 6 wheels actuated for driving and steering

Get the wheel driving and steering torques to the soil for good traction performance

Typical examples of wheel tracks on sandy and pebble terrain

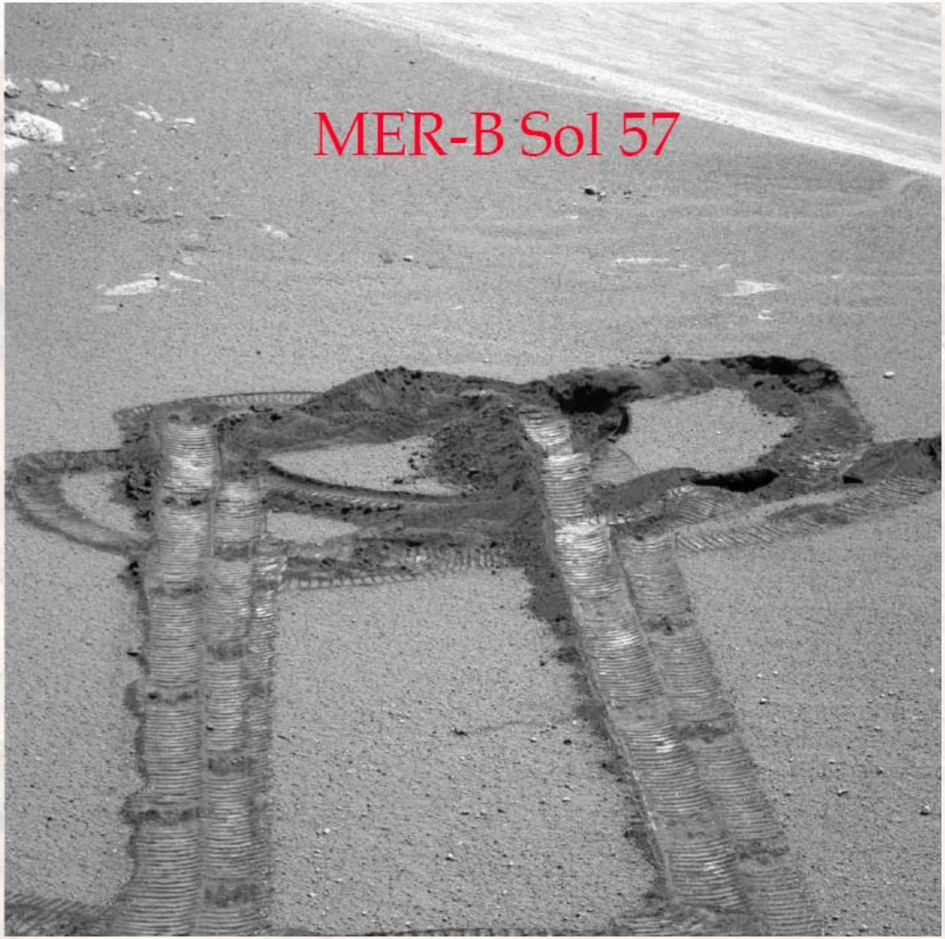


NASA's MER-rover Spirit wheel track:
MER-A Sol 61 Legacy Pan (Middle Ground Hollow)

MER on Mars: typical wheel tracks in soft soils

Opportunity (MER-B) wheel tracks: by Navcam (left) and by Pancam observation (right)

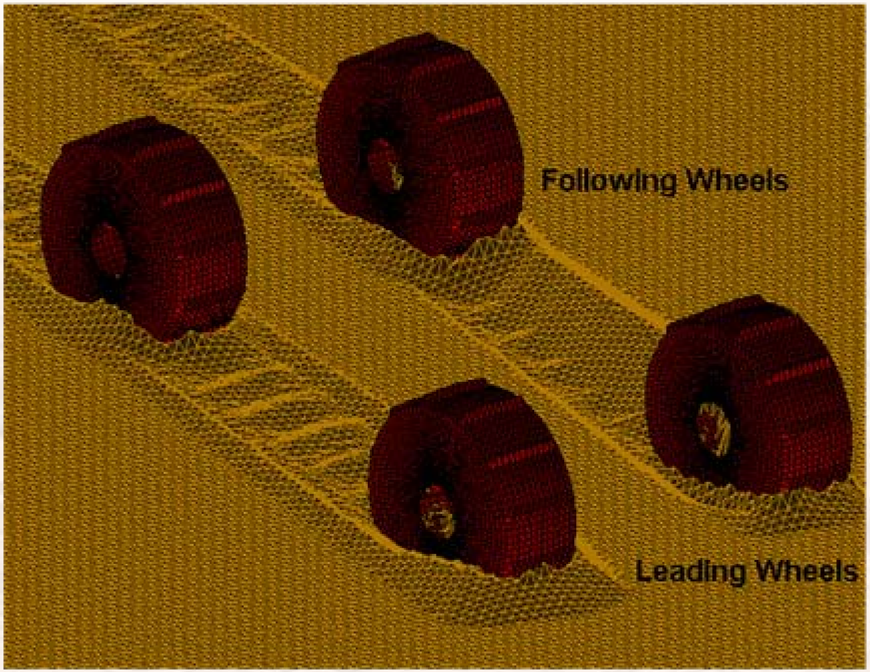
Movements over Soils - Limitations



Failed egress from 'Eagle Crater' (got stuck)

Climbing 'Husband Hill'

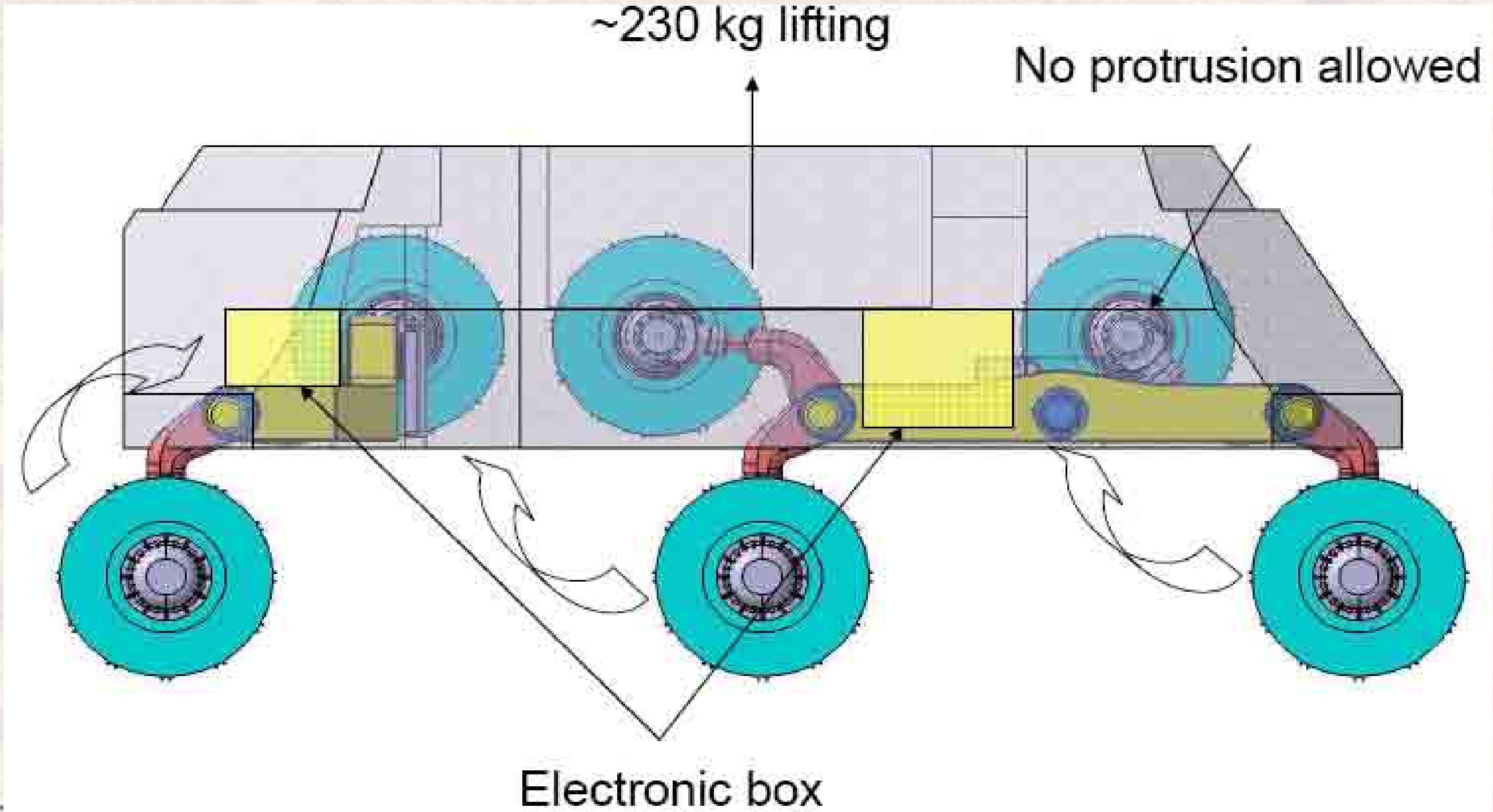
Wheel-Soil Contact: Modelling the Reality



- 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 (PCM and SCM) for soft and hard 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

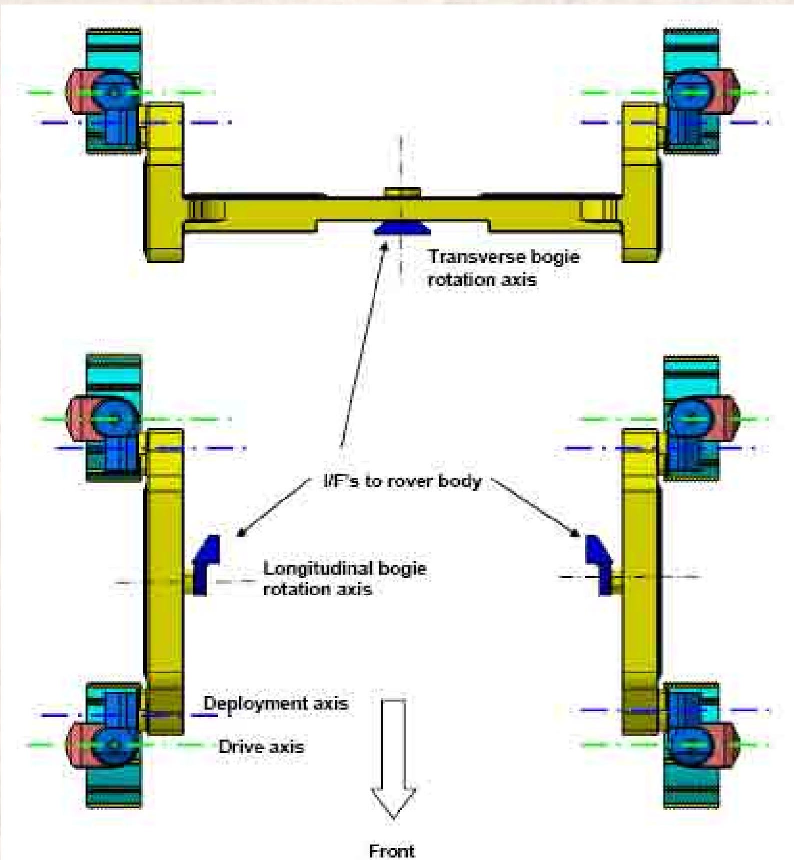
ExoMars Multibody System:

chassis, suspensions, wheels, actuators, joints
→ multiple rigid bodies, wheel deployment & walking

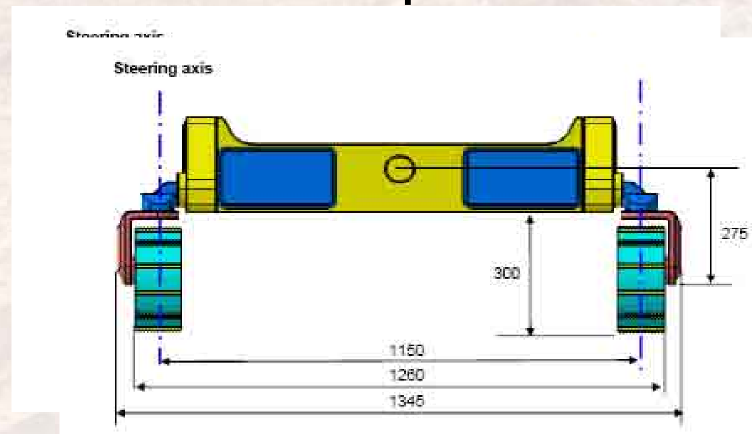


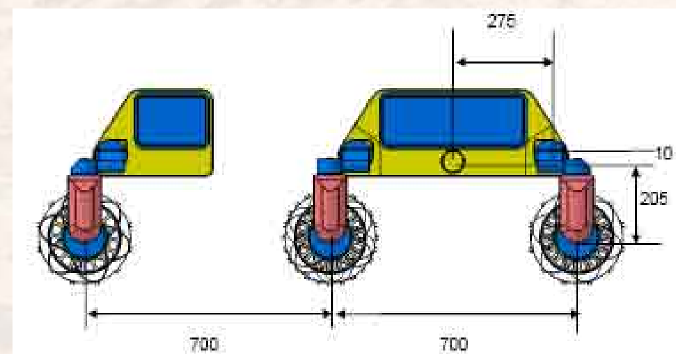
ExoMars: suspension 3-bogy concept

Baseline concept: top view



Baseline concept: front view

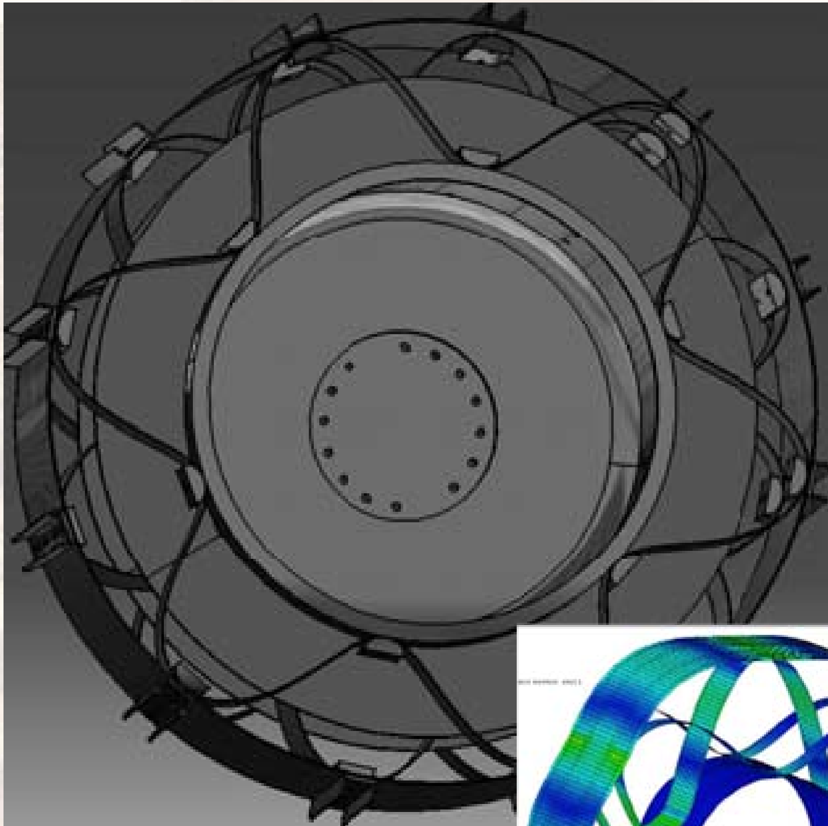


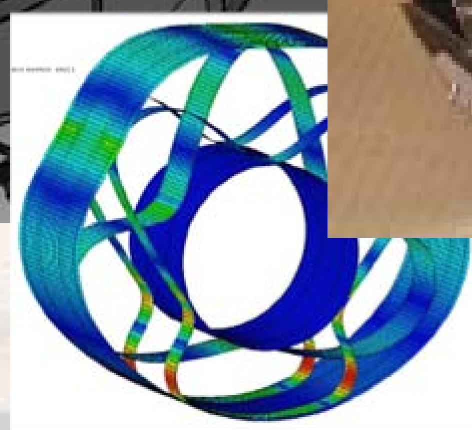


Baseline concept: side view

ExoMars: Rover Breadboard in Testbed

Flexible Wheel Design (with Grousers)



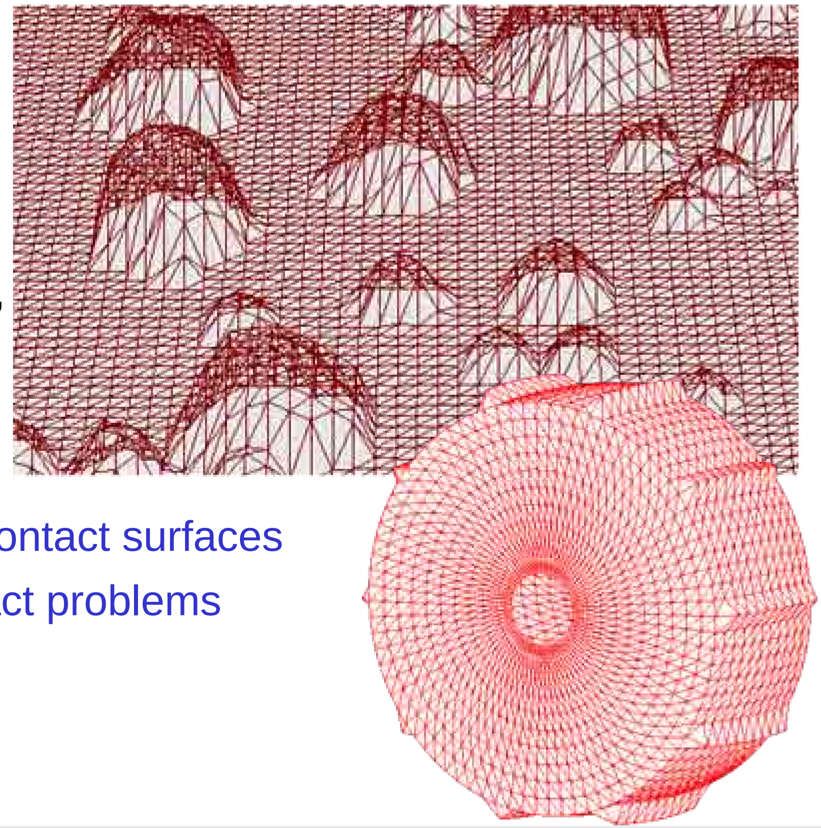


Motivation for Rover Mobility/Locomotion Simulations in Software

- Rover chassis in project phases A/B not available
  - Support of chassis development on subsystem level
    - design of wheel drives (max. required torques)
    - design of steering drives
    - wheel design (number and shape of grousers)
    - bogie design (single, parallel)
  - Prove of skills of overall system - rover
    - Trafficability and gradeability (uphill/downhill and crosshill) in both, rocky and sandy terrain
    - Drawbar pull DP = traction performance metric
    - DP = Max. tractive thrust available from soil over the vehicle wheel-soil contact area - Resistances
    - force/torque impact on chassis
- Support of procedure and control development (phases C/D/E)
  - Parameter variations (soil properties, trajectories)
  - Hardware-in-the-loop simulations (controller, onboard computer)

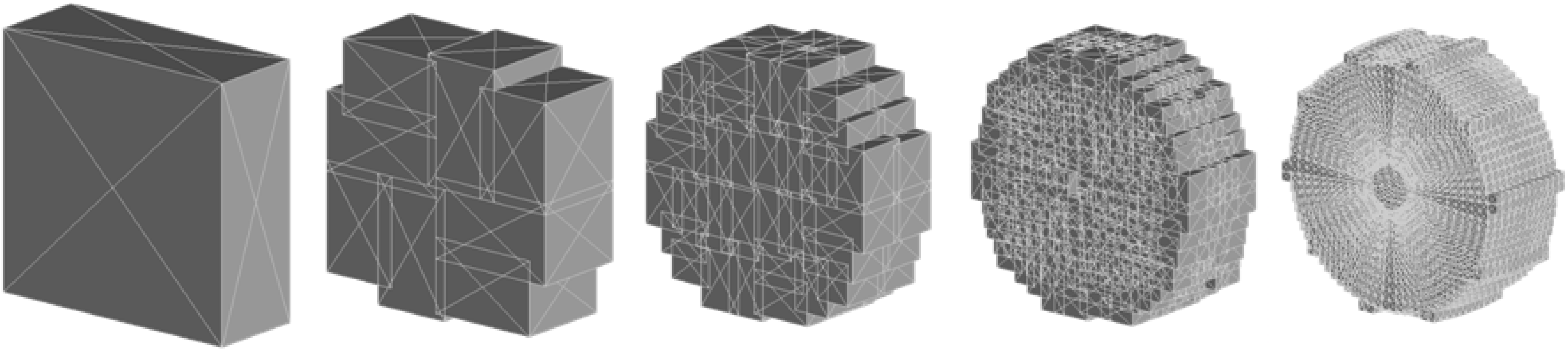
Polygonal Contact Model – PCM / 1
Wheel-Ground-Interaction in Rocky Terrain

- Terrain and wheel surfaces represented by polygon meshes
- Individual polygon properties
  - Vertex positions
  - Surface normal orientation
  - Area size
  - Stiffness (Young's modulus, Poisson ratio)
  - Areal damping coefficient
  - Friction coefficient
- Applicable for arbitrarily shaped contact surfaces
- Applicable for multiple point contact problems

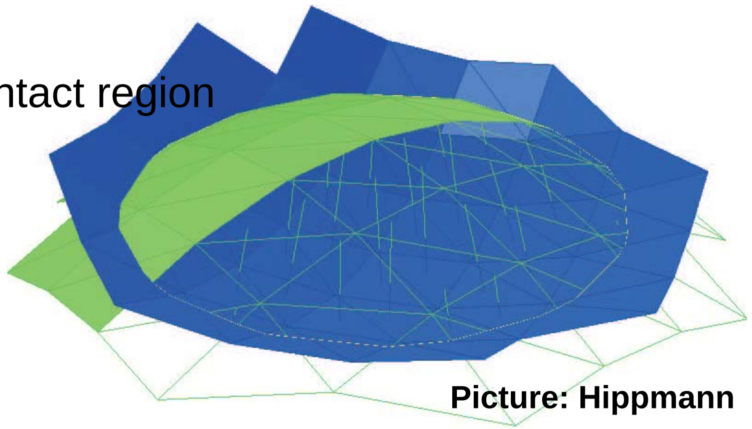


Polygonal Contact Model – PCM / 2
Wheel-Ground-Interaction in Rocky Terrain

- Contact detection by Boundary Volume Hierarchy algorithm (Binary Box Tree)

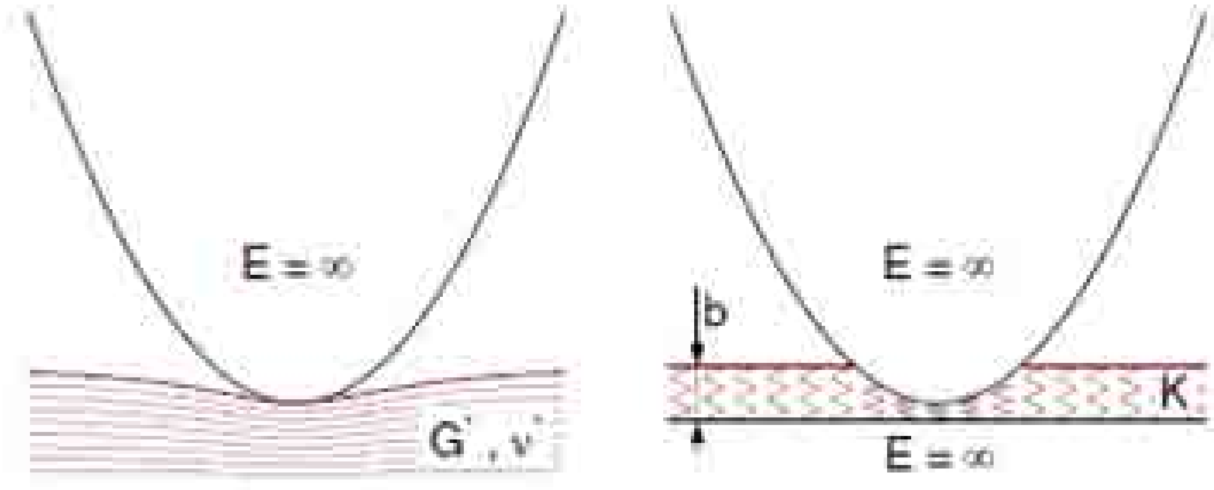


- Calculation of relative kinematics at contact region
  - Intersection border polygon
  - Penetration depth inside polygon
  - Relative velocities



Picture: Hippmann

Polygonal Contact Model – PCM / 3a
Wheel-Ground-Interaction in Rocky Terrain



- Comparison of half-space approximation (left) and surface layer model (right)
- Contact region to be small compared to the overall dimensions of the bodies
- Surface layer method uses a rigid half space for both contact surfaces (E=inf) with linearly elastic surface layer

Polygonal Contact Model – PCM / 3b
Wheel-Ground-Interaction in Rocky Terrain (Multiple Contact Problem)

- Contact dynamics by Elastic Foundation Model

$$p_i = \frac{K}{s} u_i; \quad K = \frac{1-\nu}{(1+\nu)(1-2\nu)} \cdot E$$

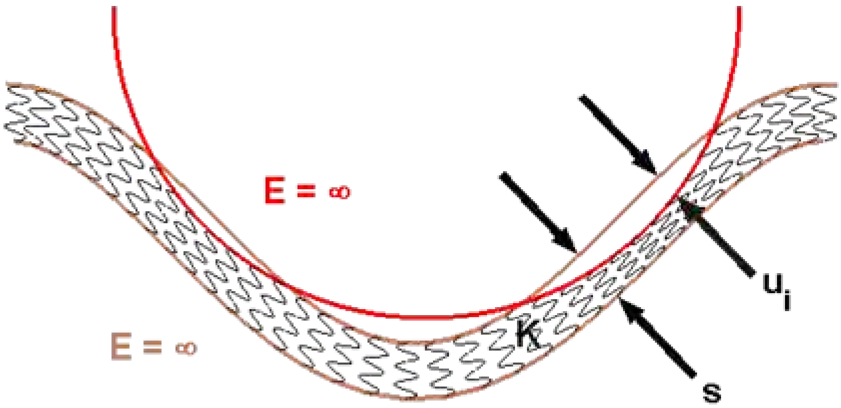
p_i: Individual contact pressure

u_i: Individual contact penetration

E: Young's modulus of elastic layer

ν: Poisson ratio of elastic layer

s: Elastic surface layer thickness



- Negligible impact on center of mass / inertia tensor by deformation of elastic surface layer

Polygonal Contact Model – PCM / 4
Wheel-Ground-Interaction in Rocky Terrain

- Application of contact forces/torques at body fixed reference frame of wheel

$$\left.\begin{aligned}\mathbf{F}_{n,i} &= -A_i\left(p_i\mathbf{n}_i + d\mathbf{v}_{n,i}\right)\\ \mathbf{F}_{t,i} &= \mu\left|\mathbf{F}_{n,i}\right|\frac{\mathbf{v}_{t,i}}{\left|\mathbf{v}_{t,i}\right|}\\ \mathbf{T}_i &= \mathbf{r}_i \times \left(\mathbf{F}_{n,i} + \mathbf{F}_{t,i}\right)\end{aligned}\right\}; \quad \mathbf{F} = \sum_i\left(\mathbf{F}_{n,i} + \mathbf{F}_{t,i}\right); \quad \mathbf{T} = \sum_i \mathbf{T}_i$$

$\mathbf{F}_{n,i}, \mathbf{F}_{t,i}$: Individual contact forces (normal / tangential)

$\mathbf{T}_i$: Individual contact torques

p_i: Individual contact pressure

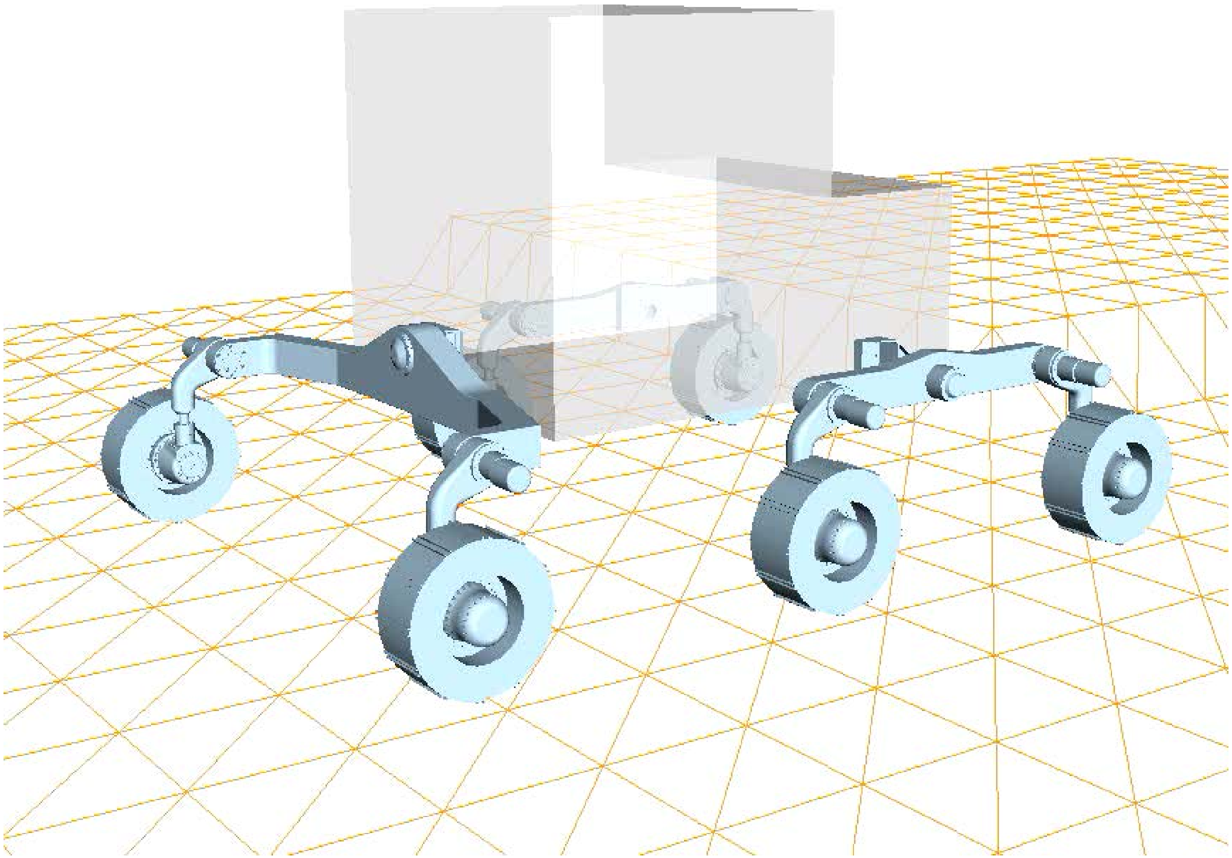
A_i: Individual contact area size

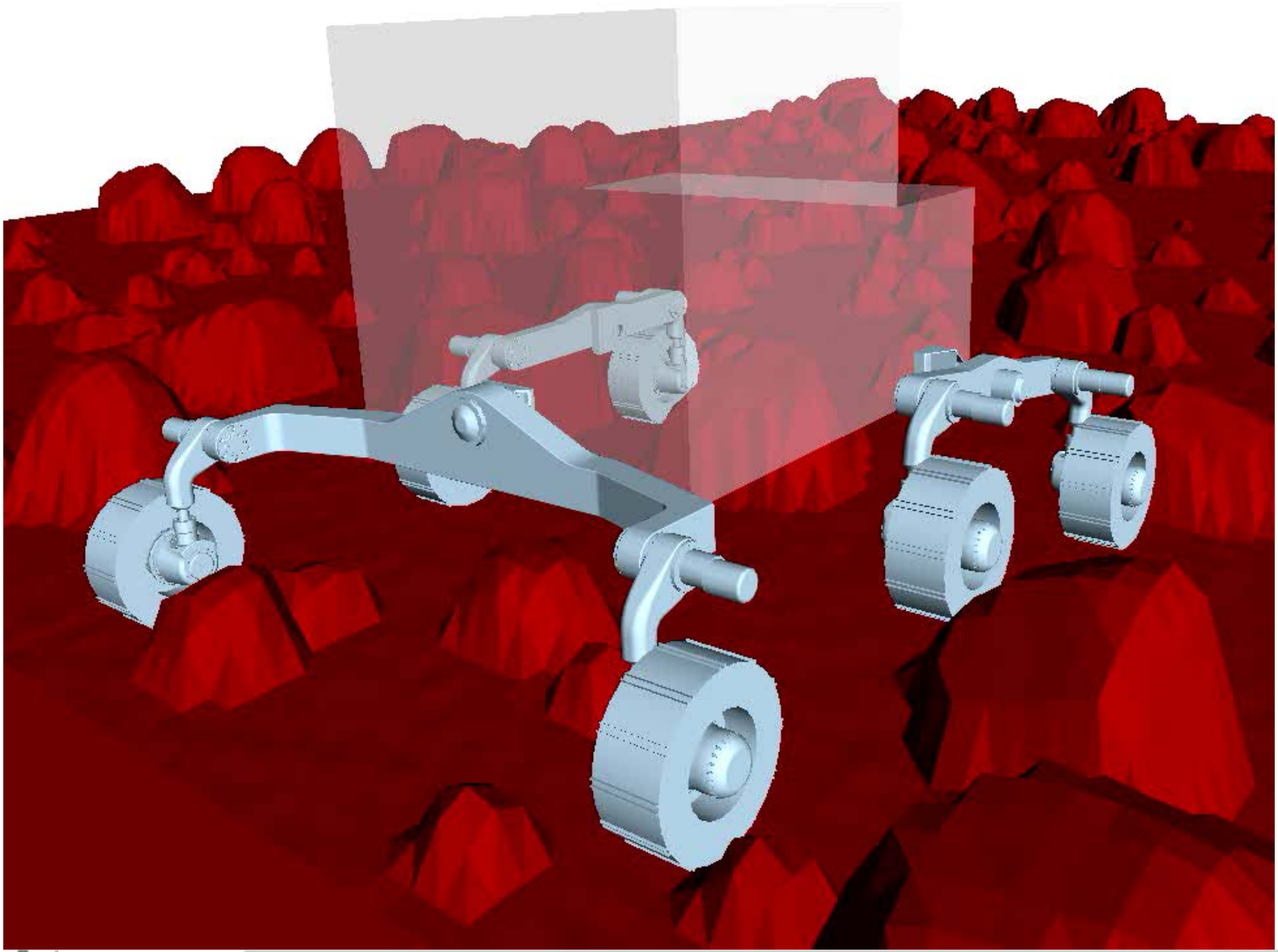
μ, d: Friction coefficient, areal damping coefficient

$\mathbf{n}_i$: Individual surface normal vector

$\mathbf{r}_i$: Individual distance from body fixed reference frame

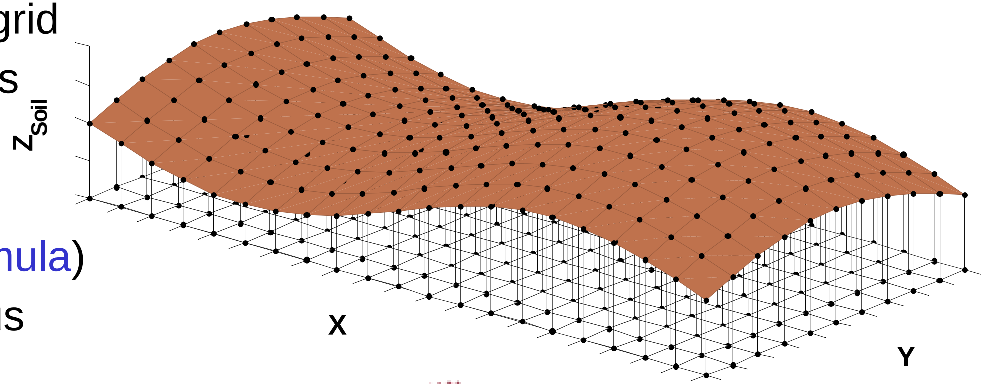
$\mathbf{v}_i$: Individual relative velocity (normal / tangential)



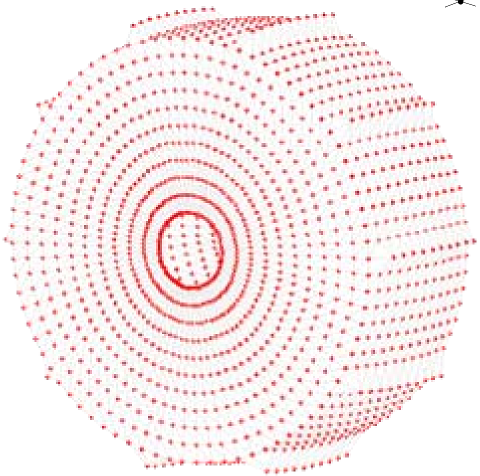


Soil Contact Model – SCM / 1
Wheel-Ground-Interaction in Sandy Soil

- Soil description by elevation grid
- Individual grid node properties
  - Grid resolution
  - Soil parameters
    (e.g. by Bekker's formula)
    - Cohesive modulus
    - Friction modulus
    - Exponent of sinkage
    - Internal friction

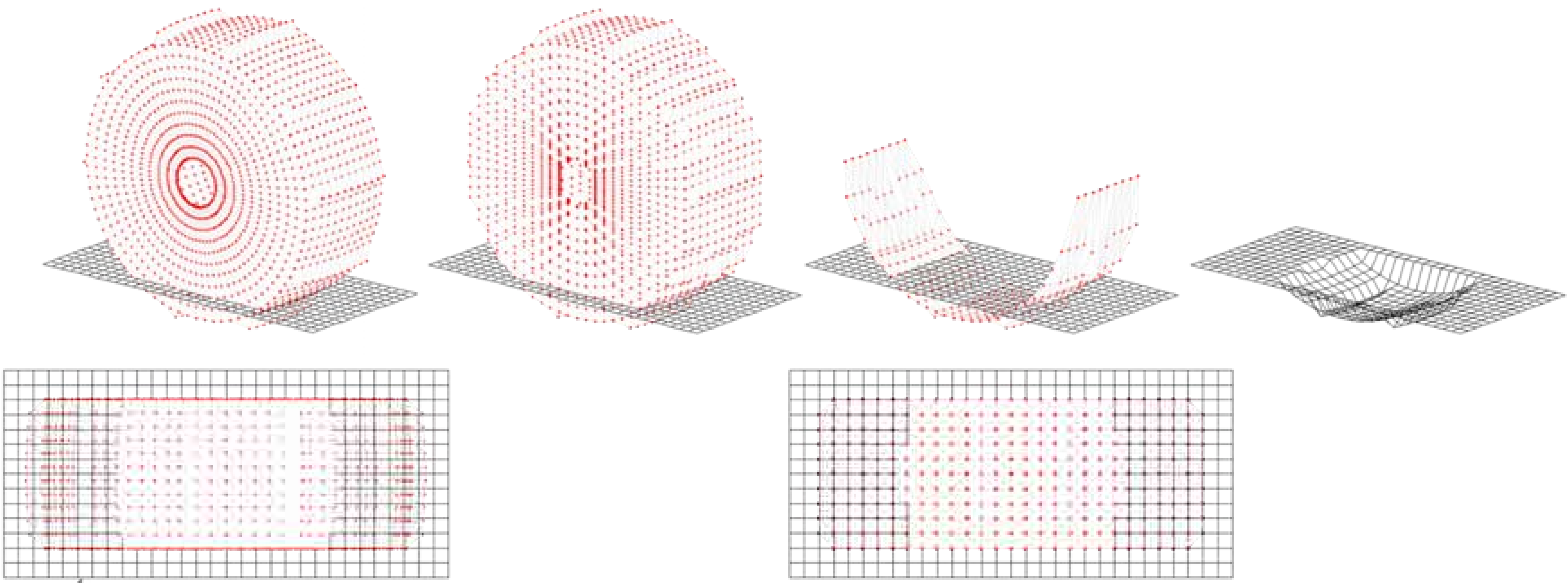


- Wheel description by surface point cloud
  - Vertex coordinates
  - Wheel resolution higher than soil resolution



Soil Contact Model – SCM / 2
Wheel-Ground-Interaction in Sandy Soil

- Contact detection based on elevation comparison at soil grid nodes (sinkage and relative velocities)
- Plastic deformation of soil (footprint)



Soil Contact Model – SCM / 3
Wheel-Ground-Interaction in Sandy Soil

- Contact dynamics according to Bekker's empirical formula:

$$p_i = \left(\frac{k_c}{b} + k_\varphi \right) z_i^n; \quad \mu = \tan(\varphi);$$

p_i: Individual contact pressure at grid node

z_i: Individual sinkage at grid node (plastic soil deformation)

k_c, k_φ: Cohesive and frictional modulus

n: Exponent of sinkage

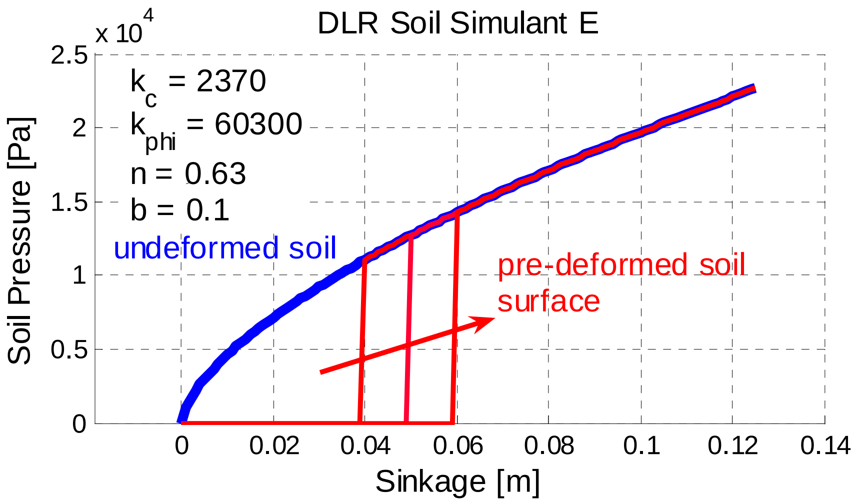
b: Width of contact object (wheel)

μ: Friction coefficient

φ: Angle of internal friction (soil)

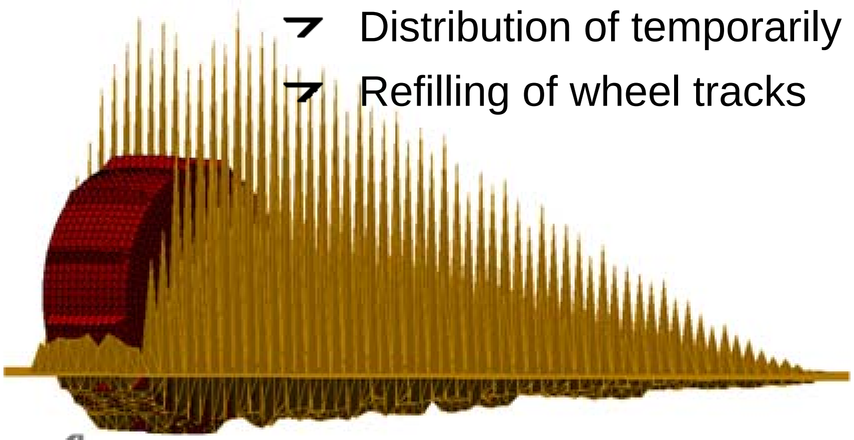
- After soil deformation:

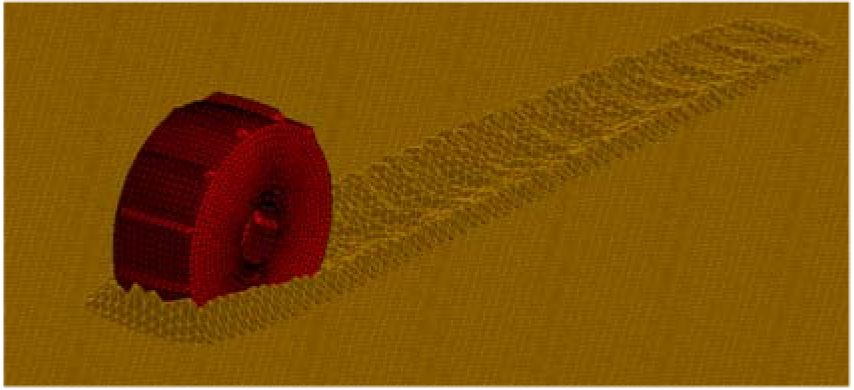
$$p_i = \begin{cases} \left(\frac{k_c}{b} + k_\varphi \right) z_i^n; & z_i > z_{i,\max} \\ 0; & z_i \le z_{i,\max} \end{cases}$$



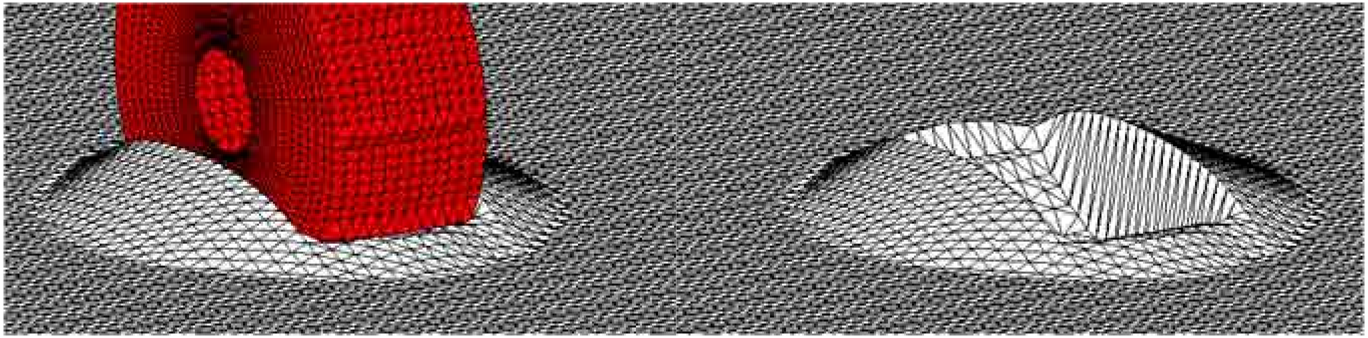
Soil Contact Model – SCM / 4
Wheel-Ground-Interaction in Sandy Soil

- Soil **displacement** from contact interference volume (wheel tracks)
- Temporary **deposition** of displaced soil volume at contact zone border
  - Each sub-volume displaced from a contact grid node is spread over all border grid nodes.
  - The closer the border node the bigger the fraction of the displaced volume (fraction ~ 1/distance).
- Thermal **erosion** of the soil depending on the internal friction of the soil
  - Distribution of temporarily deposed volume
  - Refilling of wheel tracks

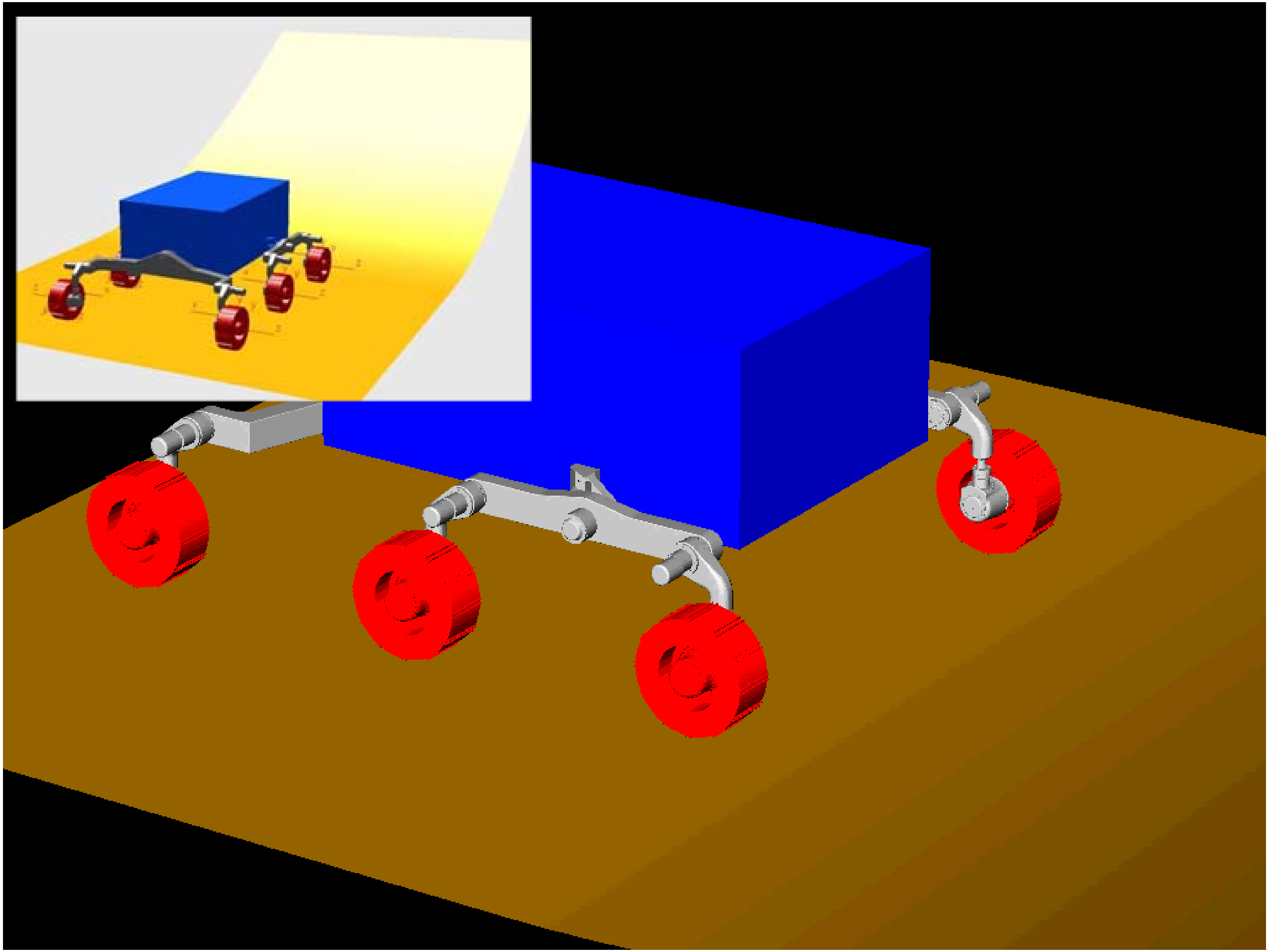




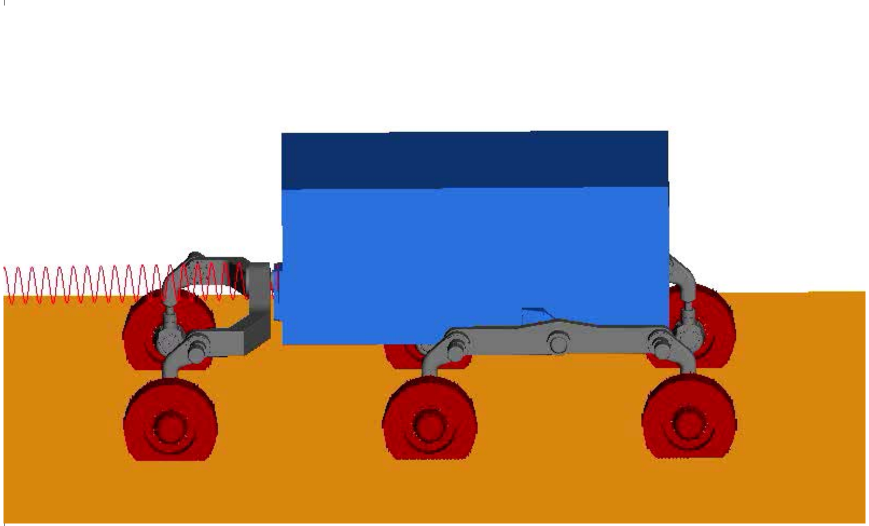
Soil Contact Model – SCM / 5
Wheel-Ground-Interaction in Sandy Soil



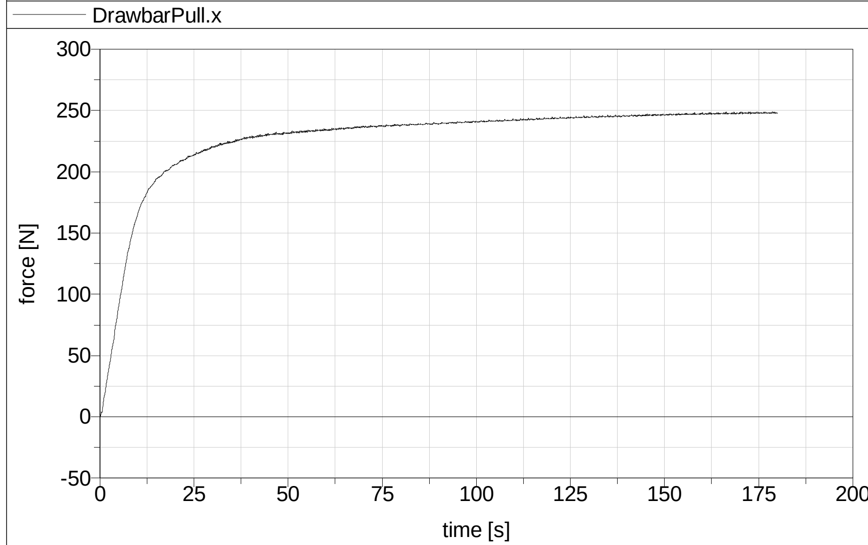
- Re-calculation of contact surface by soil displacement is the key for modeling sand specific wheel-terrain dynamics
  - Normal forces in lateral directions (in addition to friction forces)
    - Wheel rolling resistance
    - Drawbar pull
  - Multi-pass effects



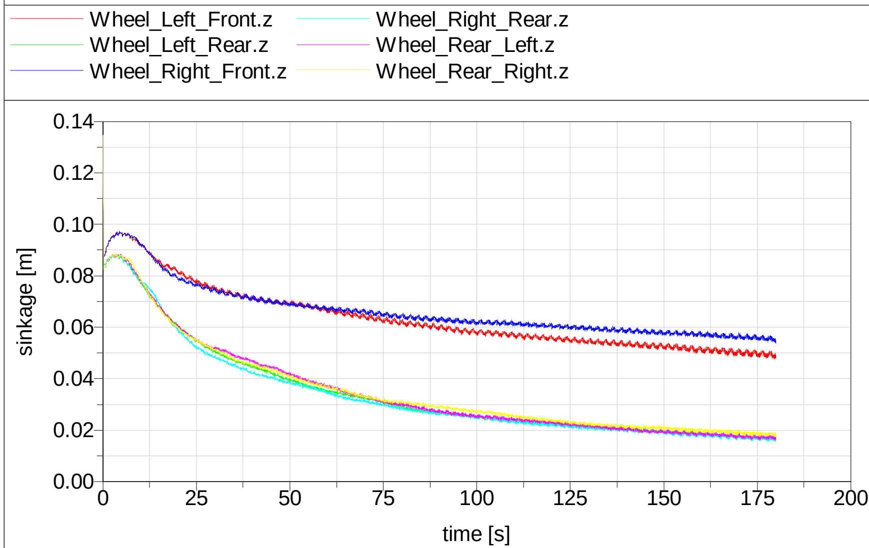
Drawbar Pull Simulation



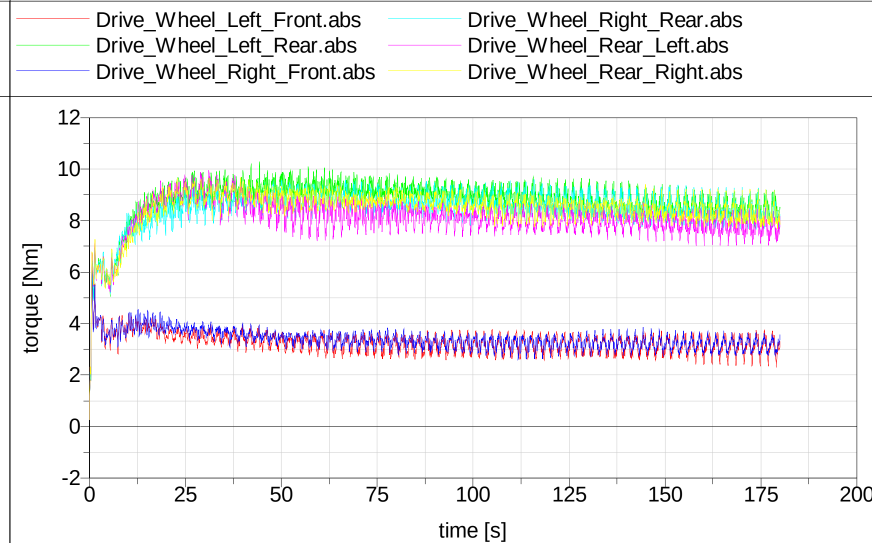
Drawbar Pull

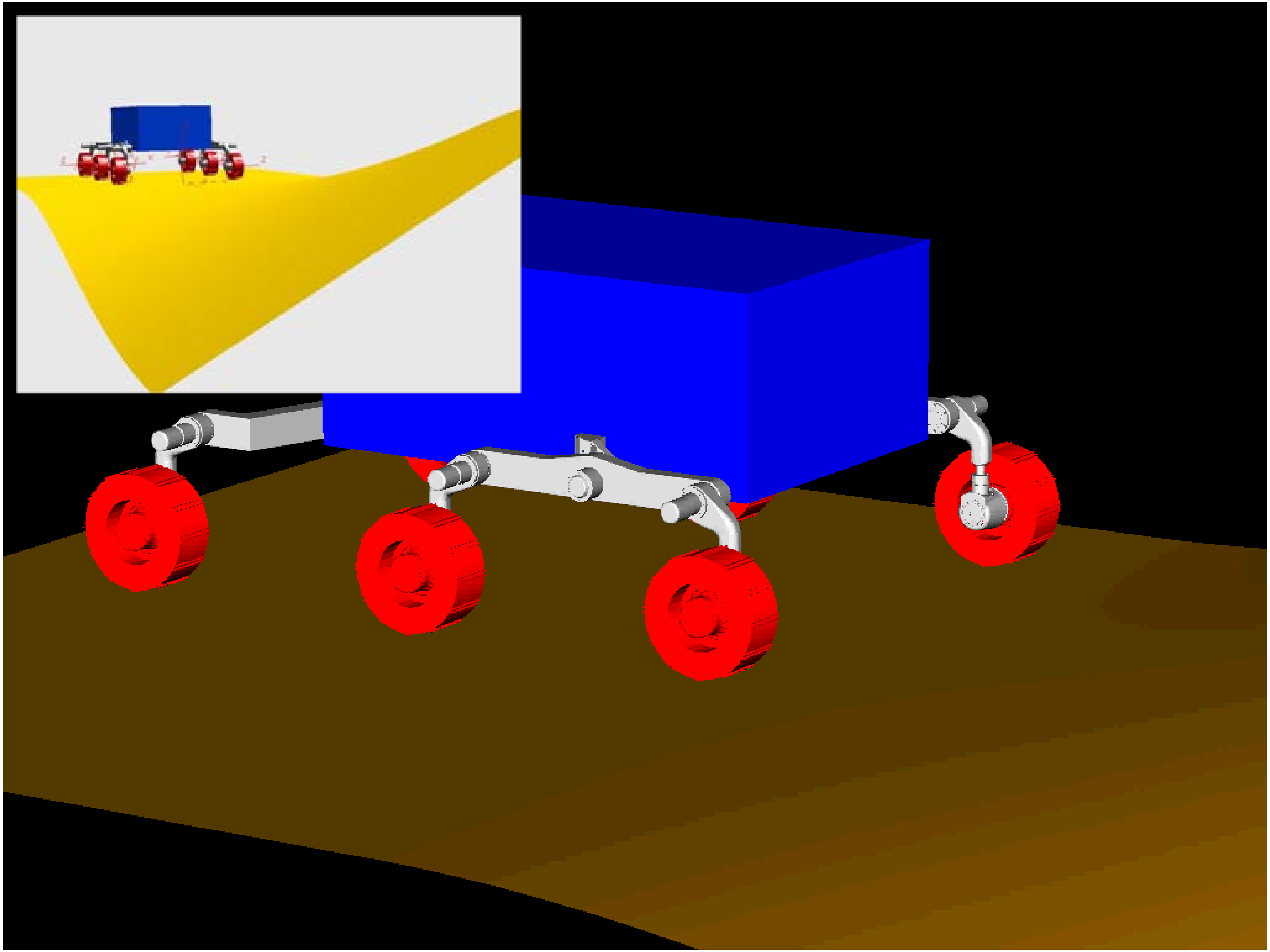


Wheel Sinkage

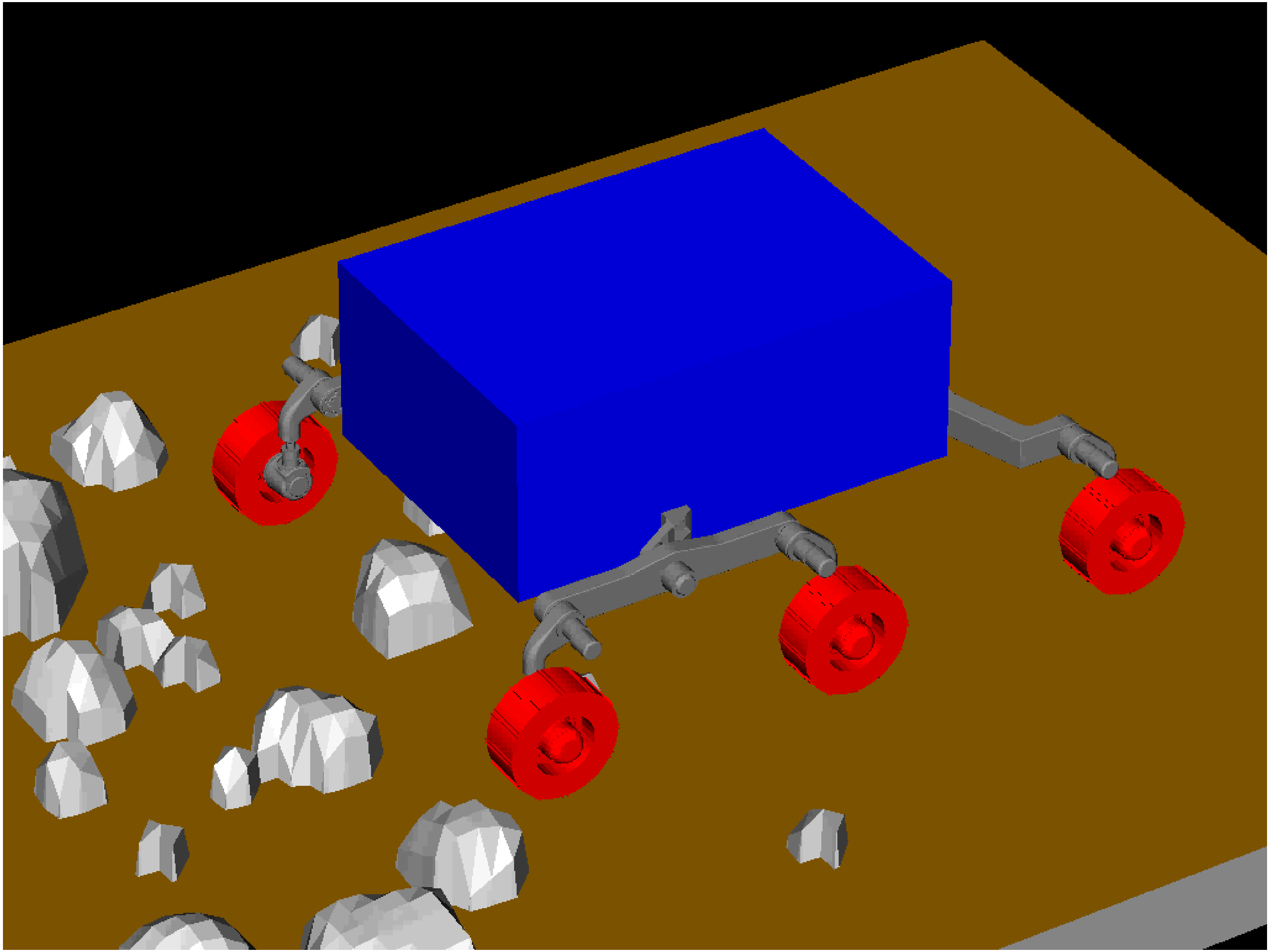


Joint Torque

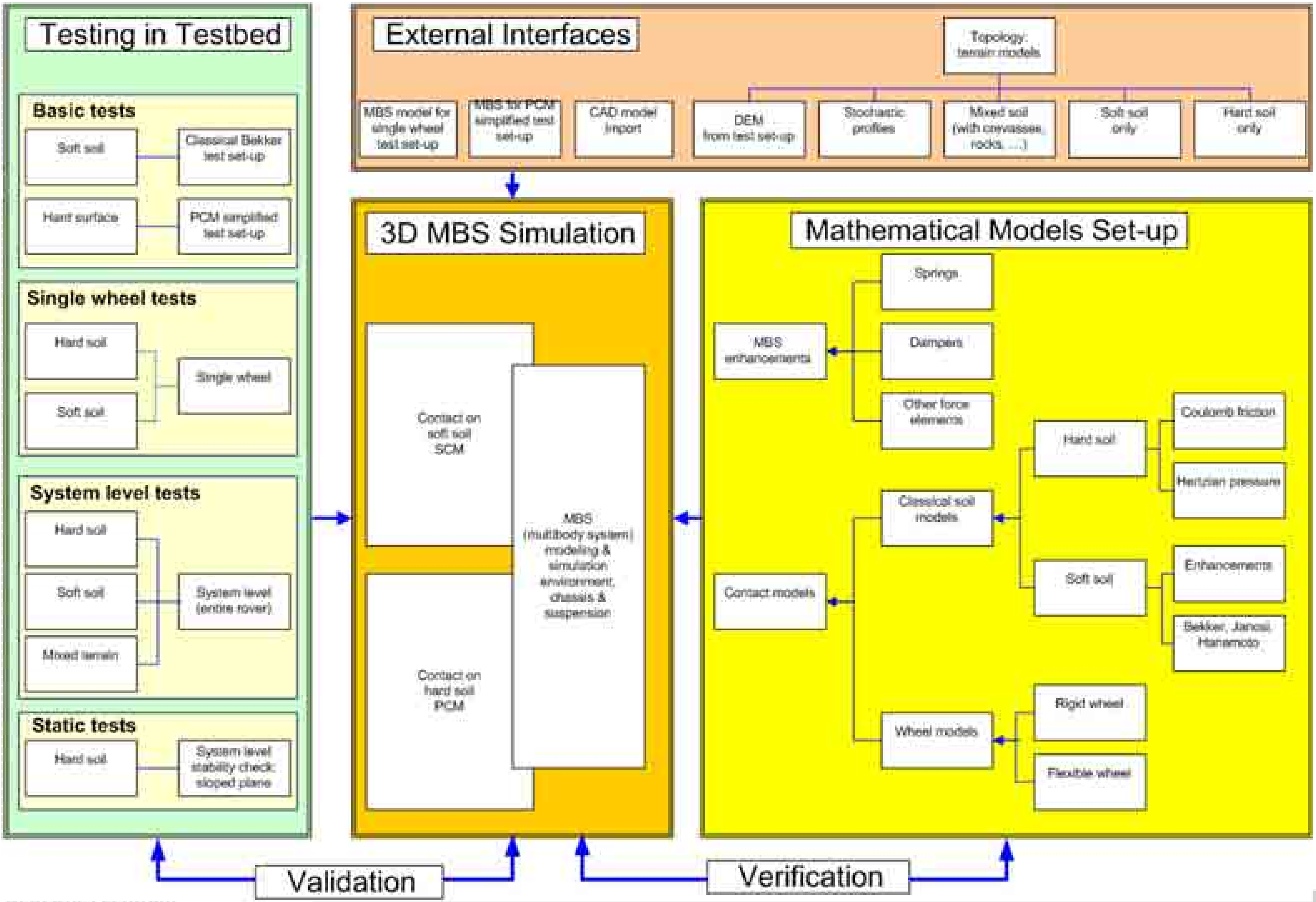




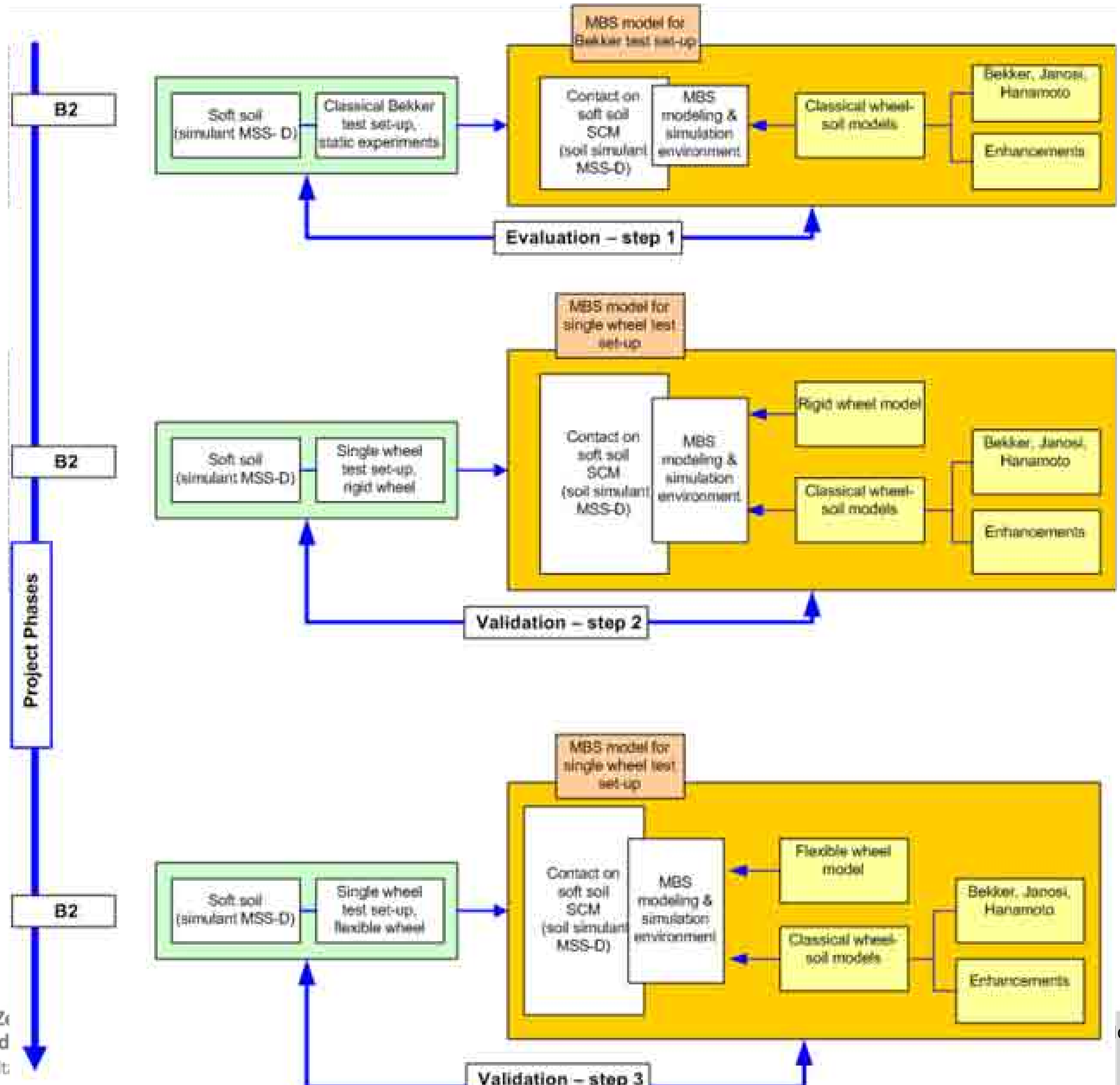
Conclusion: PCM + SCM



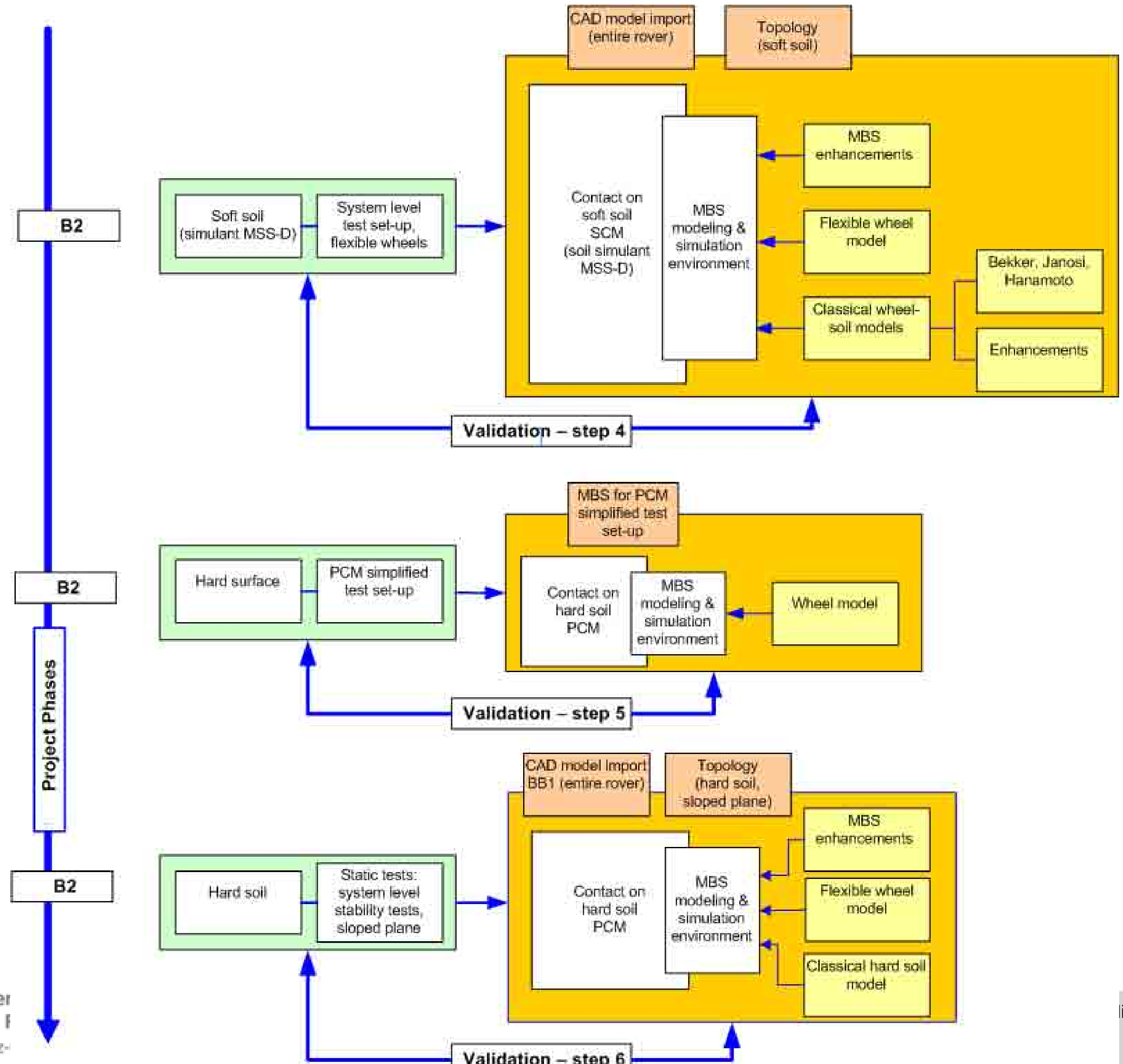
Validation and Verification V&V



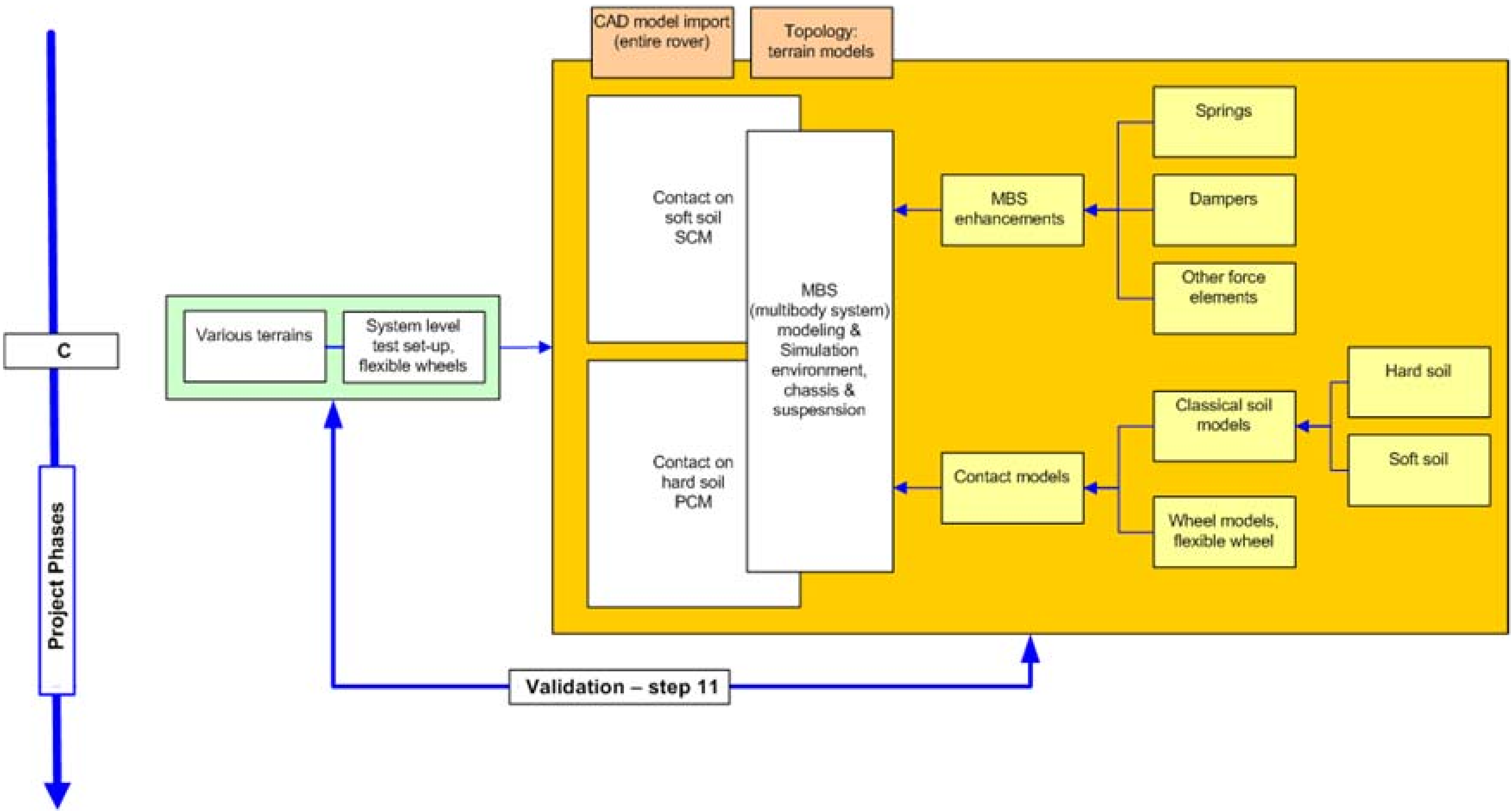
Validation steps 1, 2 and 3



Validation steps 4, 5 and 6

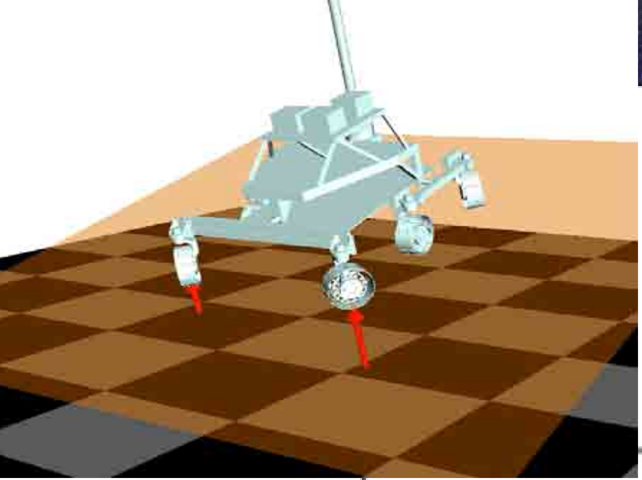


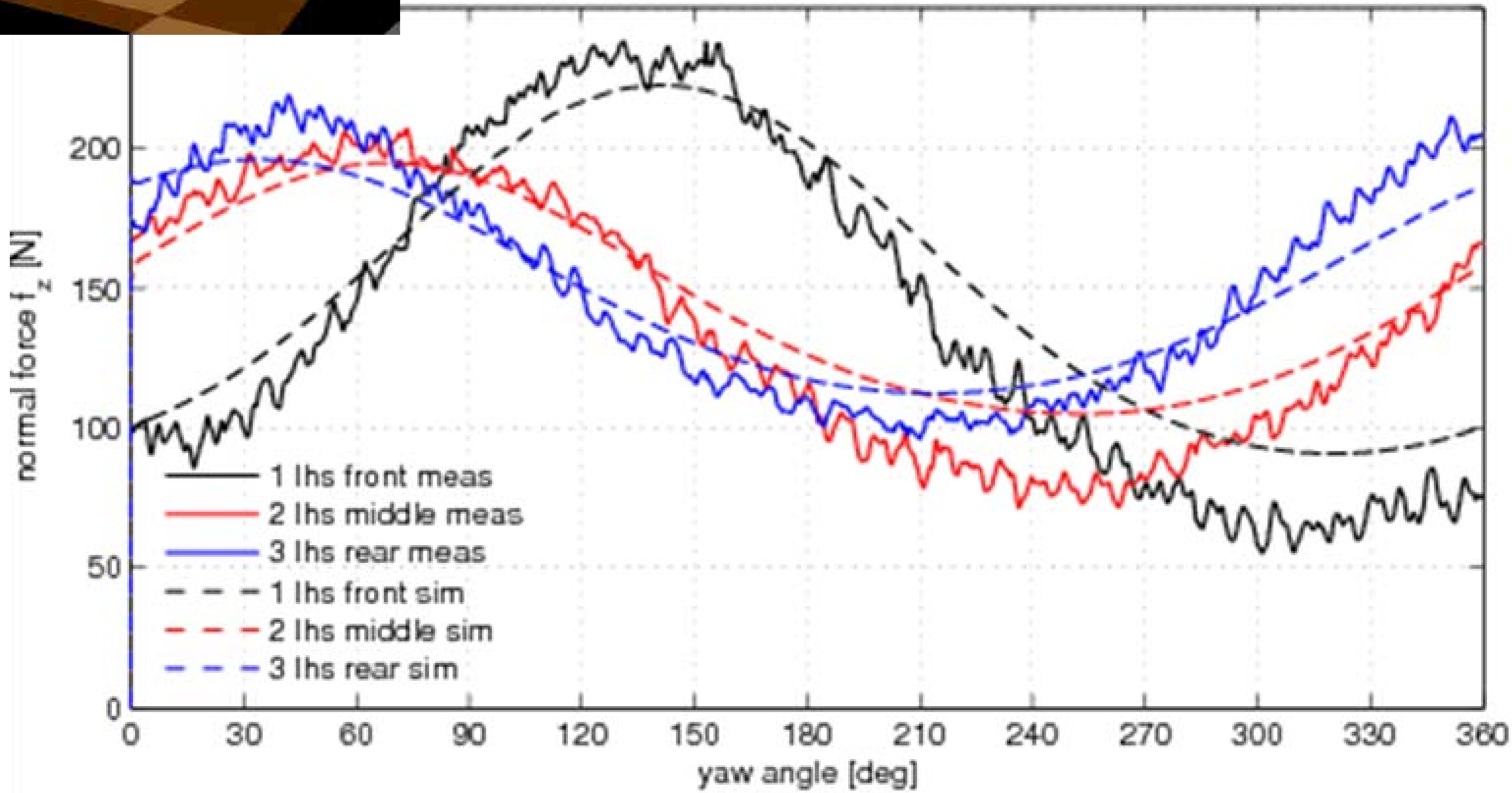
Validation step 11 (final)



Correlation Results (Experiment – Simulation)

- Correlation lhs 15° slope
- Good correlation





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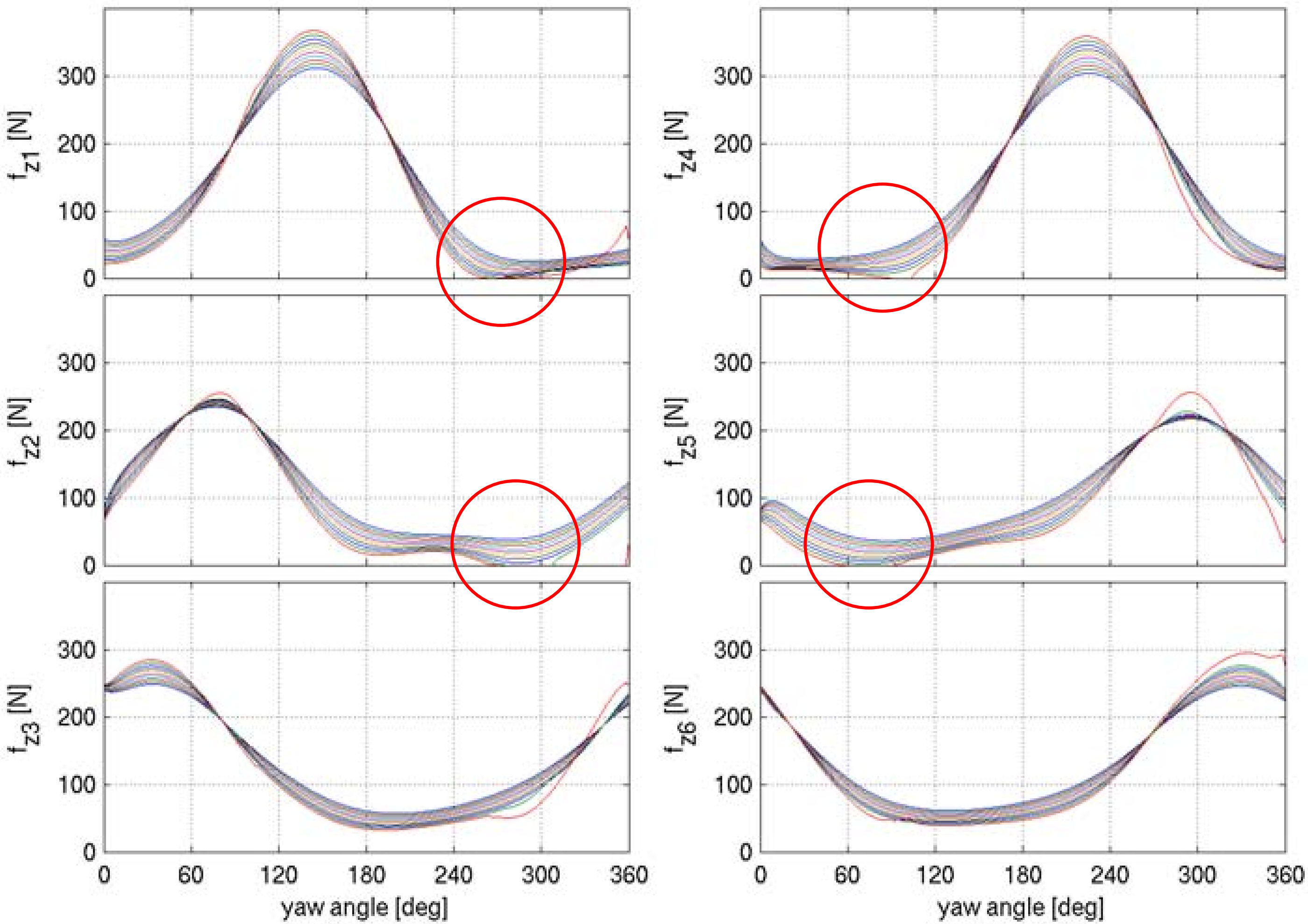
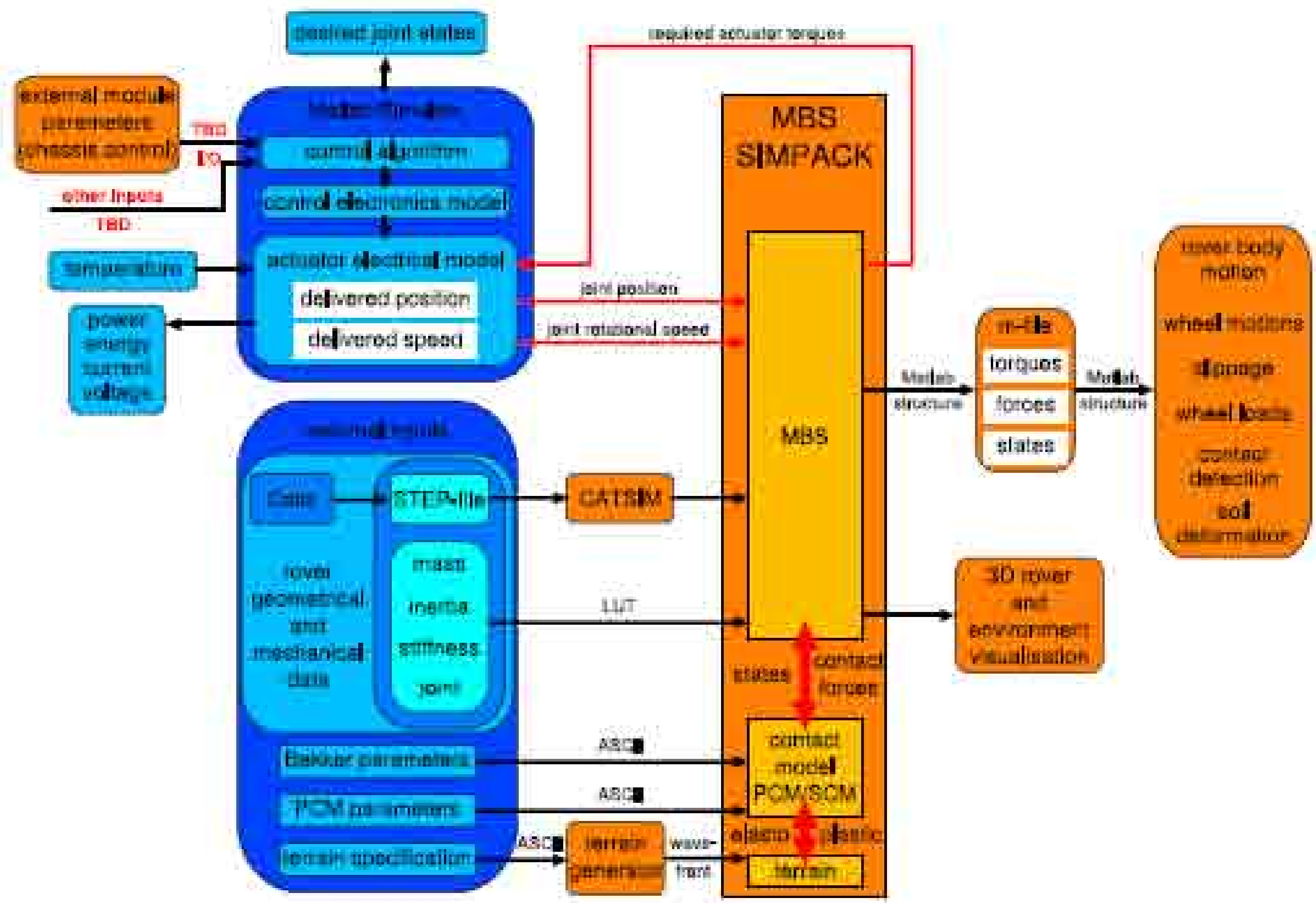
Simulation Results

- Slope angle parameter variation from 34-44° with flexible wheels
- Symmetric stability limit for front and middle wheels
- Rear bogie not at stability limit



Simulation Architecture

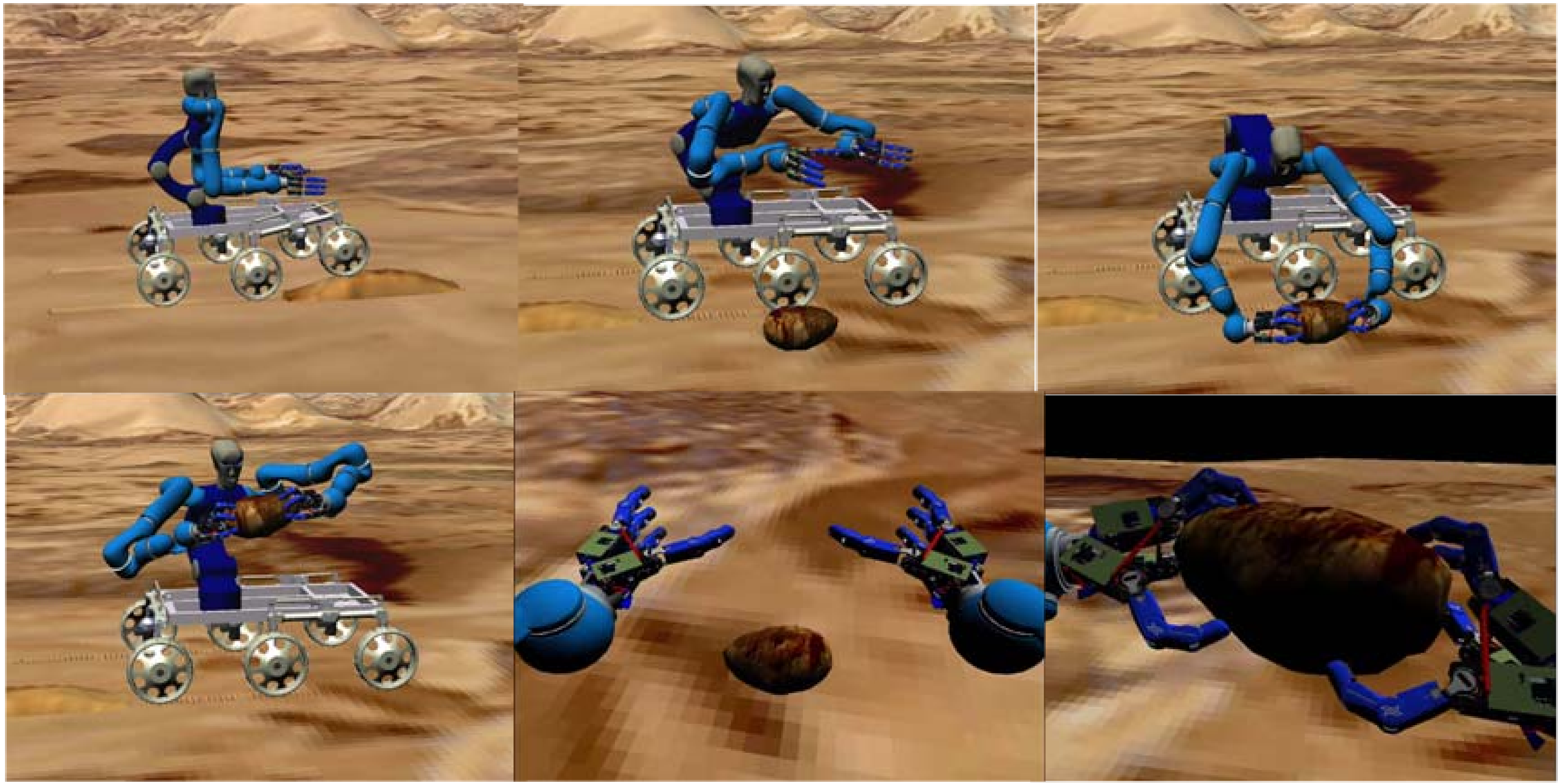


ROCC Rover Operations Control Center (ALTEC, I)

Recommendation:
3D-S Tool to be used for rover operational phases

- 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
- To increase reliability into the next trajectories to be determined by the ground operator

Future Planetary Exploration:
Rovonaut = Robonaut on Rover



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