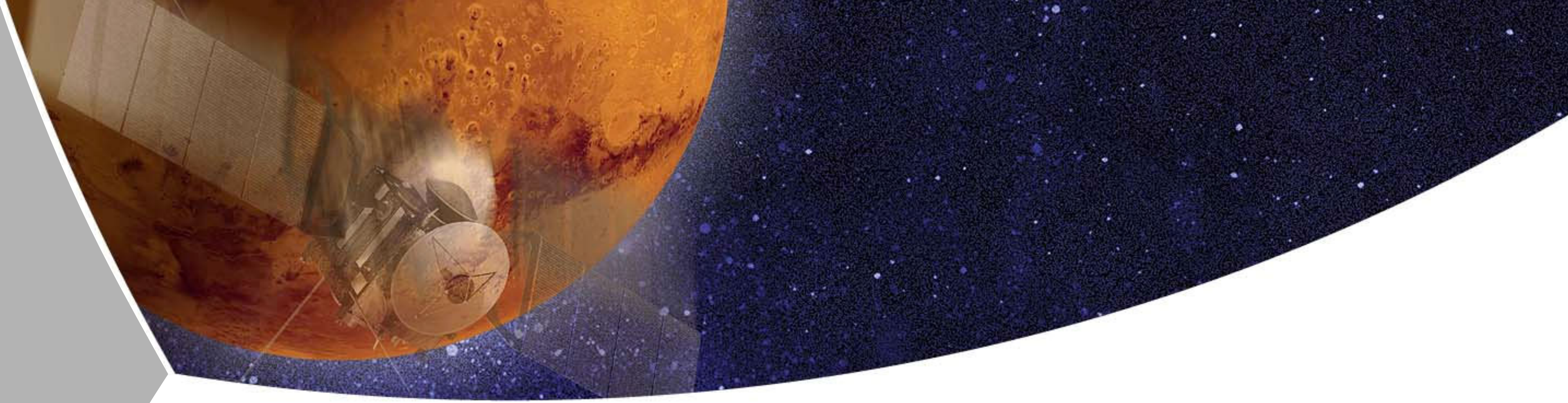


MBS Simulations and Performance Testing of Planetary Rover Locomotion

Rainer Krenn, Max Apfelbeck, Andreas Gibbesch, Bernd Schäfer, Annett Chilian, Martin Görner

DLR, German Aerospace Center, Institute of Robotics and Mechatronics
Oberpfaffenhofen, DE-82234 Wessling

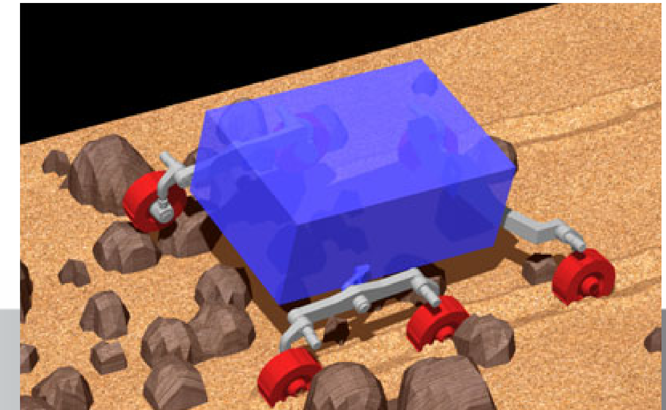
ICRA10 Planetary Rover Workshop,
2010 International Conference on Robotics and Automation

Anchorage, Alaska, USA, May 3, 2010

Deutsches Zentrum
für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

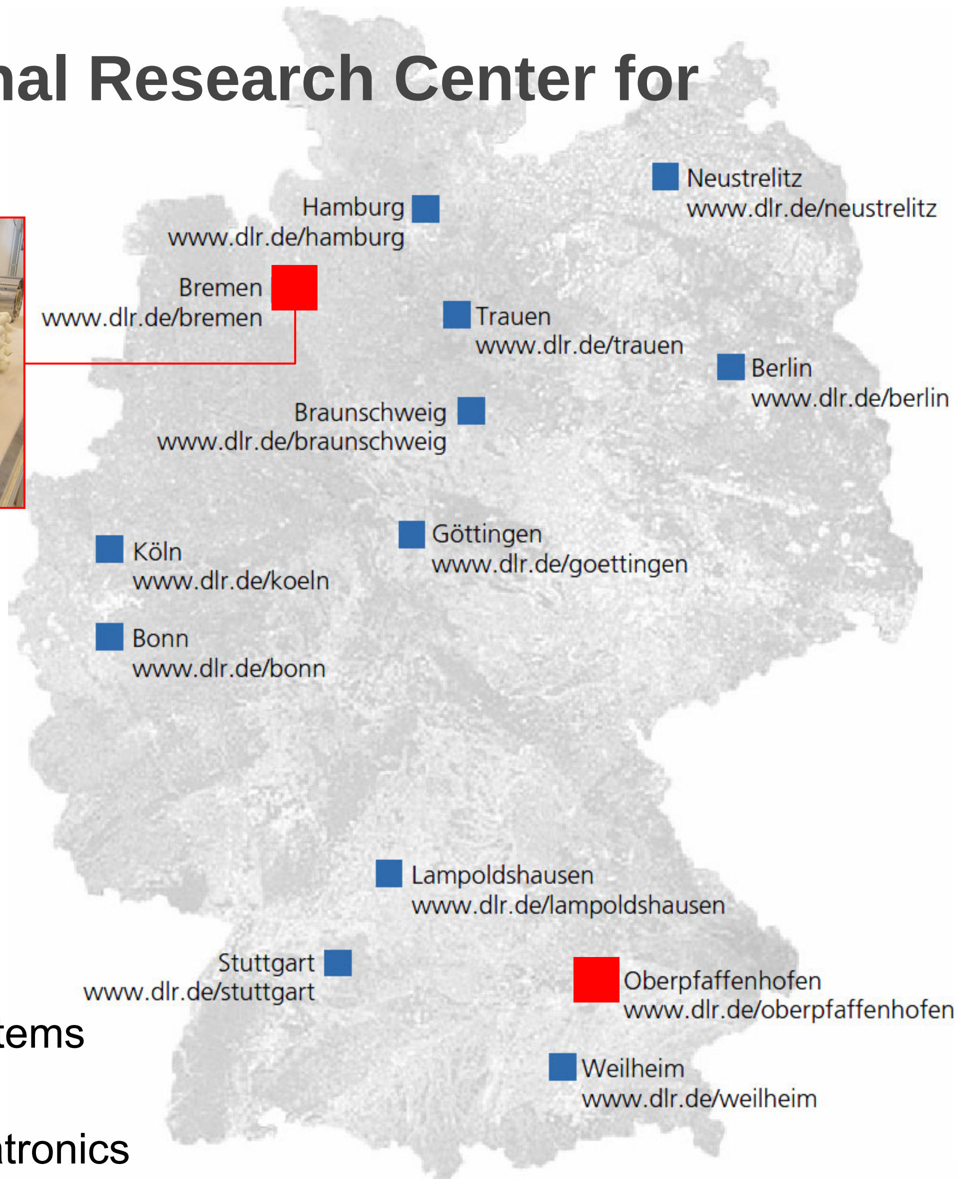
Topics of Presentation

- Generally:
  Involvement of DLR in Robotics Mobility in terms of Planetary Applications
  - Rough and uneven terrain
  - Soft terrain
  - Unknown terrain
- In particular:
  Research and development results
  - Locomotion system
  - Navigation method
  - Simulation technique



DLR, Germany‘s National Research Center for Aeronautics & Space

- Research Programs
  - Aeronautics
  - Space
  - Transport
  - Energy
  - Security

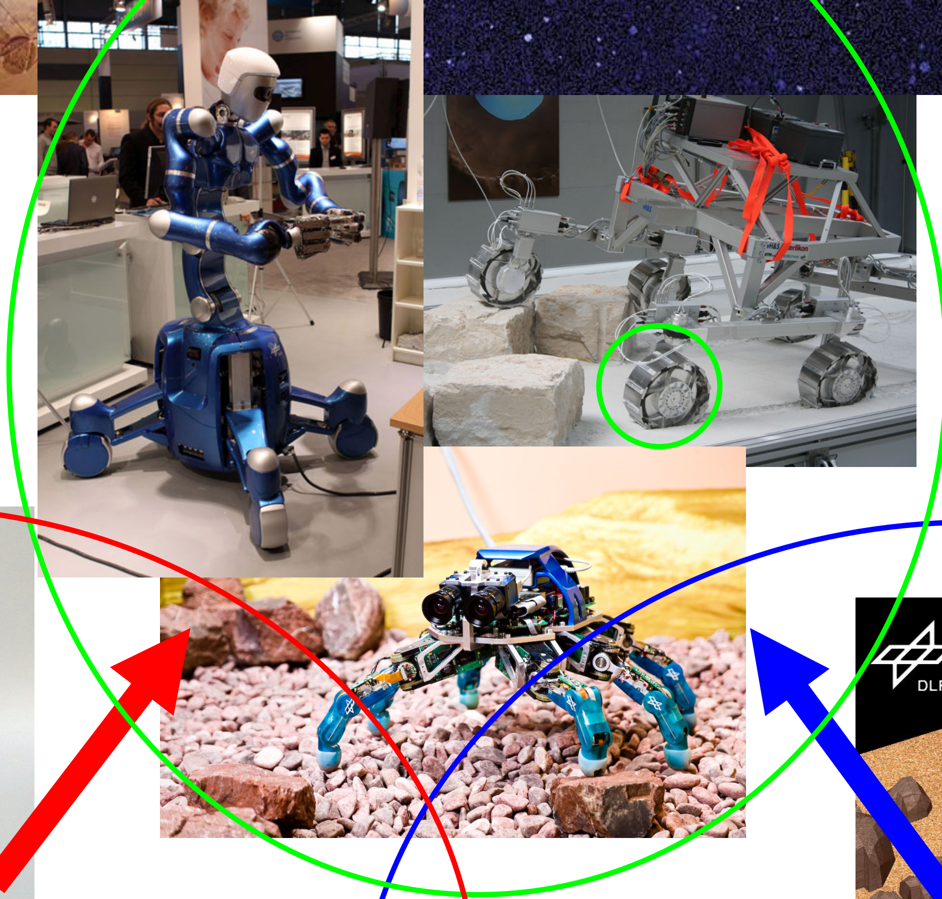


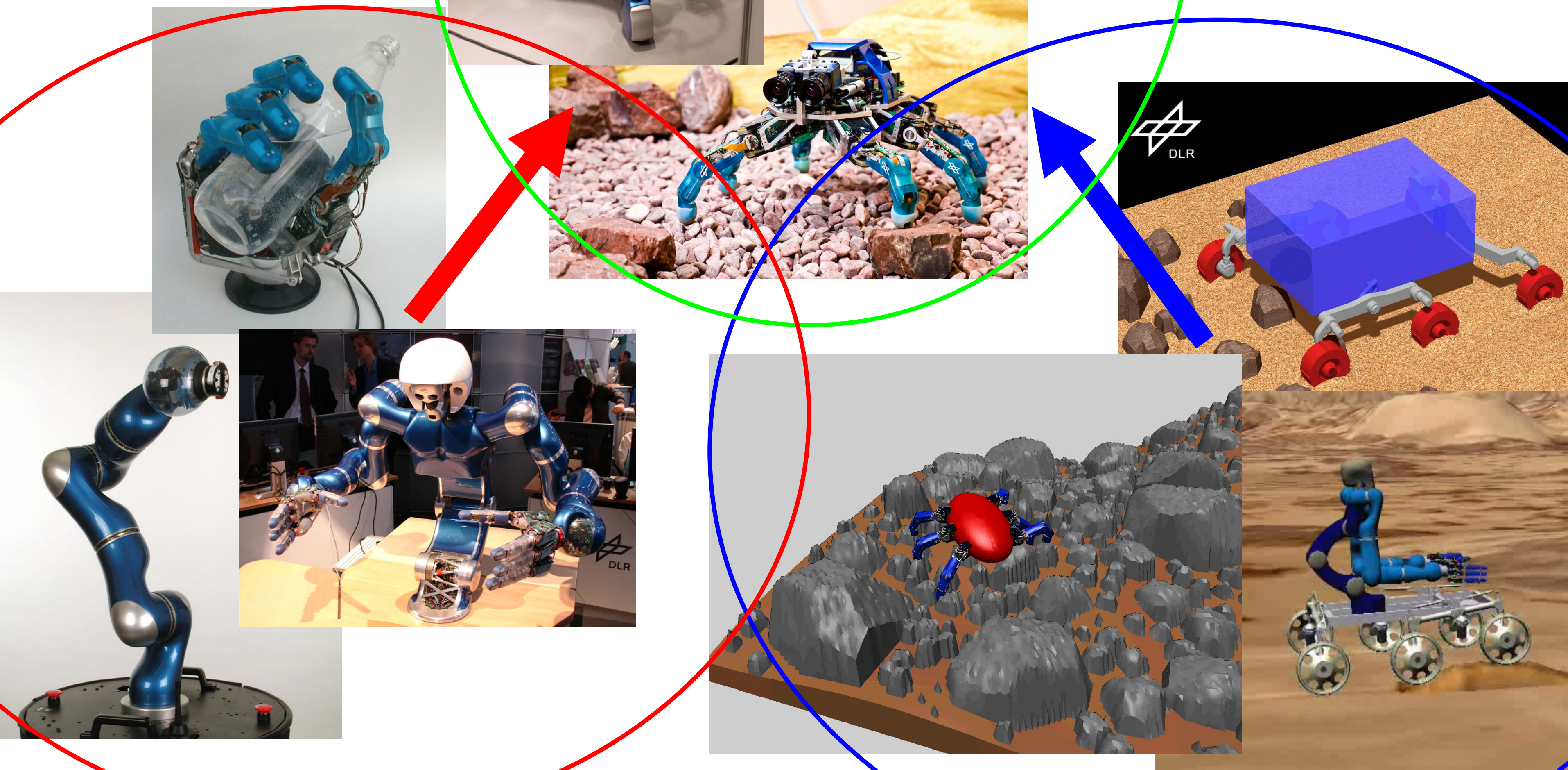
- 13 Locations
- 29 Scientific Institutes
- 6500 People

- Planetary Rover Activities
  - Bremen, Institute of Space Systems
  - Oberpfaffenhofen (Munich), Institute of Robotics and Mechatronics

Institute of Robotics and Mechatronics

“Transfer of Technology”





DLR Crawler (Example for Technology Transfer)

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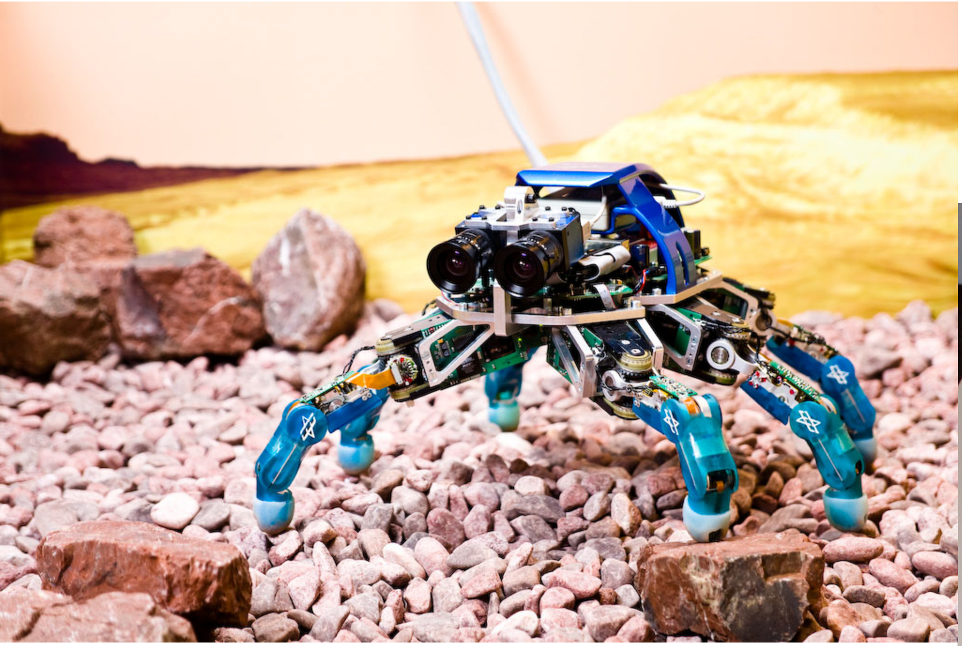
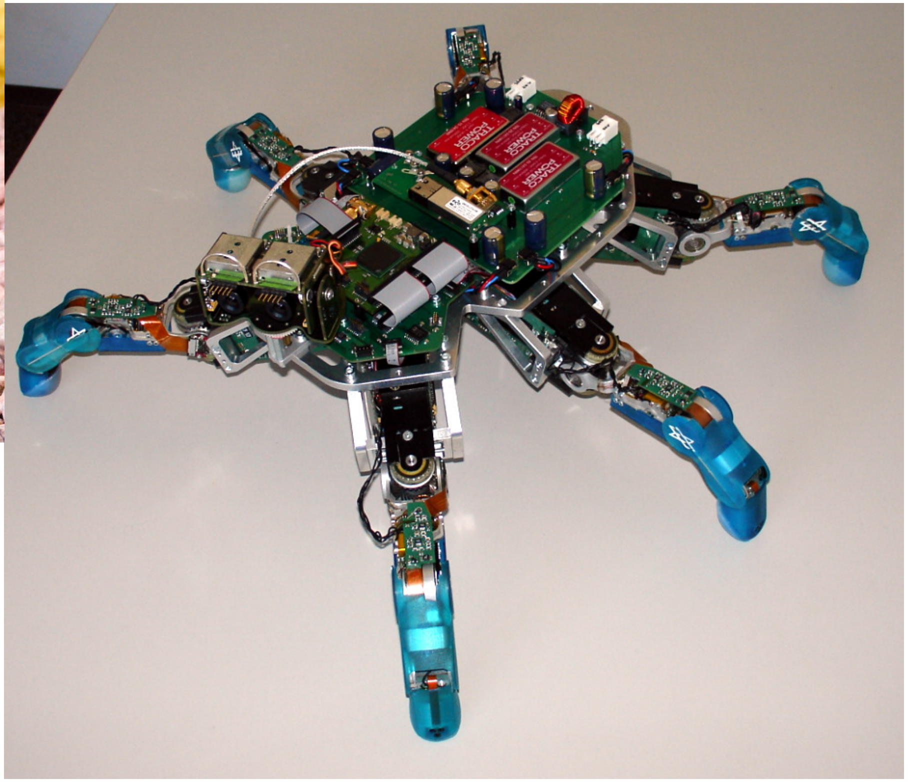


- Insect-like off-road locomotion system
- made from fingers of DLR hand

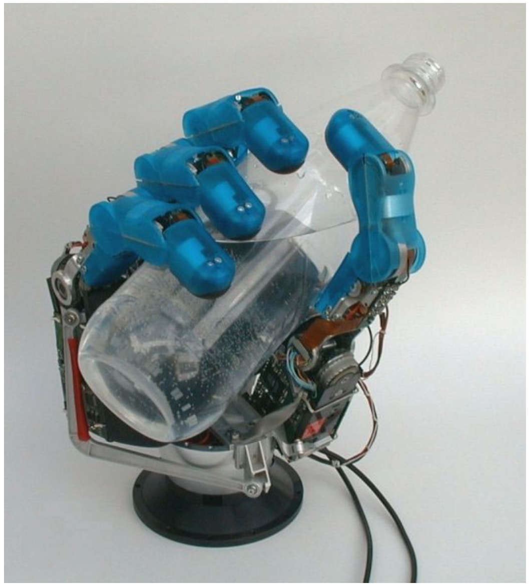


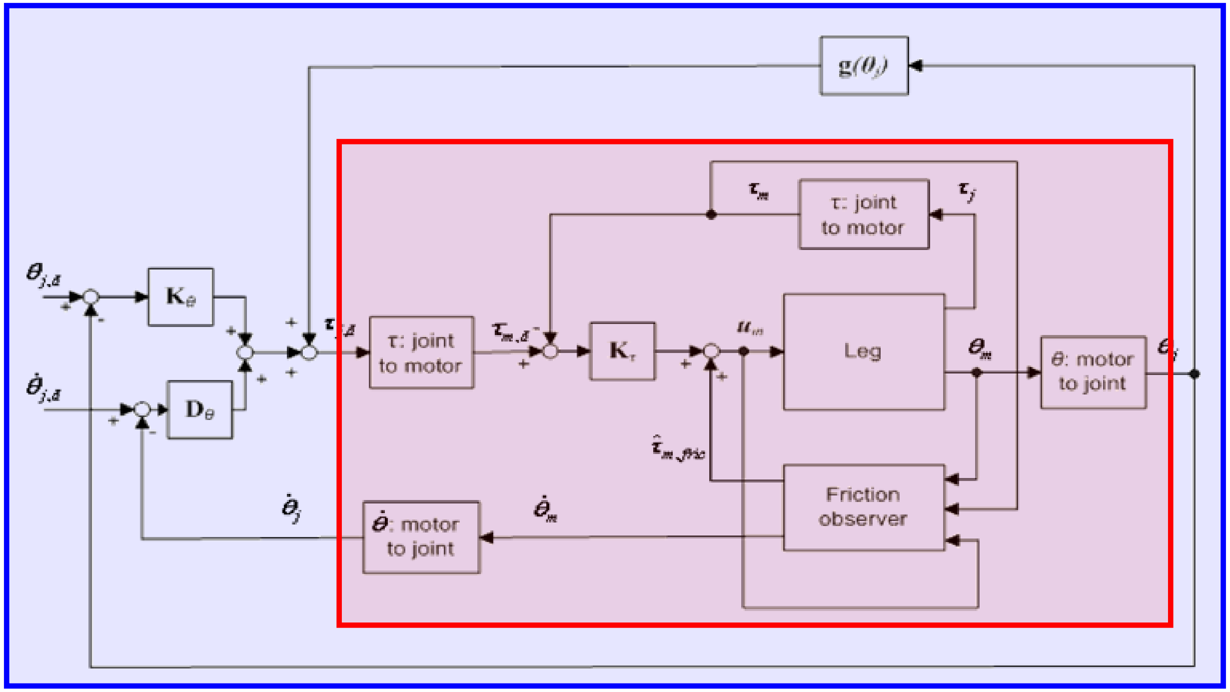
Paper ThE3.3 16:40 – 16:55

Analysis and Evaluation of the Stability
of a Biologically Inspired, Leg Loss Tolerant Gait
for Six and Eight-Legged Walking Robots

DLR Crawler: Active Joint Compliance Control

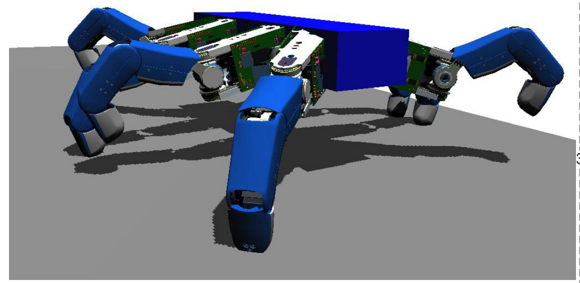
- Crawler control based on DLR hand control
- Adjustable stiffness/damping for each joint
- Compliant motion (like spring suspended chassis)

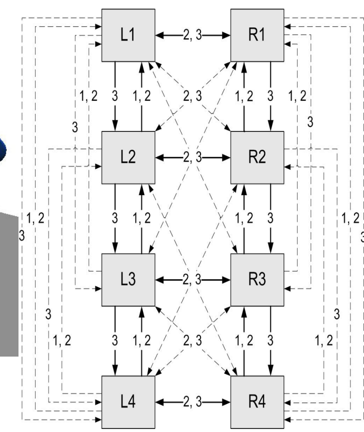


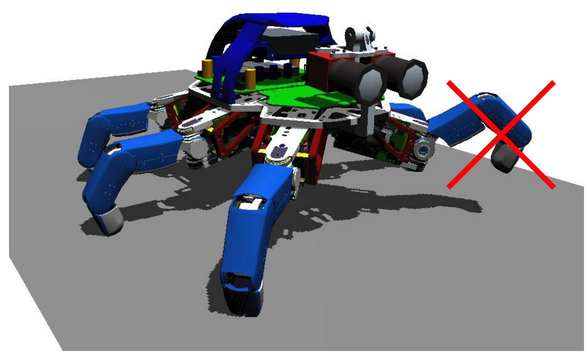


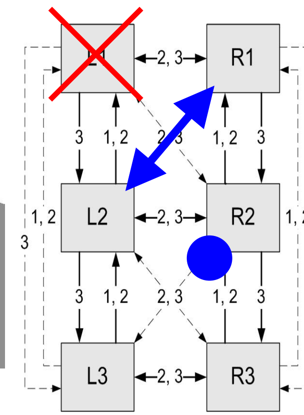
DLR Crawler: Gait inspired by Cruse‘s Rules

- Employs rules for leg coordination that biologists identified for the Stick Insect
- Gait implementation of Crawler:
  - No fixed gait pattern
  - No centrally controlled gait
  - Minimal set of central instruction
  - Each leg controls its own activities based on state information from neighbor legs in the network
- Modular control solution
  - Extension of attendees:
    6 legs → 8 legs
  - Reduction of attendees:
    Leg loss handling by
    re-definition of neighborhood









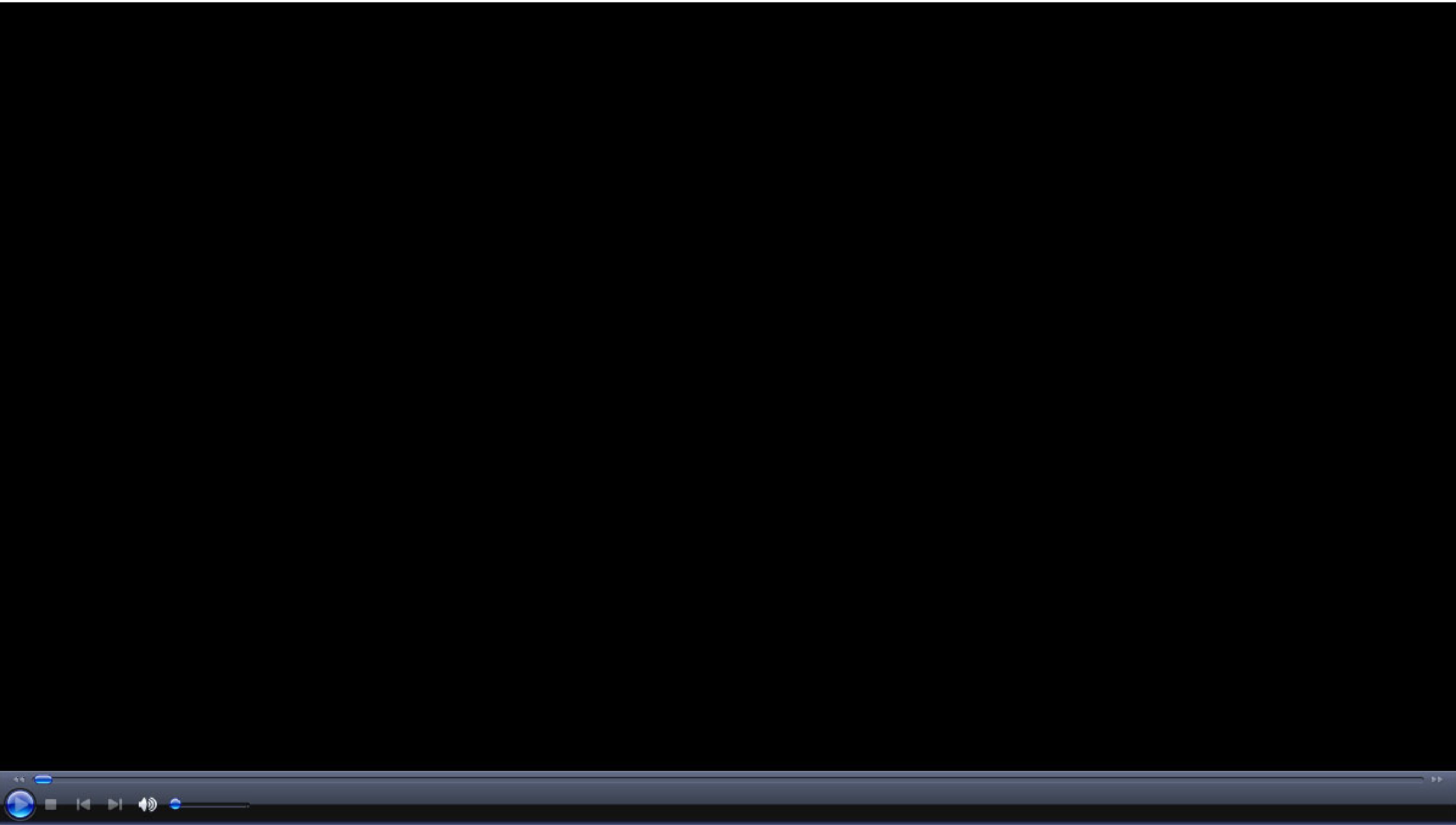
Biologically Inspired,
Leg Loss Tolerant Gait
for an
Actively Compliant,
Walking Hexapod Robot

DLR Crawler: Reflexes

- In order to master uneven terrain and different substrates reflexes are implemented
- Stretch Reflex to enforce ground contact during stance
  - Activated to master local holes
  - Activation stretches leg
    if joint torques drop below a certain threshold
- Elevator Reflex to avoid contact during swing phase
  - Activated to master local obstacles (e.g. steps, bricks)
  - Activation retracts and lifts a leg
    if unexpected joint torques are encountered
- Both reflexes in combination allow the Crawler to master obstacle heights of about 6 cm autonomously without planning

Stereo Camera Based Navigation on Rough Terrain

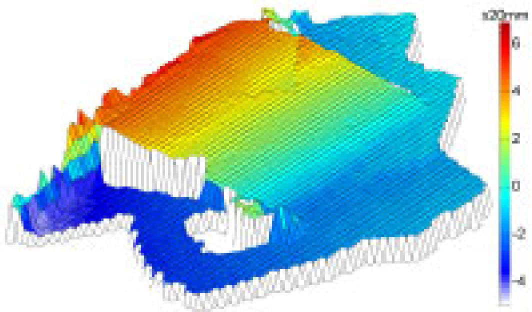
Heiko.Hirschmueller@dlr.de, Annett.Chilian@dlr.de



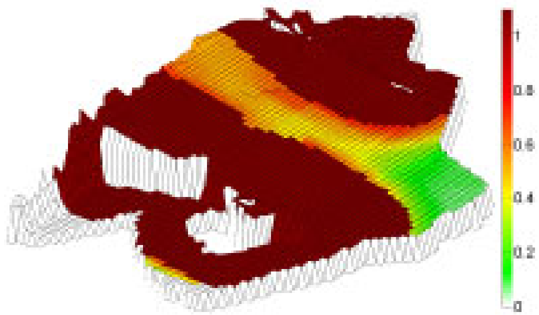
Stereo Camera Based Navigation on Rough Terrain

Annett.Chilian@dlr.de

Terrain Traversability Estimation

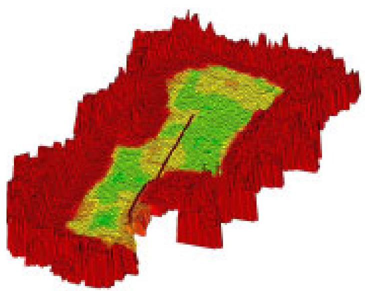


Digital Elevation Map

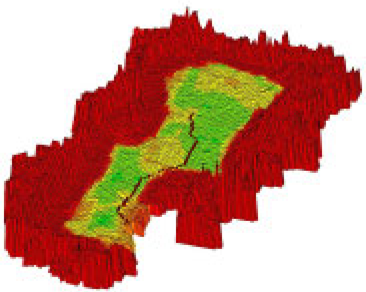


Traversability Values

Path Planning

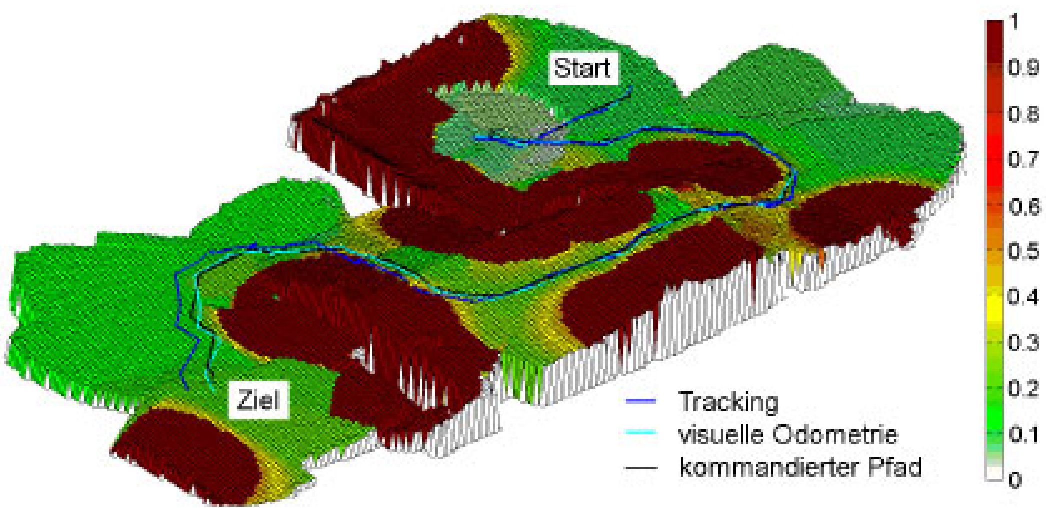


Focus on short path

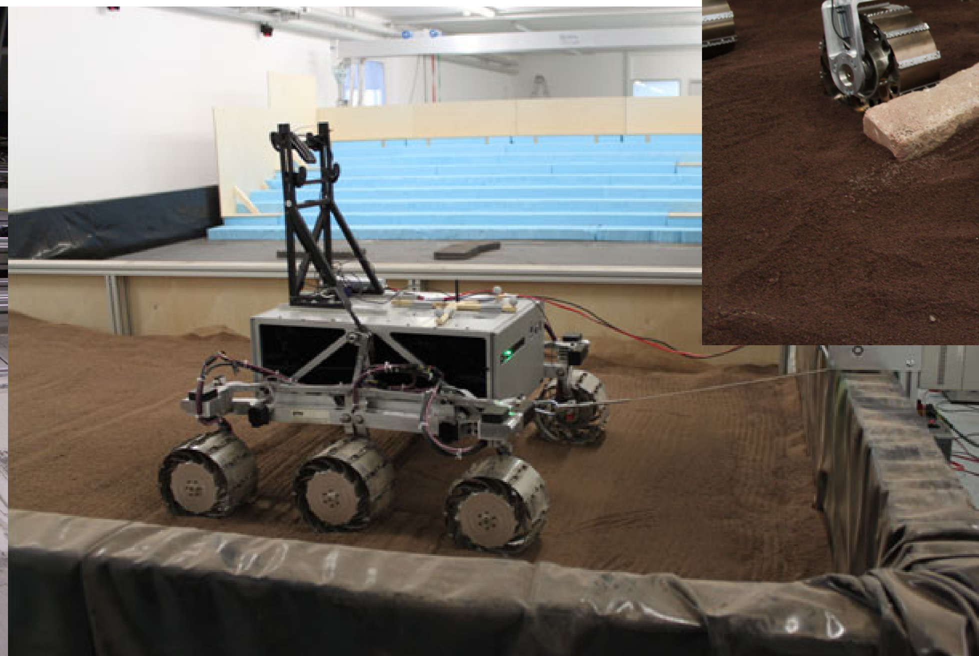


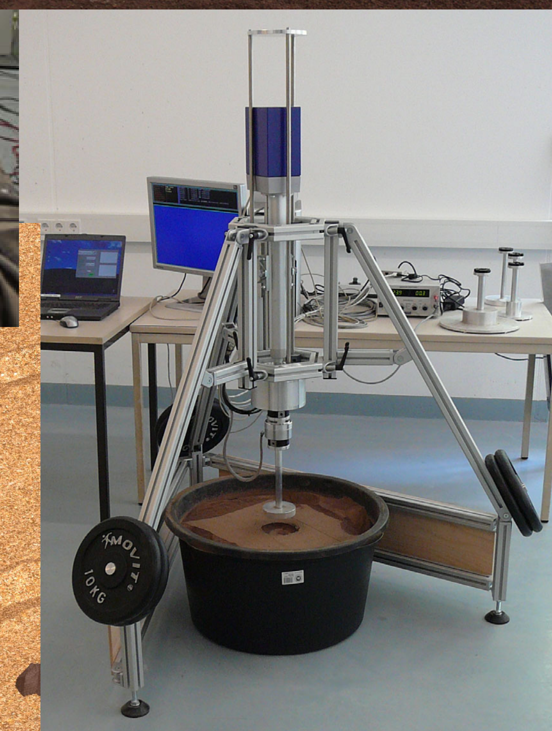
Focus on safe path

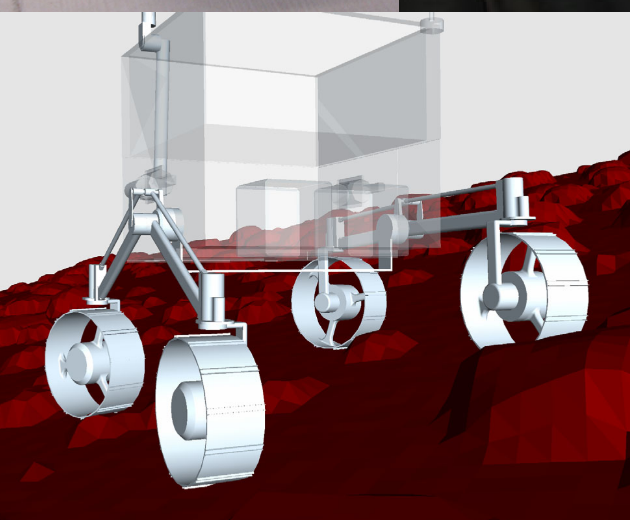
Navigation to a given goal point in unknown rough terrain

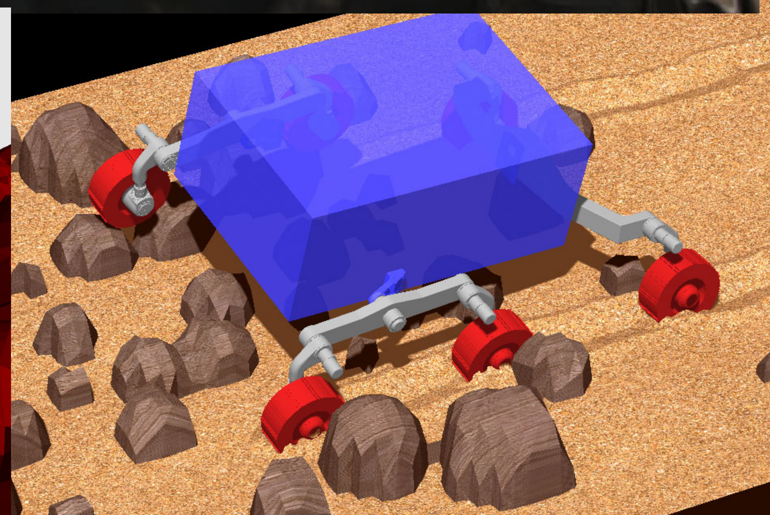


Modeling & Simulation of Wheel-Soil Interaction



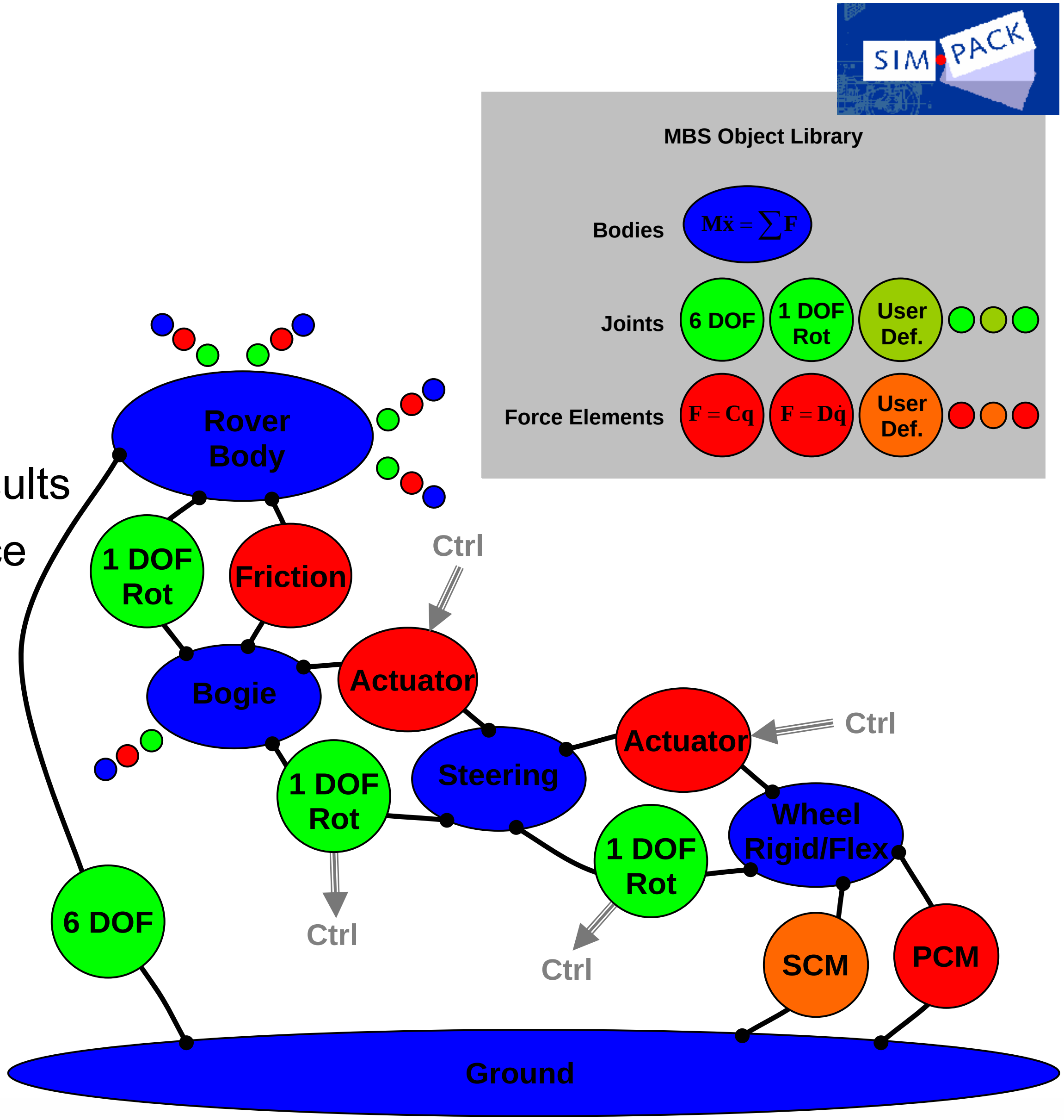




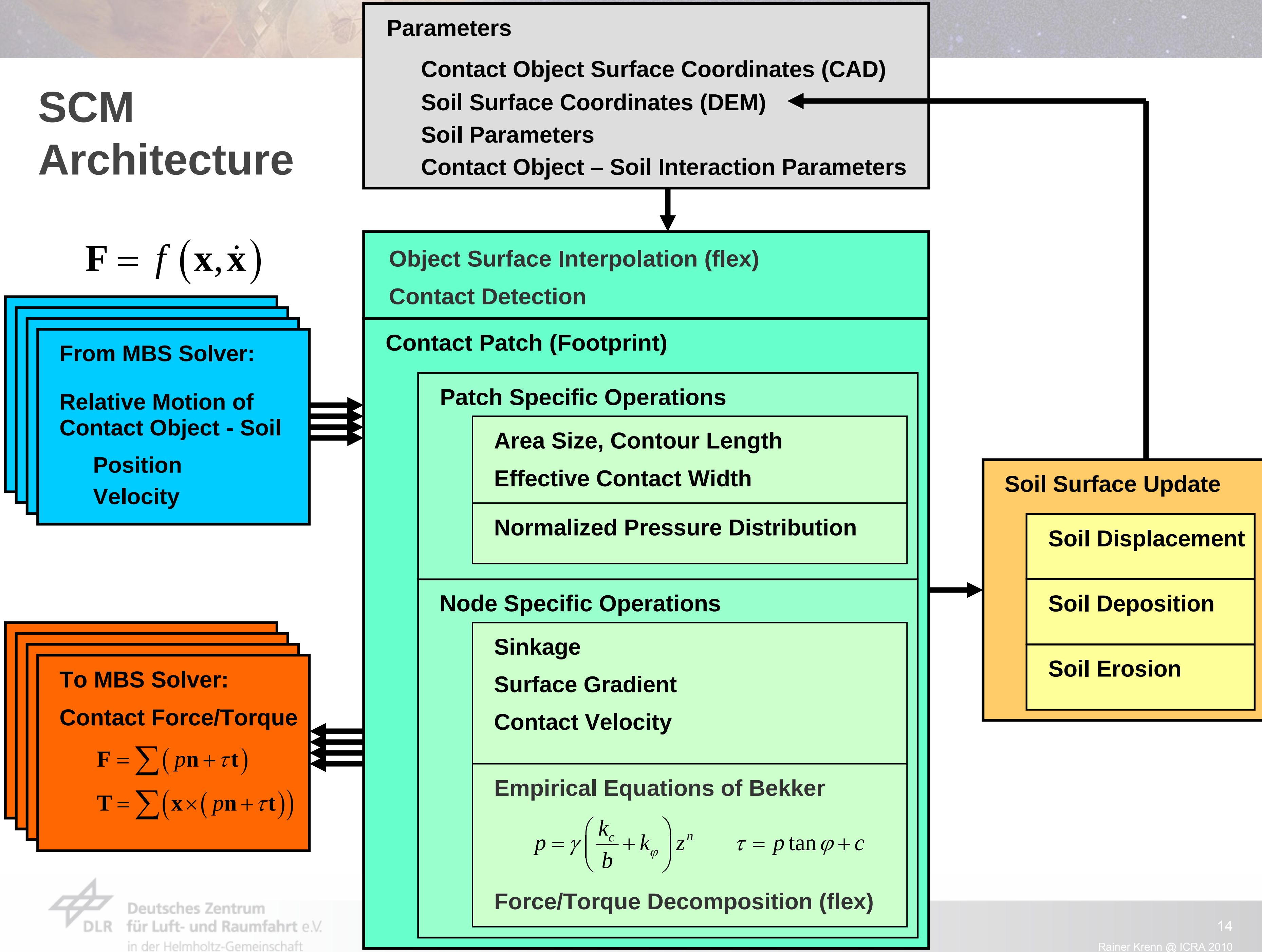


Requirements for Soil Contact Model

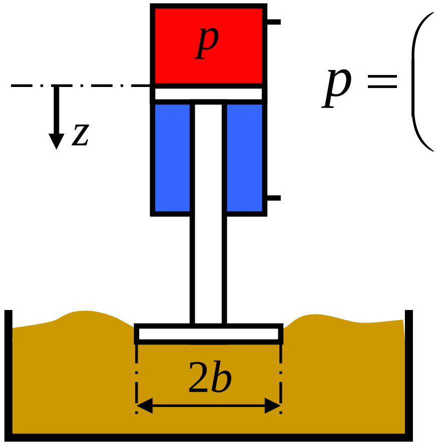
- Multi-Body System Simulation: Good compromise of
  - model complexity
  - accuracy of simulation results
  - computational performance
- Object based modeling
- Application independent contact model implementation
  - Soft terrain
  - Arbitrarily shaped bodies
  - Full 3D / 6 DOF
  - Rigid and flexible objects



SCM Architecture



Bekker Theory → SCM



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

	Applied Bekker Theory	SCM Implementation
Dimensions	1D, 1DOF	3D, 6DOF
Sinkage z	Equal to positon of piston	Discrete local sinkage at contact patch
Contact width b	Contact width of geometric primitives (circle, rectangle)	Effective contact with of arbitrarily shaped contact patches
Pressure p	Proportional to hydraulic pressure	Discrete local contact pressure at contact patch

Parameters of Soil Contact Model (3D, 6DOF)

- Soil surface description: Digital elevation model DEM
  - Gravity in z
  - Regular spaced grid in x and y
- Soil dynamics parameters (Bekker)
  - Global or individual parameters

k_c: Cohesive modulus

k_φ: Frictional modulus

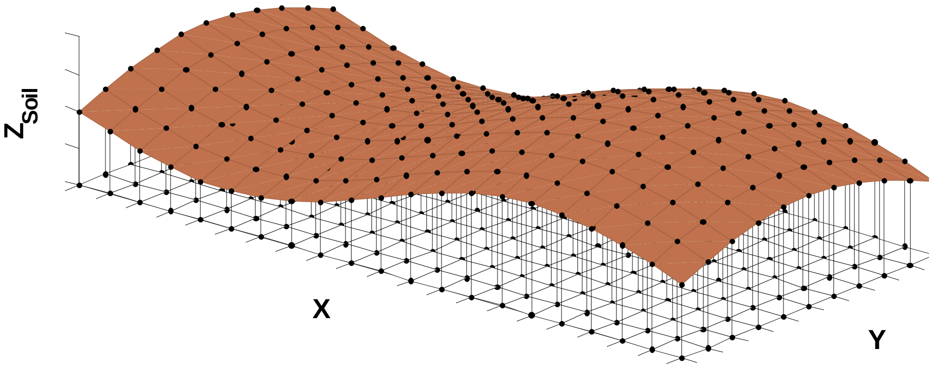
n: Exponent of sinkage

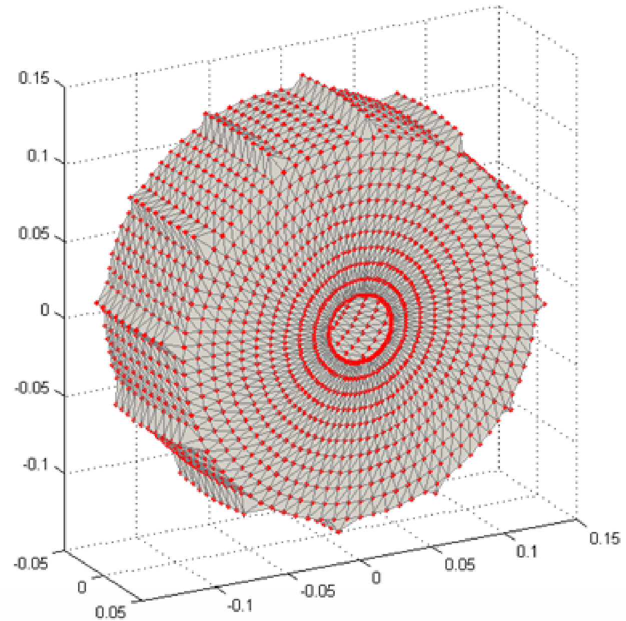
c: Soil cohesion

φ: Angle of internal soil friction

μ: Surface friction modulus

ψ: Angle of repose



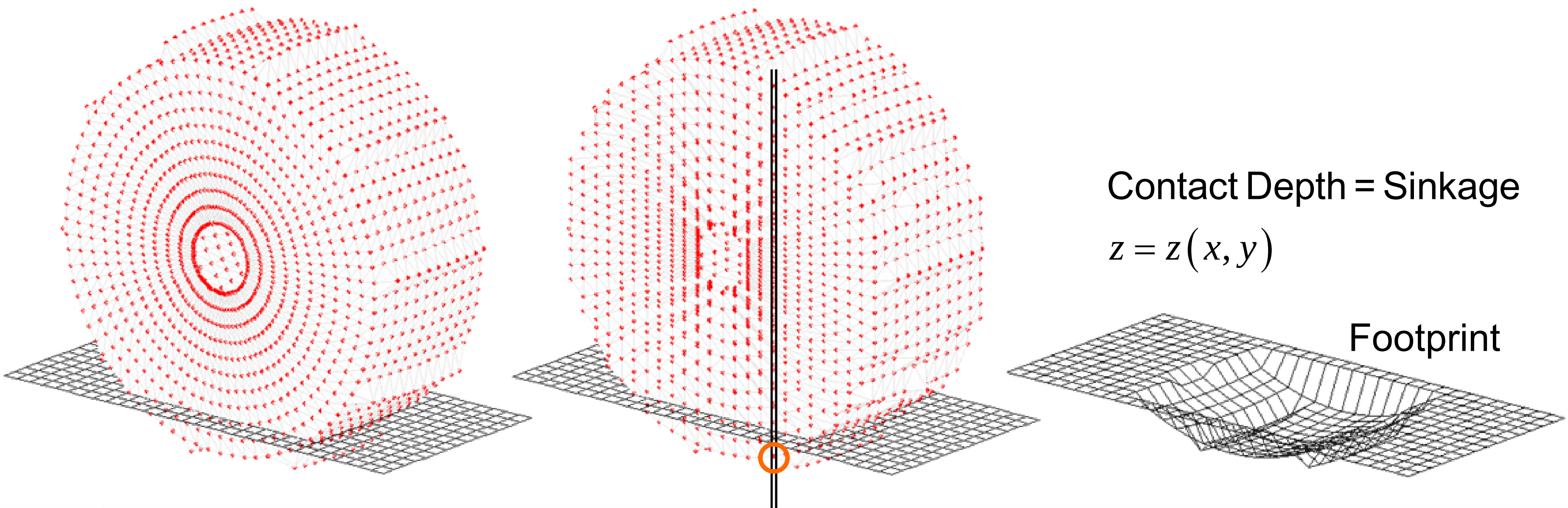


- Contact object surface description:
  Cloud of surface vertices of a polygonal mesh grid

Contact Detection, Footprint Computation (*z*)

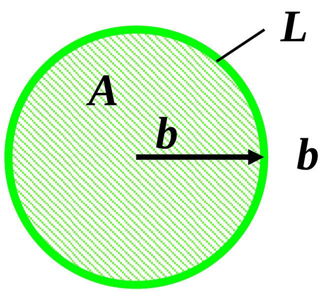
$$p = \left(\frac{k_c}{b} + k_\varphi \right) z^n$$

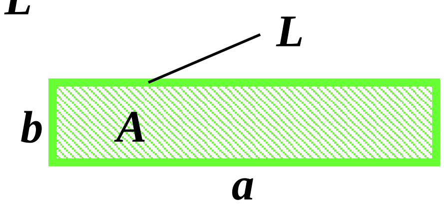
- Mapping of vertex co-ordinates (x,y) onto grid of soil DEM → Vertex columns at soil grid nodes
- Contact detection: Column minimum < Soil grid node height
- Brute force method or BV-tree contact detection (AABB tree)

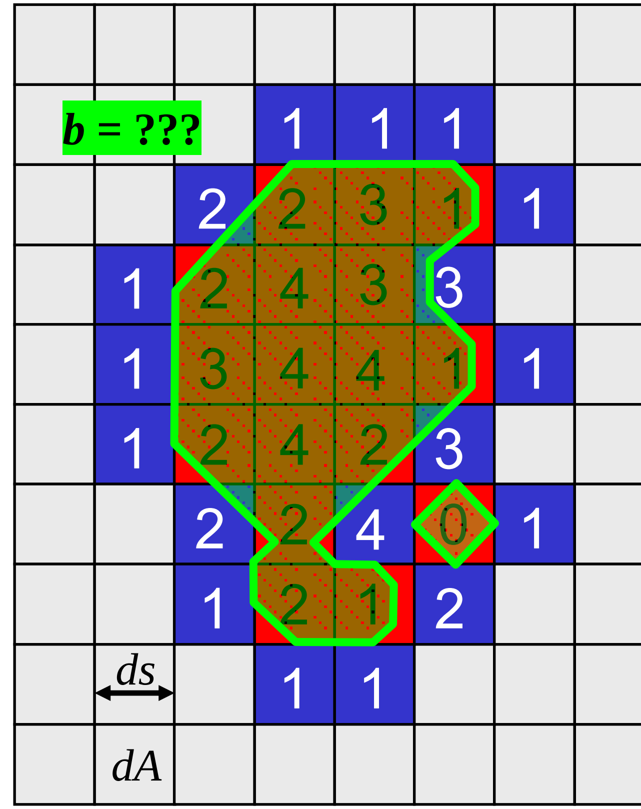


Effective Footprint Width (b)

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







Circular Probe: $b = r; \quad A = b^2\pi; \quad L = 2b\pi; \quad b = \frac{2A}{L}$

Rectangular Probe: $b \ll a; \quad A = a \cdot b; \quad L = 2a + 2b; \quad b \approx \frac{2A}{L}$

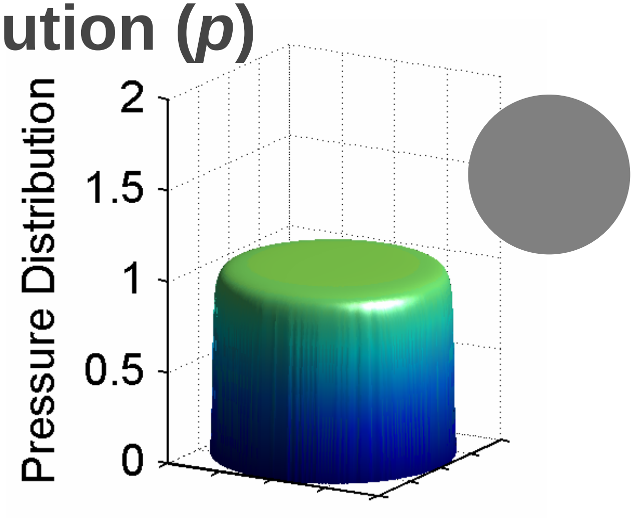
$b_{eff} = \frac{2A}{L};$ Allways computable

Area Size: $A = \sum_{i=1}^{n_{Contact}} c_{A,Contact,i} dA + \sum_{j=1}^{j=n_{Contour}} c_{A,Contour,j} dA; \quad c_A = [0 \ldots 1]$

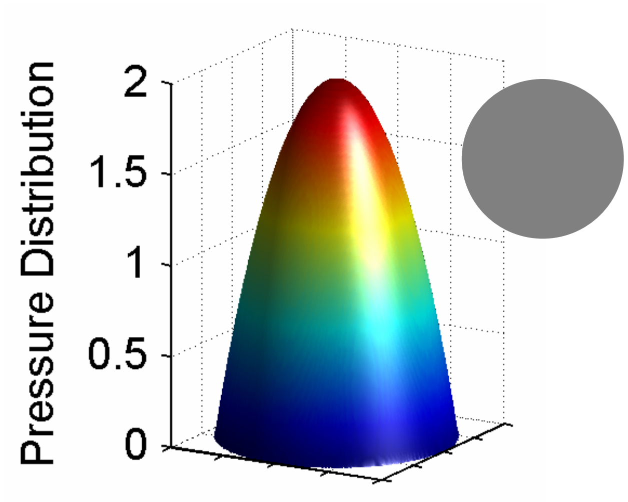
Contour Length: $L = \sum_{i=1}^{n_{Contact}} c_{L,Contact,i} ds + \sum_{j=1}^{j=n_{Contour}} c_{L,Contour,j} ds; \quad c_L = \left[0 \ldots \frac{1}{\sqrt{2}} \right]$

Pressure Distribution (*p*)

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



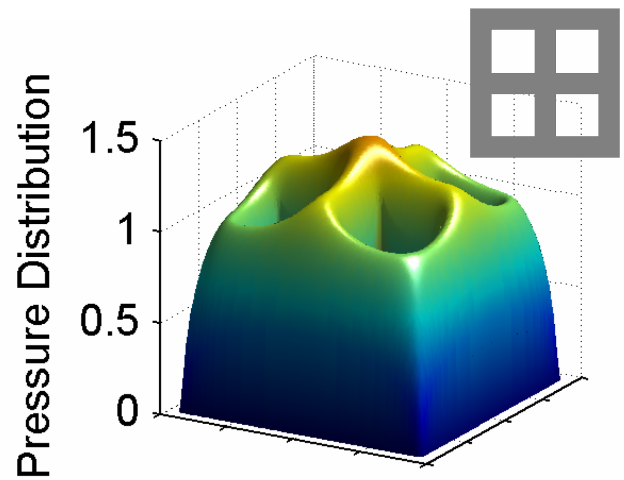
Dominant internal soil friction *φ*, max ≈ 1 (dry hard soil)



Dominant soil cohesion *c*, max ≈ 2 (saturated clay)

$$\gamma_i = \frac{n_{Contact} R_i}{\sum_{j=1}^{n_{Contact}} R_j}; \quad R_i = \sum_{j=1,\, j \neq i}^{n_{Contact}} \frac{1}{\left(\left(\mathbf{r}_j - \mathbf{r}_i \right)^T \left(\mathbf{r}_j - \mathbf{r}_i \right) \right)^{f\left(\frac{\tan\varphi}{c} \right)}}$$

- Computation as function of
  - Centrality of contact node location
  - Relationship soil cohesion — internal soil friction
- Mean value = 1



Contact Forces / Torques

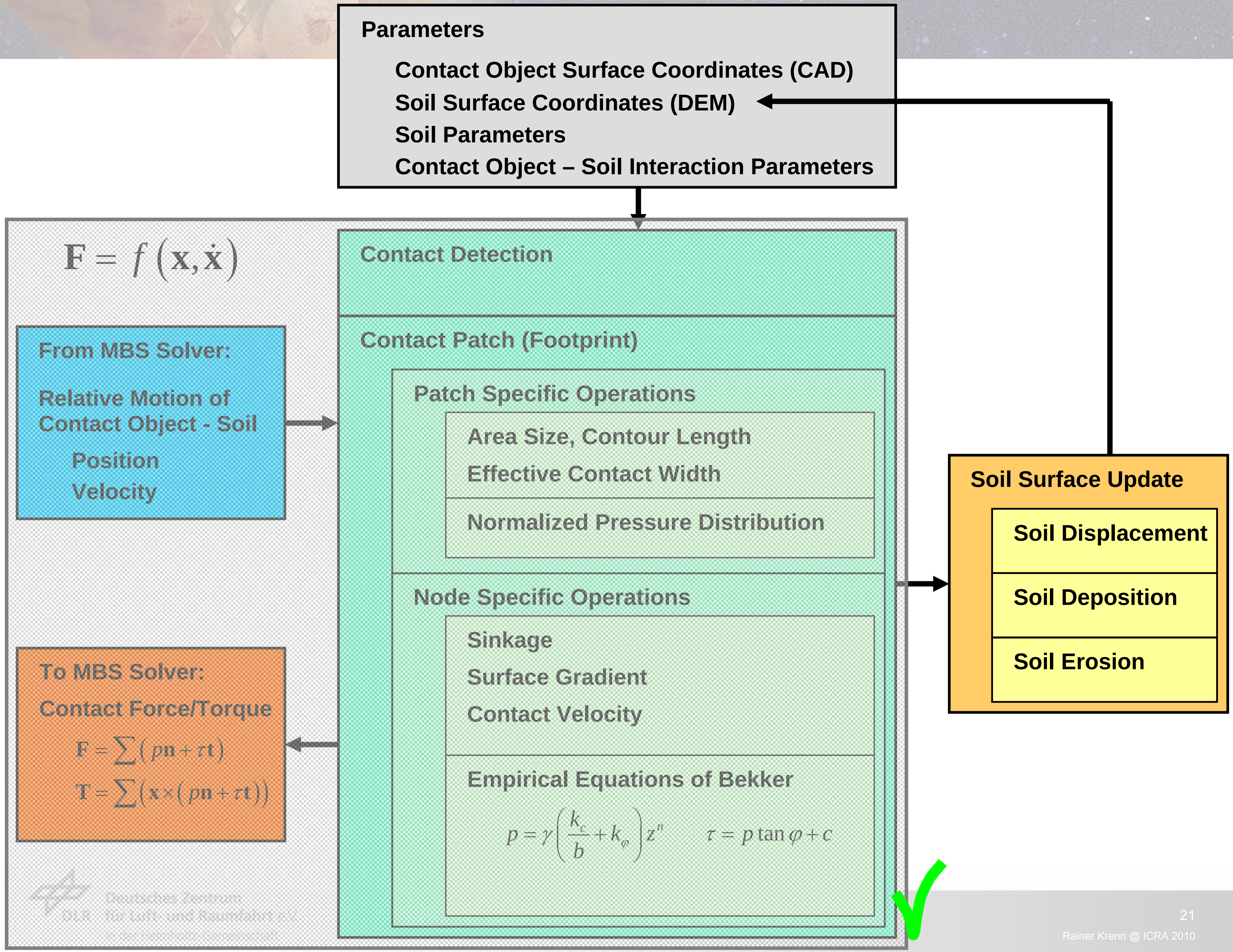
$$p_i = \gamma_i \left(\frac{k_c}{b_{eff}} + k_\varphi \right) z_i^{\,n}$$

$$\mathbf{F}_i = \left(\begin{pmatrix} c \\ c \\ 0 \end{pmatrix} + p_i \begin{pmatrix} \tan\varphi & 0 & 0 \\ 0 & \tan\varphi & 0 \\ 0 & 0 & 1 \end{pmatrix} \right) \mathbf{n}_i + \mu p_i \mathbf{t}_i$$

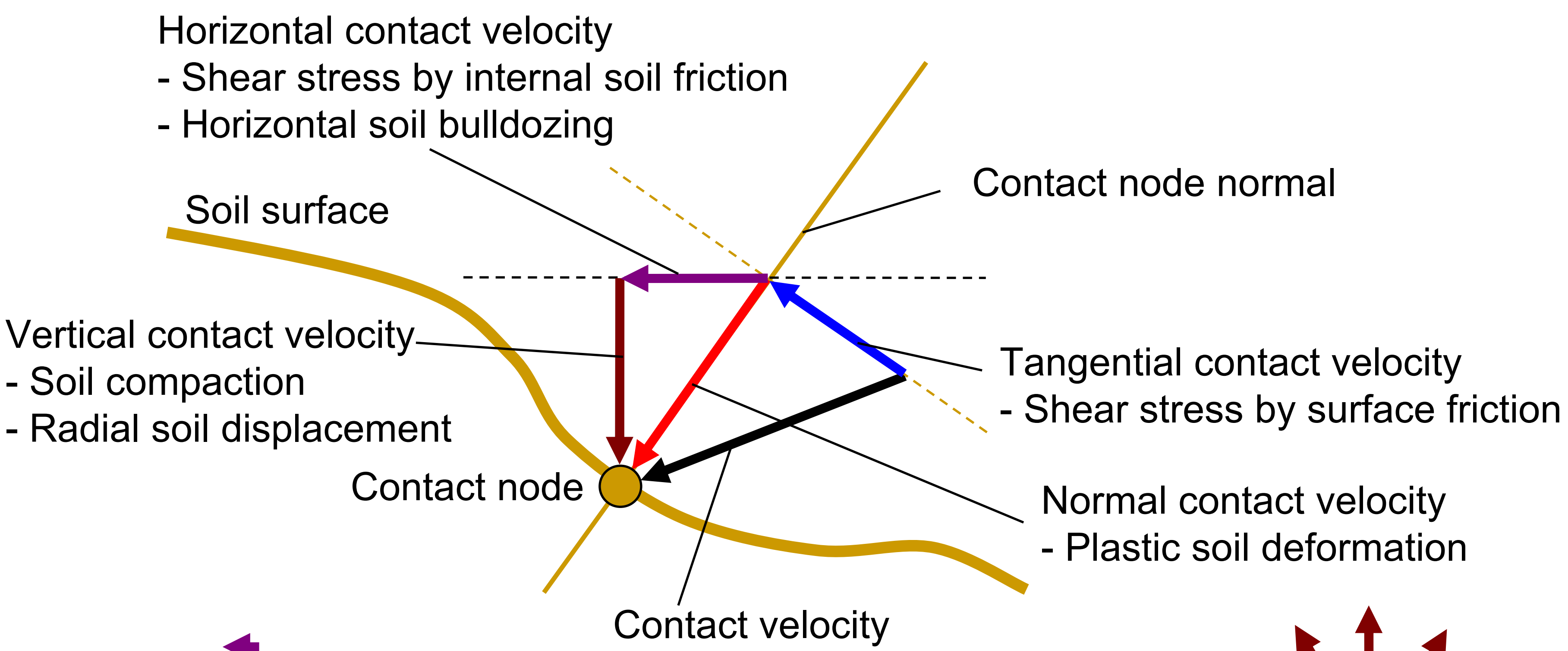
Internal soil friction (Mohr - Coulomb) : $\tau_1 = c + p \tan\varphi$

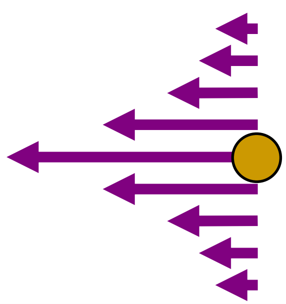
Contact surface friction (Coulomb) : $\tau_2 = p\mu$

$$\mathbf{F}_{Total} = \sum_{i=1}^{n_{Contact}} \mathbf{F}_i; \quad \mathbf{T}_{Total} = \sum_{i=1}^{n_{Contact}} \left(\mathbf{r}_i \times \mathbf{F}_i \right)$$


Parameters
Contact Object Surface Coordinates (CAD)
Soil Surface Coordinates (DEM)
Soil Parameters
Contact Object – Soil Interaction Parameters
$\mathbf{F} = f(\mathbf{x}, \dot{\mathbf{x}})$
From MBS Solver:
Relative Motion of Contact Object - Soil
Position
Velocity
To MBS Solver:
Contact Force/Torque
$\mathbf{F} = \sum (p\mathbf{n} + \tau\mathbf{t})$
$\mathbf{T} = \sum (\mathbf{x} \times (p\mathbf{n} + \tau\mathbf{t}))$
Contact Detection
Contact Patch (Footprint)
Patch Specific Operations
Area Size, Contour Length
Effective Contact Width
Normalized Pressure Distribution
Node Specific Operations
Sinkage
Surface Gradient
Contact Velocity
Empirical Equations of Bekker
$p = \gamma\left(\frac{k_c}{b} + k_\varphi\right) z^n \qquad \tau = p \tan\varphi + c$
Soil Surface Update
Soil Displacement
Soil Deposition
Soil Erosion

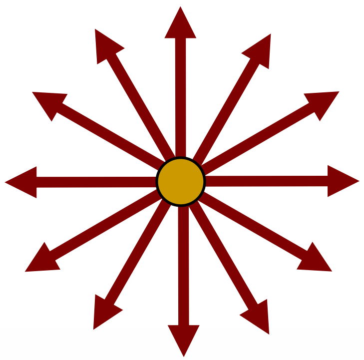
Footprint Soil Displacement – Soil Flow Fields





$$dV_i = z_i dA$$

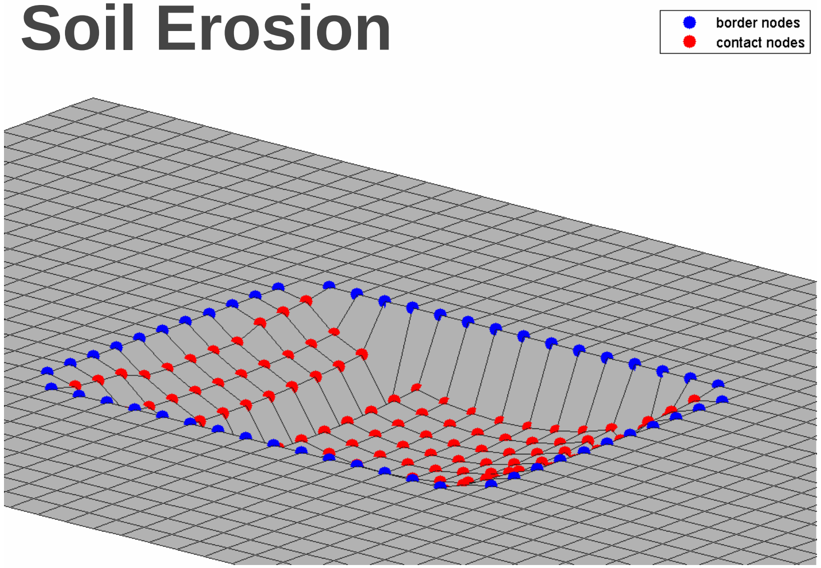
$$dV_{horizontal,i} = dV_i \frac{\left|\mathbf{v}_{horizontal}\right|^2}{\left|\mathbf{v}_{normal}\right|^2}; \qquad dV_{vertical,i} = dV_i \frac{\left|\mathbf{v}_{vertical}\right|^2}{\left|\mathbf{v}_{normal}\right|^2}$$

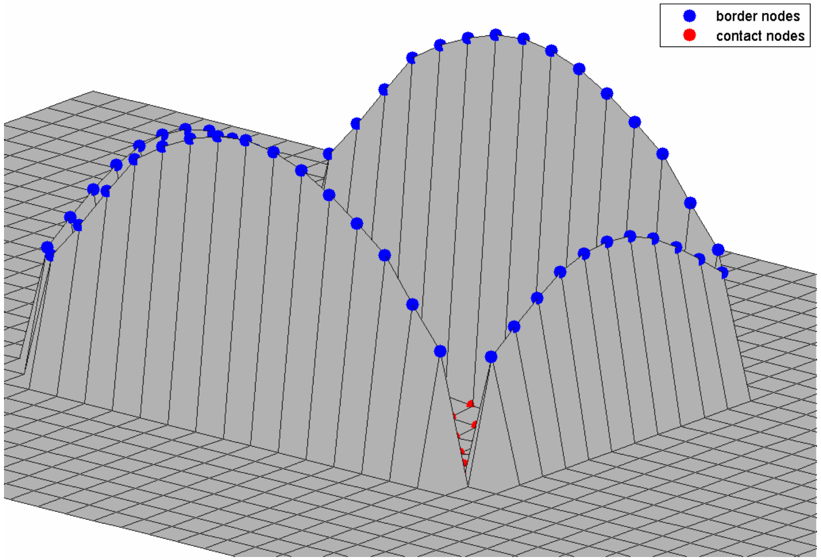


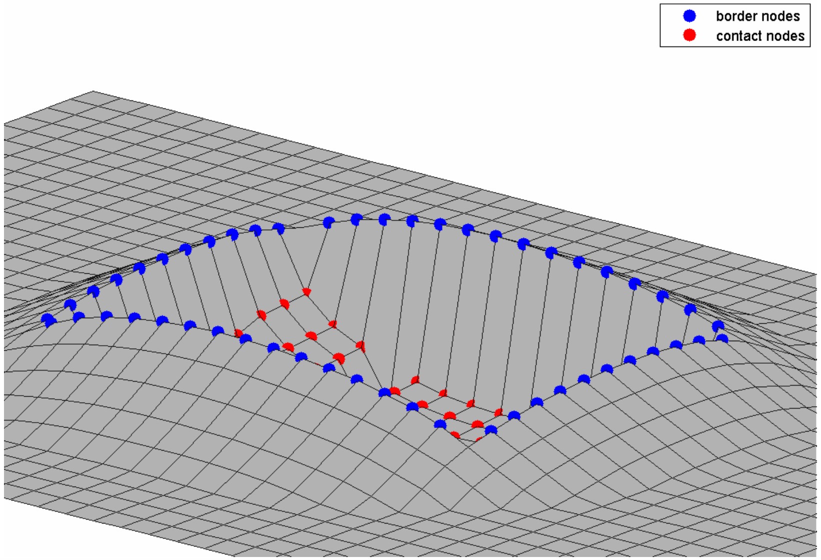
Soil Deposition, Soil Erosion

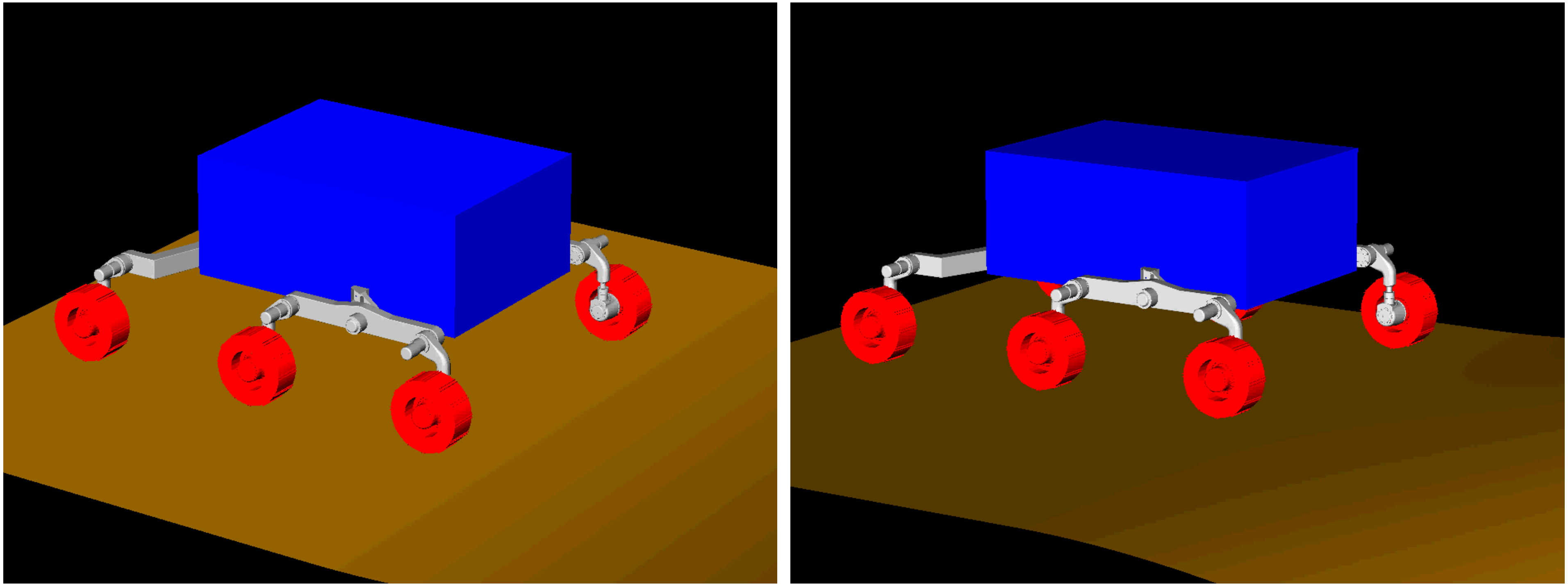
- Each border node receives soil from each contact node depending on the local intensity of the soil flow fields.
- Erosion:

$$\frac{\left|z_j - z_i\right|}{ds} \le \tan\psi; \quad j = 1 \ldots n_{Neighbour}$$





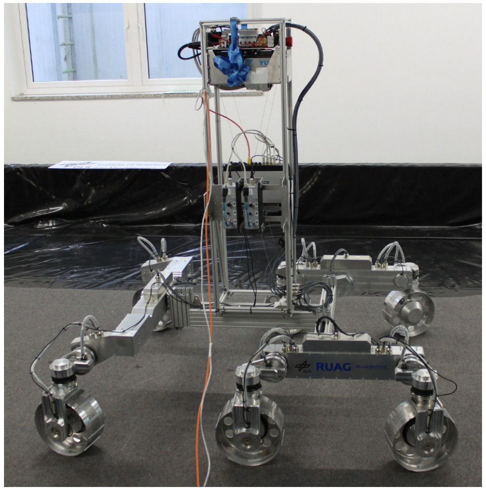


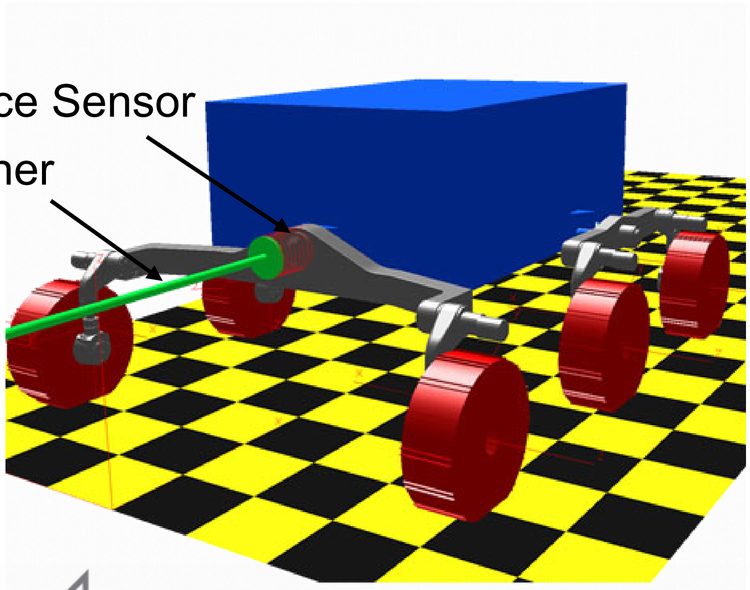


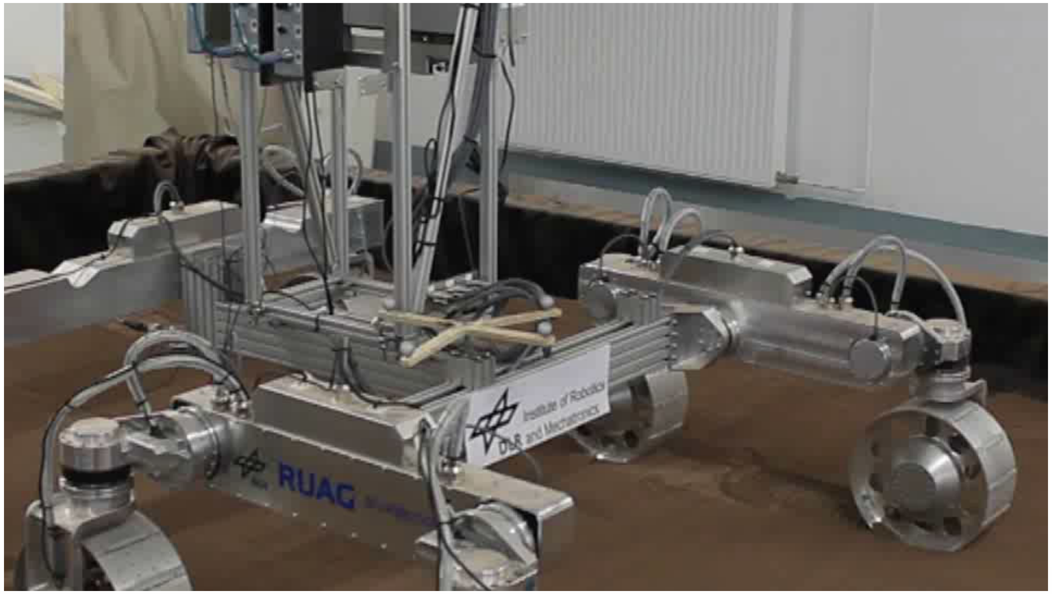
- Computation of plastic soil deformation is an essential pre-requisite for correct simulation of typical terramechanical phenomena
  - Bulldozing effects: Increasing rolling resistance caused by humps in front
  - Multi-pass effects: Reduced rolling resistance inside pre-deformed ruts
  - Lateral guidance forces inside ruts
  - Drawbar-pull as function of slippage

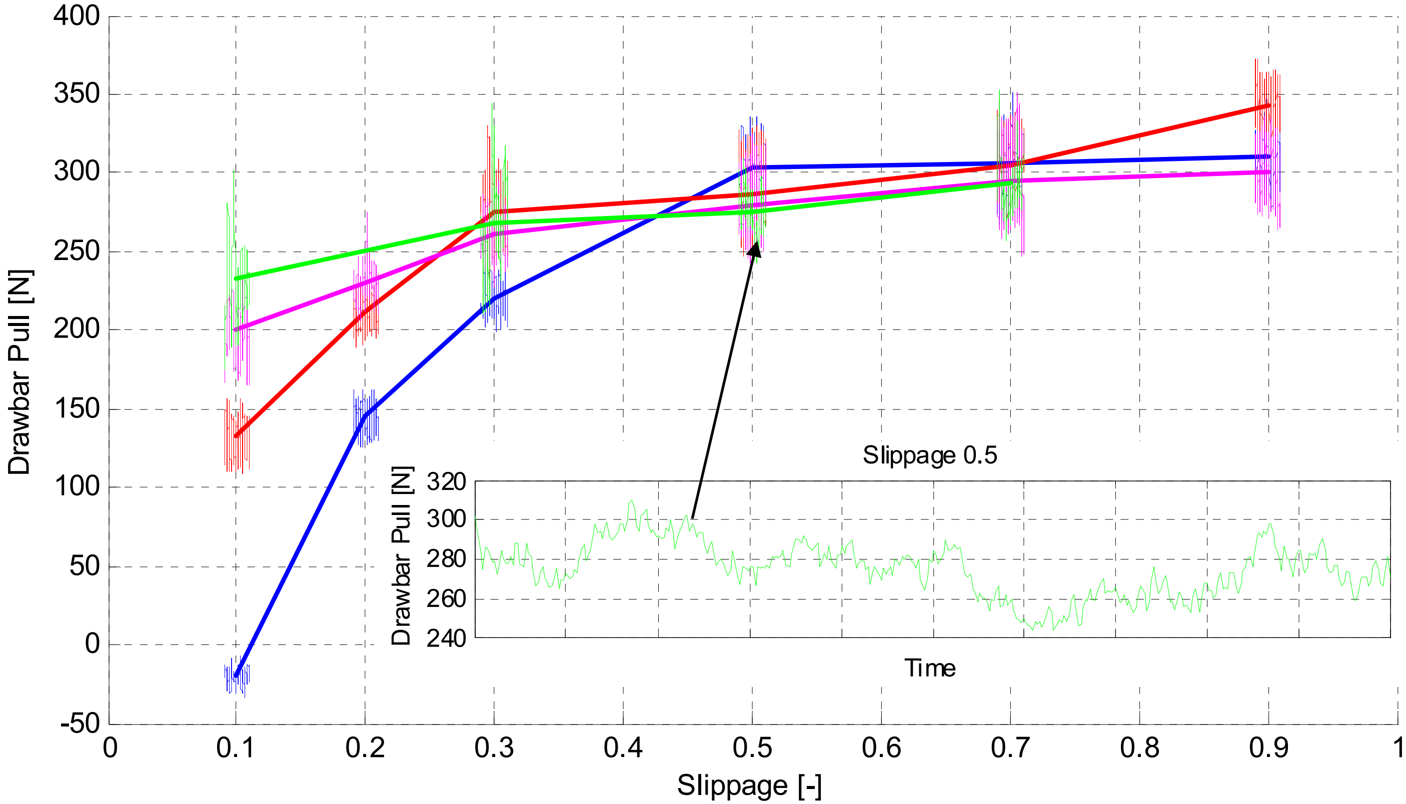
Correlation of Simulation Results and Experimental Results

- Drawbar pull tests:
  Measurement of the applicable pull force vs. slippage
- Tethered vehicle
- Slippage adjustment: $s = 1 - \frac{v_{Tether}}{v_{Rover,desired}} = 1 - \frac{v_{Tether}}{\omega_{Wheel} r_{Wheel}}$



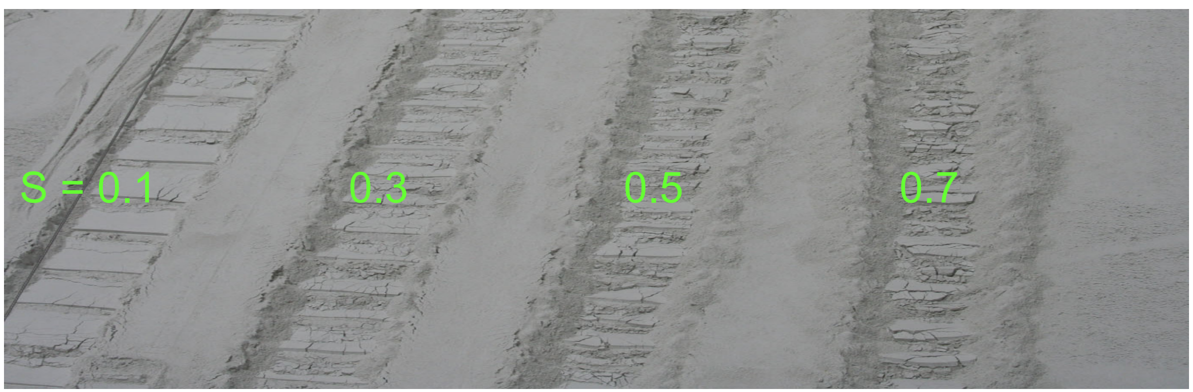






Reference:
ExoMars rover test campaign, Phase B1

(ESA, Oerlikon/RUAG, ETH Zurich, vH&S, DLR)



MSS-D

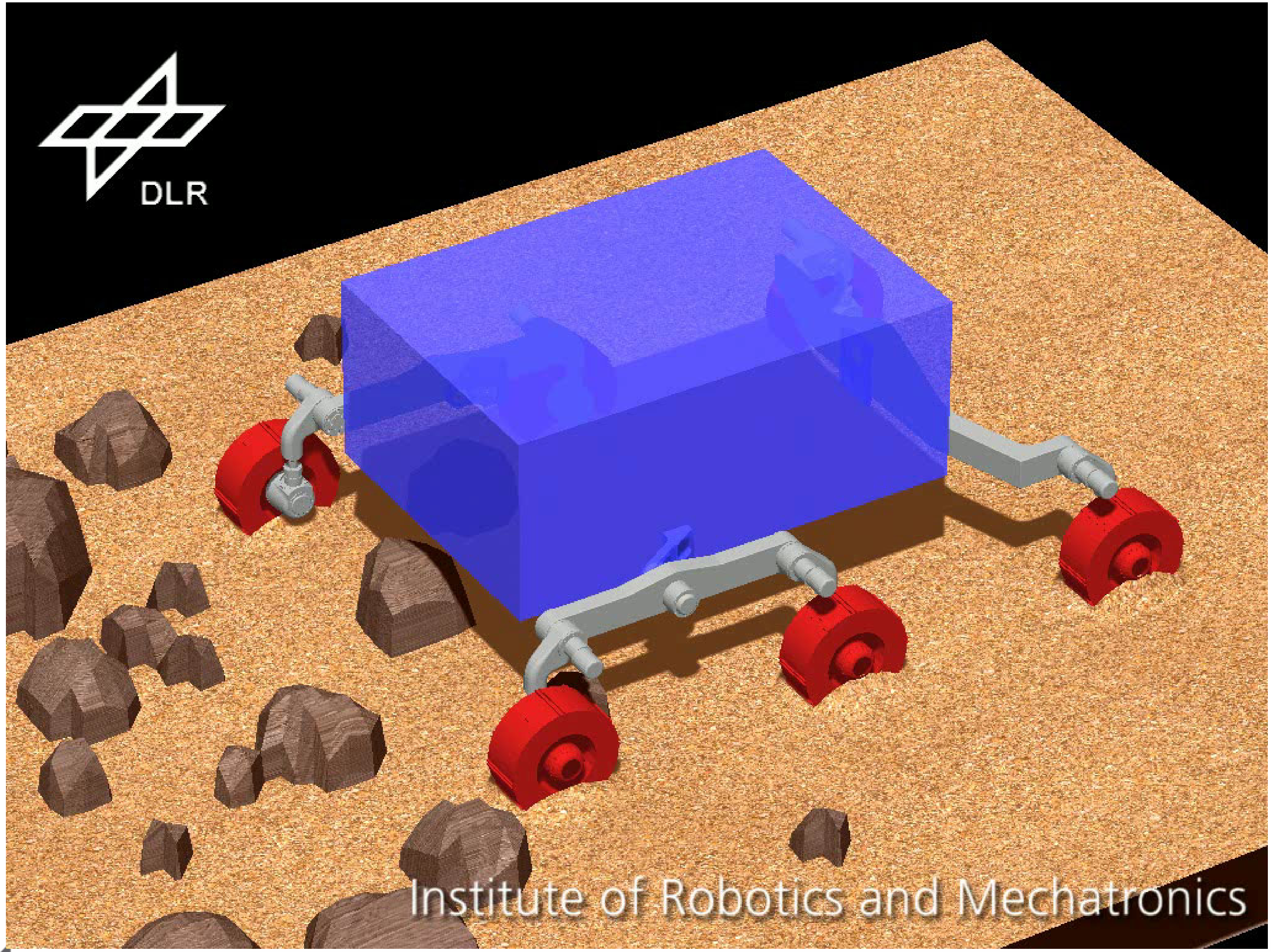
$$n = 1.8\,[-]$$

$$k_c = -6.675e5\,\frac{N}{m^{n+1}}$$

$$k_\varphi = 1.920e8\,\frac{N}{m^{n+2}}$$

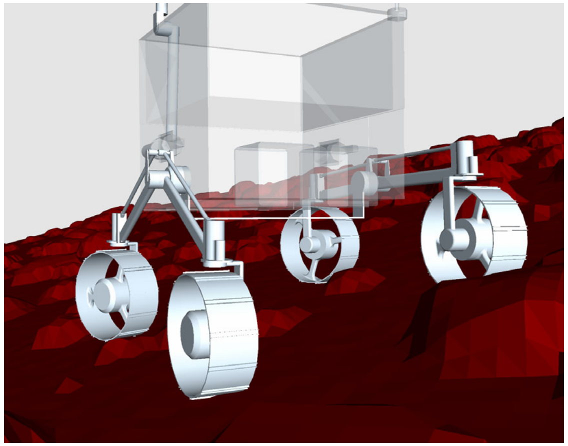
$$c = 13.4\,Pa$$

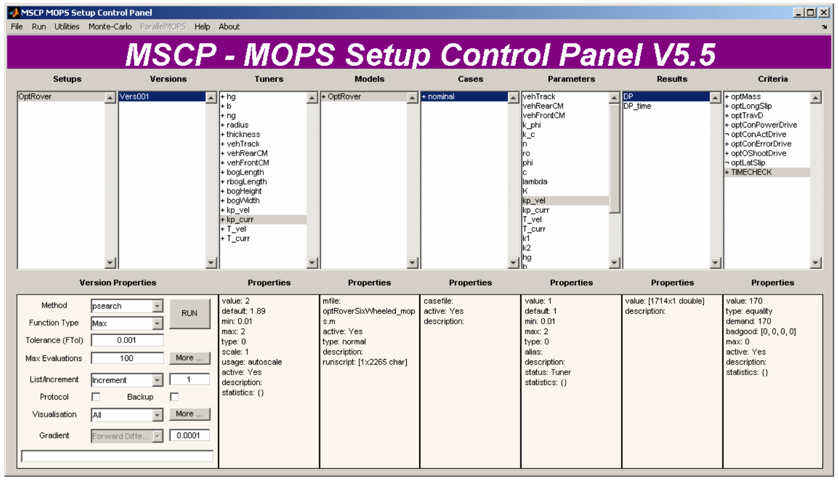
$$\varphi = \psi = 32^\circ$$

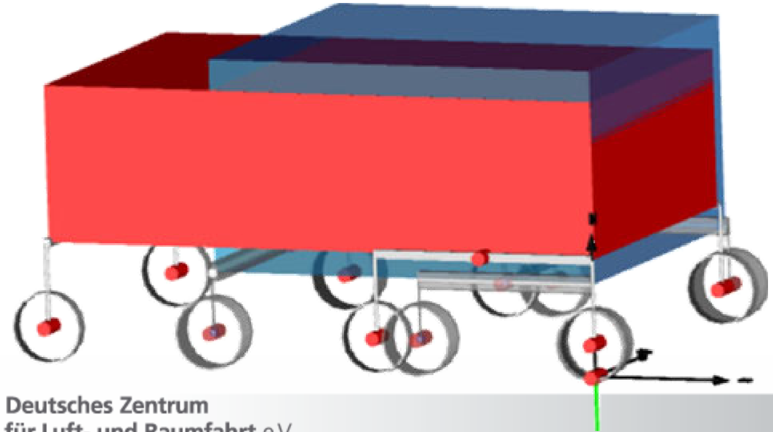

DLR
Institute of Robotics and Mechatronics

Outlook / Future Activities

- Application of SCM in Model Predictive Control for rover locomotion and navigation (ESA)
- Rover chassis design optimization
  - To be applied for Lunar rover design
    - MoonNext mission (ESA)
    - NextLunarLander (Astium)
    - Chassis (DLR)
  - Objective function includes SCM
  - Experience in the audience?







Deutsches Zentrum
DLR für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft