Evaluation of Mobility Concepts for a Martian Rover

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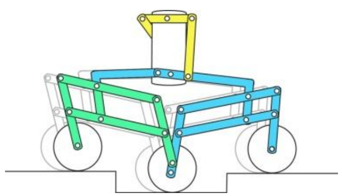
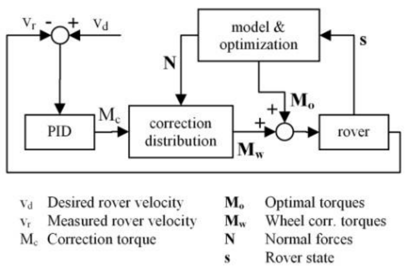
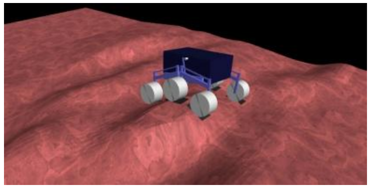
Outline

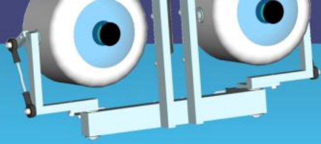
- Rover Comparison
- Controller
- CRAB Model
- Simulations
- Tactile Wheel
- Conclusion







ESA ExoMars

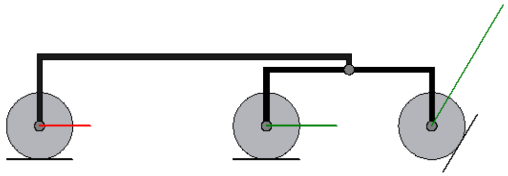


- **Objective: Development of a Mars Rover**
- **Our implication: part of the team that develops the Rover Chassis**
- **Time scale:**
  - Take off: 2013
  - Landing: 2016

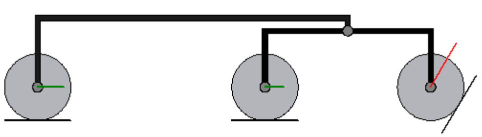
Rover Comparison: Motivation

- Evaluation and comparison of locomotion performance of rovers is a difficult, though very important issue.

- Three different rovers were analyzed from a kinematic point of view. Based on a kinematic model, the optimal velocities at the actual position were calculated for all wheels and used for characterization of the suspension of the different rovers.



Reference on rear wheel



Reference on front wheel

- Simulation results show significant differences between the rovers.
- Substantial reduction of slip can be achieved by integrating kinematics in a model based velocity controller.

Comparison Metrics

- **Difference between input and optimal velocities**
  - Measure for the risk of violation of kinematic constraints through deviation from optimal velocity.

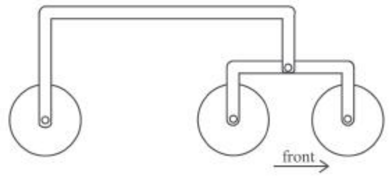
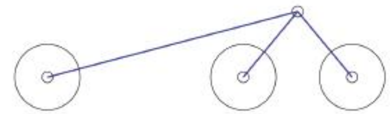
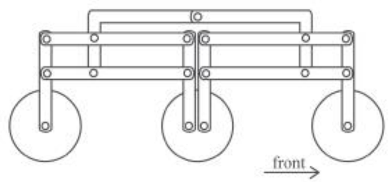
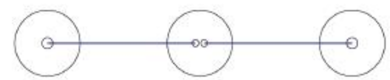
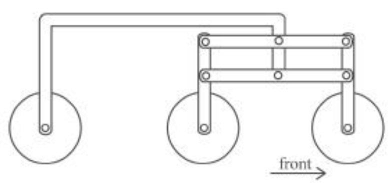
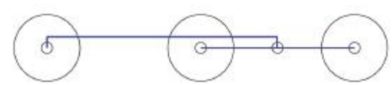
$$\Delta vel_{opt} = \sum_{i=1}^{n} |\vartheta_{ref} - \vartheta_{opt_i}| \quad with \quad i \neq ref$$

$$\begin{aligned} \text{where} \quad \vartheta_{ref} &= \text{velocity of reference wheel,} \\ \vartheta_{opt_i} &= \text{optimal velocity of wheel } i, \\ n &= \text{number of wheels.} \end{aligned}$$

- **Slip**
  - Difference between the displacement of a wheel measured at the wheel center point and the displacement derived from encoder data.

$$slip = \sum_{i=1}^{n} |\Delta pos_{wheelcenter_i} - \Delta pos_{encoder_i}|$$

Compared Systems

Breadboard	Schematic view	Kinematic model
MER by NASA (rocker-bogie type)		
		
CRAB by ASL (symmetric structure based on four parallel bogies)		
		
RCL-E by RCL (three parallel bogies, no differential mechanism)		
		

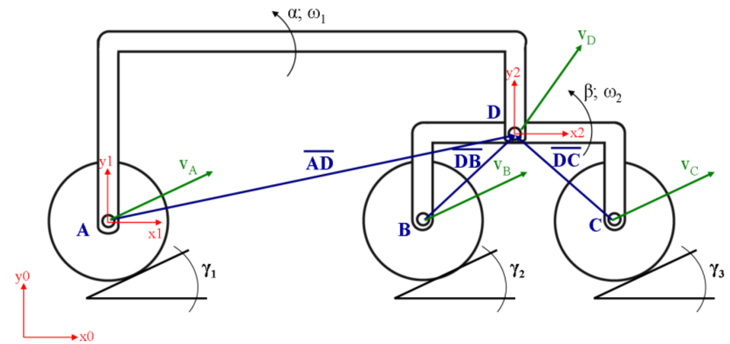
Kinematic Models

- **Kinematic modeling**

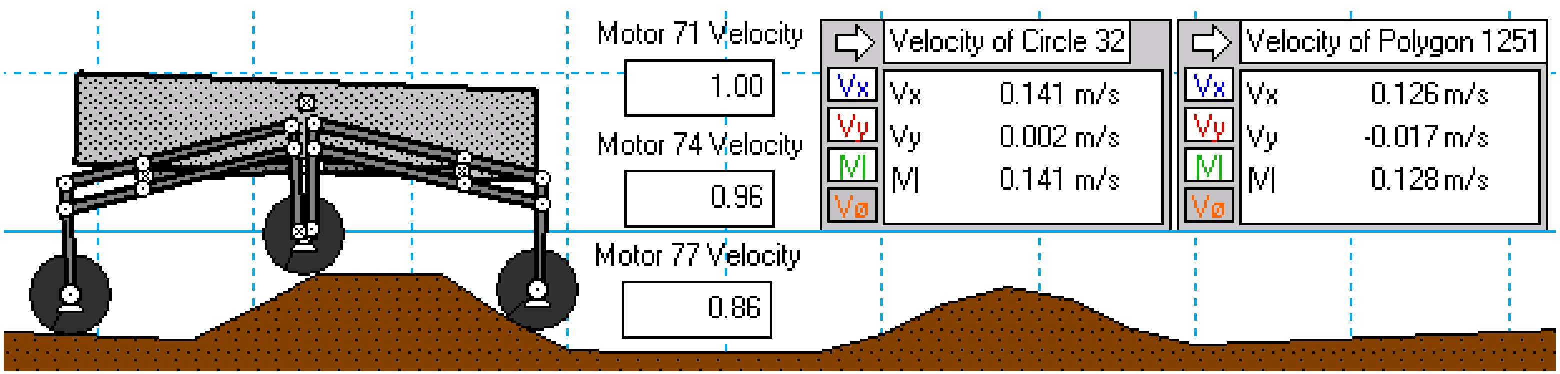
$$\vartheta_{D_A} := \vartheta_D = \vartheta_A + \omega_1 \times {}^0_1R(\alpha)\, {}^1\overline{AD}$$

$$\vartheta_{D_B} := \vartheta_D = \vartheta_B + \omega_2 \times {}^0_2R(\beta)\, {}^2\overline{DB}$$

$$\vartheta_{D_C} := \vartheta_D = \vartheta_C + \omega_2 \times {}^0_2R(\beta)\, {}^2\overline{DC}$$



- **Simulation setup: Working Model 2D interfaced with Matlab**



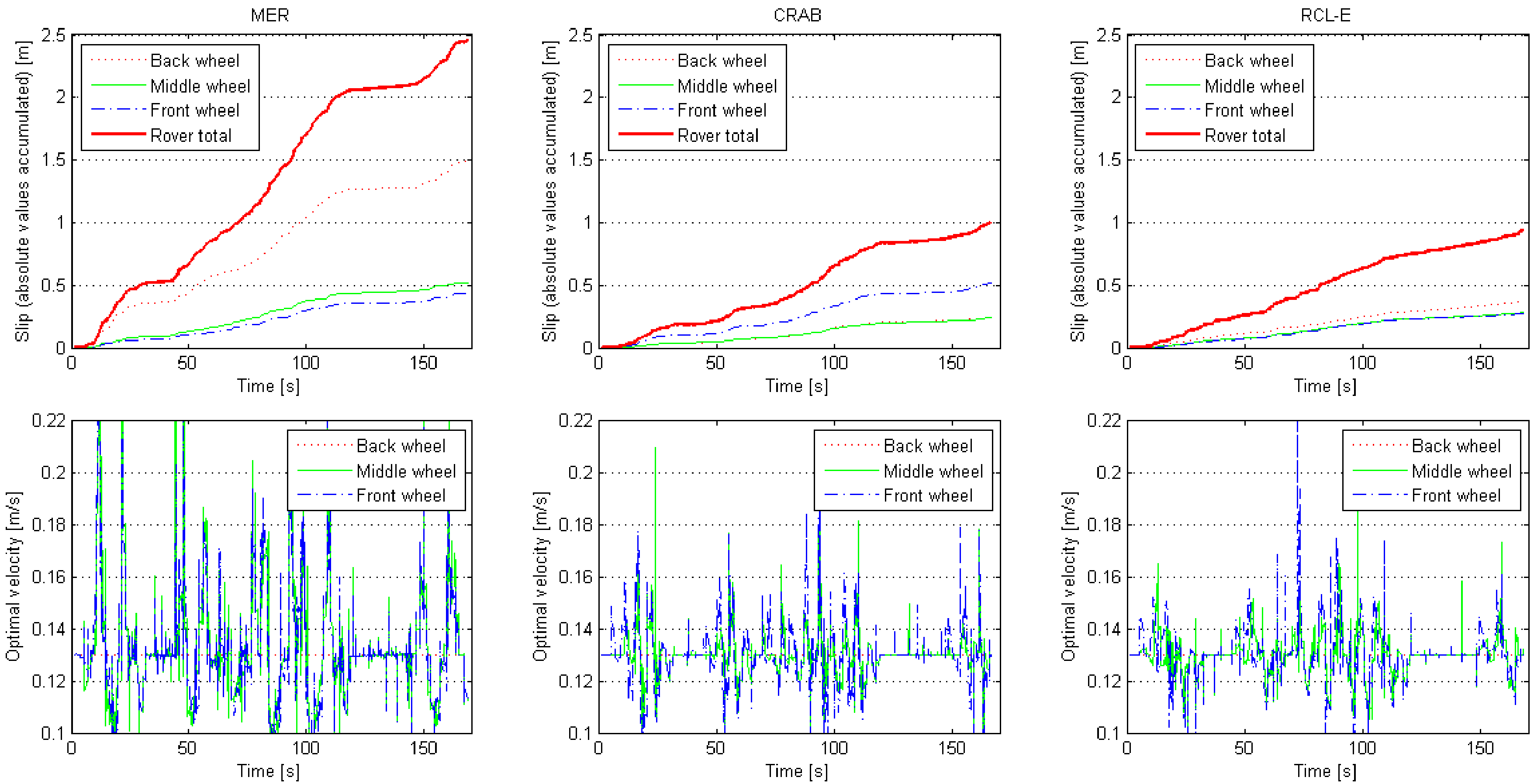
Rover Comparison: Simulation Results

Rover	Ref. wheel	Test	$\sum(\Delta vel_{opt})$ [m/s]	Test	$\sum(\Delta vel_{opt})$ [m/s]
MER	1	1	27.87	7	93.71
CRAB			12.17		37.53
RCL-E			12.72		35.69
MER	2	2	15.87	8	55.46
CRAB			10.00		28.00
RCL-E			11.12		29.96
MER	3	3	17.25	9	55.20
CRAB			12.02		37.87
RCL-E			11.69		33.70
Terrain type		Truncated pyramid		Uneven terrain 24m	

Performance regarding metric Δvel_{opt}

- Significant difference between the performance of rocker-bogie type (~15-27 m/s) and the other rovers (~10-13 m/s), CRAB and RCL-E.
- If a constant speed control was used on the rovers, the error would be much bigger on the rocker-bogie type; it has a higher need to adapt the wheel velocities in order to satisfy the kinematic constraints and reduce slip.

Rover Comparison: more Simulation Results

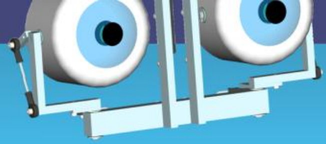


Performance regarding slip

Control optimisation

Motivation

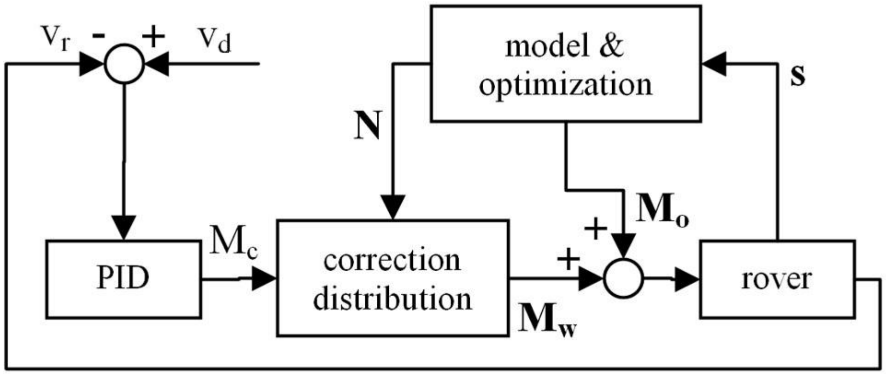
- Control Strategy
  - Diverse possibilities
  - Focus here on torque control
  - Make the more loaded wheels contribute more to the rover movement
- Torque Control
  - An old story? [P.Lamon 2005]
  - State of an ongoing project



Controller

Torque Control

- **Control Scheme**
  - Tested in simulation with the SOLERO rover
  - Not (yet) implemented

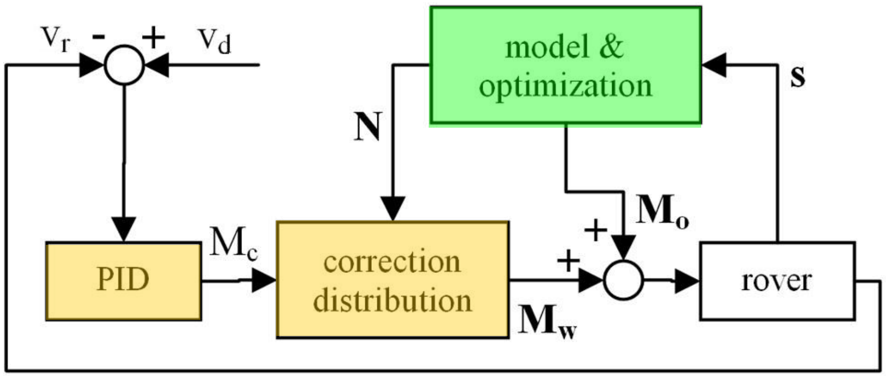


v_d	Desired rover velocity	$\mathbf{M_o}$	Optimal torques
v_r	Measured rover velocity	$\mathbf{M_w}$	Wheel corr. torques
M_c	Correction torque	**N**	Normal forces
		s	Rover state

- **Current Research**
  - Implementation on the CRAB
  - Part of trade-off study for the ExoMars Rover
  - Use of tactile wheels
  - May be possible to use only an axis-mounted force sensor

Controller
Optimization

- **Static Model**
  - Compute the wheel load
  - Compute the torques M_o needed to keep the static equilibrium
- **Move The Rover**
  - Correction torques M_w
  - M_w is based on the error of the rover speed



v_d	Desired rover velocity	$\mathbf{M_o}$	Optimal torques
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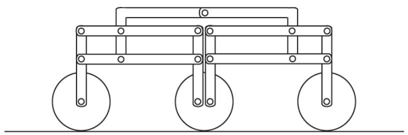
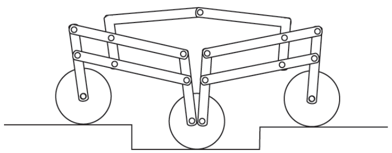
		s	Rover state

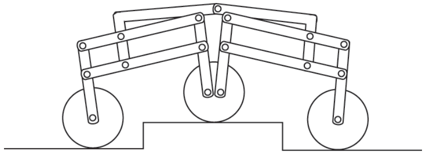
CRAB Model
Mechanical Structure

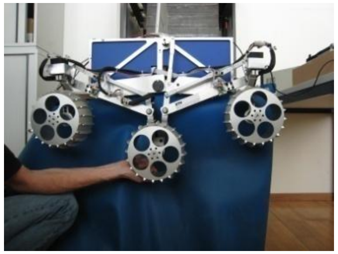
- **CRAB Rover**

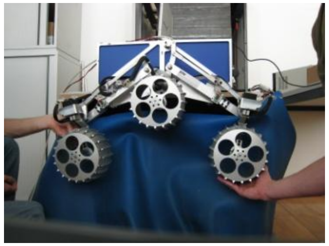
- **Passive Structure**

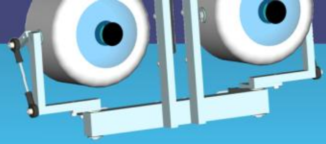








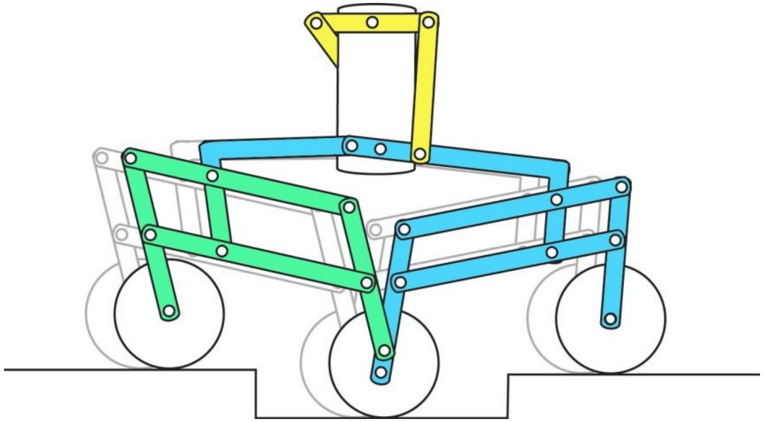




CRAB Model
Static Model

- **Mobility**
  - A rover has a mobility of 1
  - Computed with Grübler's formula:

$$MO = 6 \cdot n - 5 \cdot f_1 - 4 \cdot f_2 - 3 \cdot f_3 - 2 \cdot f_4 - f_5$$

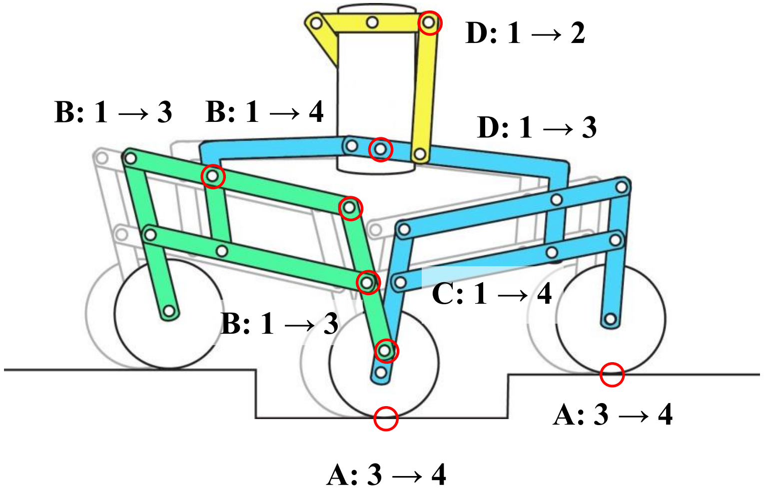


- **CRAB**
  - 30 parts, 41 pivot joints
  - wheel-ground contact as spherical joints
  - Result MO = -43

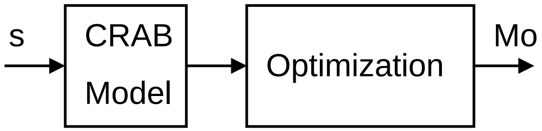
The model has to be adapted to fit the reality

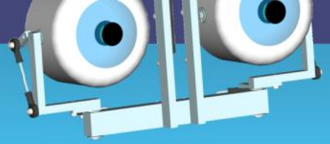
CRAB Model
Static Model

- **Modification**
  - A: Wheel-ground interaction
  - B: Parallel bogie
  - C: Mechanical loop on each side
  - D: Differential



- **Final Model**
  - MO = 1
  - internal variables removed
  - 43 equations and 48 variables

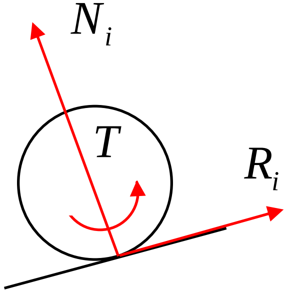




CRAB Model
Optimization

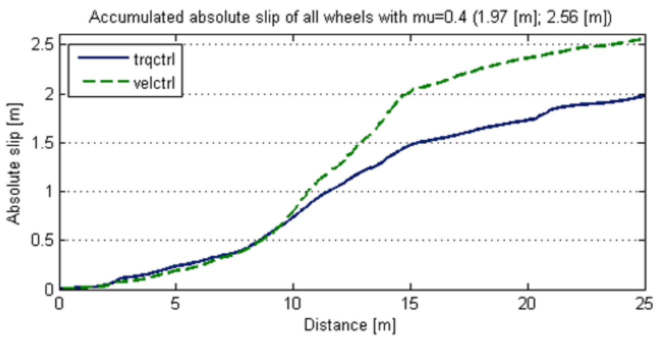
- **Optimization**
  - MO = 1 => single motor needed for control
  - All wheels motorized: system under constrained
  - Missing equations: $n_{wheel} - 1$
- **Heuristic**
  - With: $G_i = \frac{R_i}{N_i}$
  - The optimal set of torques is found as follows:

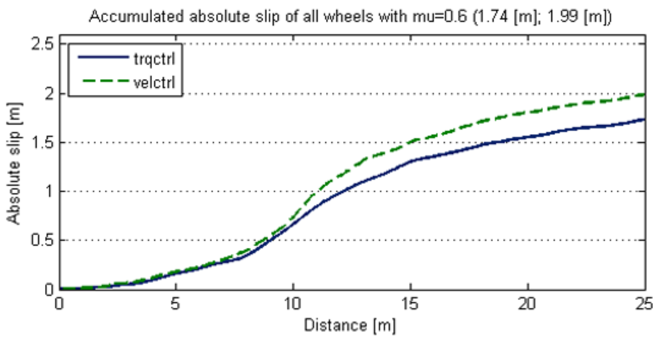
$$H = \min\left(\sum_i \left(G_i - \overline{G}\right)^2\right)$$

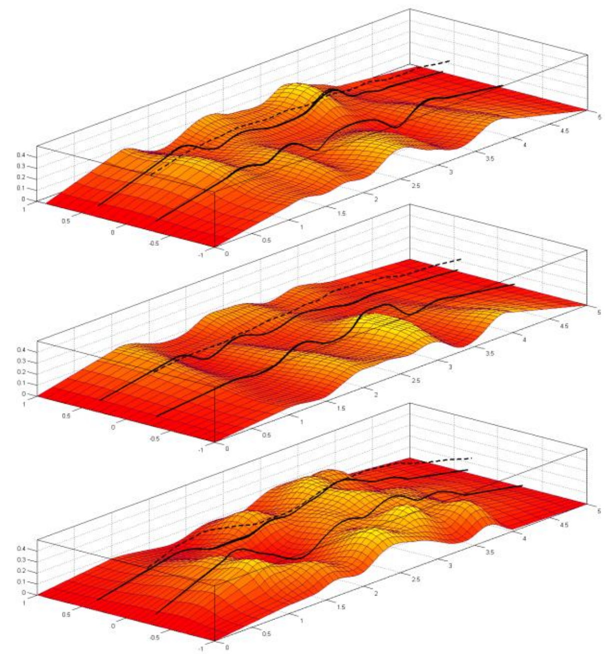


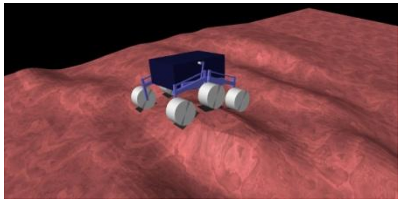
Simulations
Setup

- Performed with ODE (Open Dynamics Engine)
- 3 test terrains
- 3 different μ





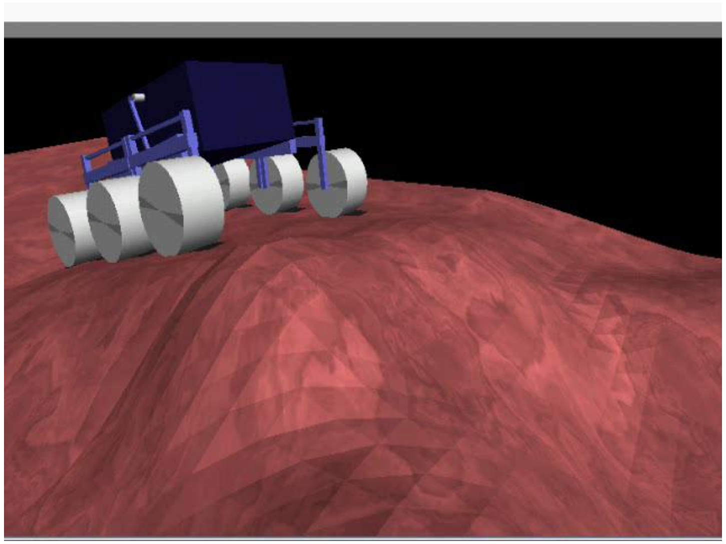




Simulations
Results

- Test
  - Torque control compared with wheel synchronization algorithm [E.T. Baumgartner 2001]

Terrain	μ	Distance Tot.	Control Type		Diff.
			Torque	Velocity	
1	0.4	25 m	1.41 m	2.41 m	42 %
2	0.4	25 m	1.02 m	1.60 m	37 %
3	0.4	25 m	1.97 m	2.56 m	23 %

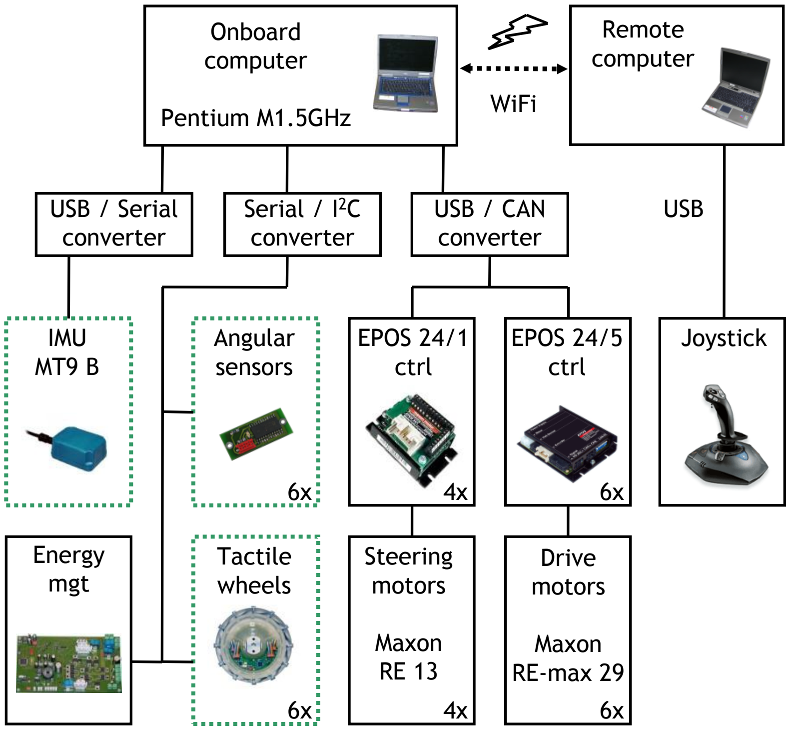


- Slippage
  - Dependent on terrain
  - Dependent on soil characteristics
  - Performs better in every case
  - Shows a great potential

Tactile Wheel

CRAB System Overview

- **Sensors Monitoring The CRAB's State**
  - IMU
  - Angular sensors
  - Tactile Wheels

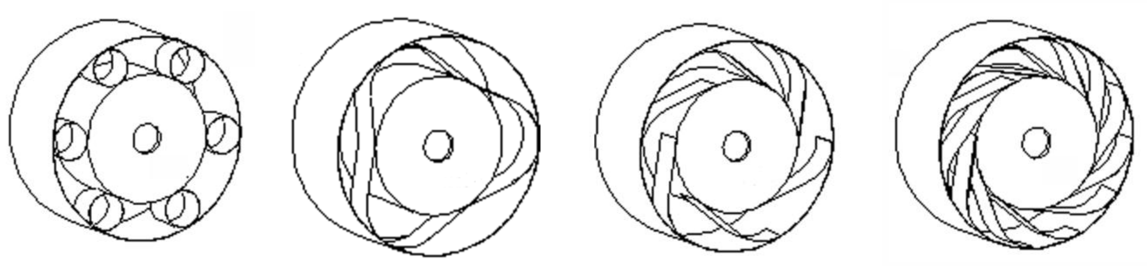


- **Tactile Wheels**
  - Specifically developed for the CRAB rover
  - Needed to obtain the wheel-ground contact angles

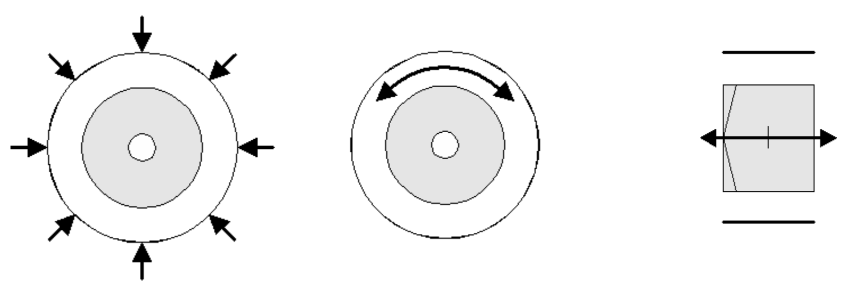
Tactile Wheel

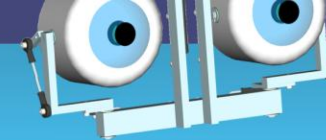
Deformable Wheel

- **Concept**
  - Deformable ring linked with springs to the rim
  - Deformation measured to determine the contact angle
- **Designs Considered**
  - Spring type
  - Number of rows



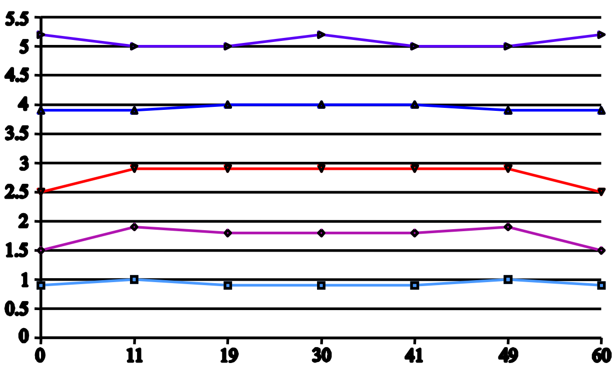
- **Mechanical Tests**
  - Radial deformation
  - Angular displacement
  - Axial displacement

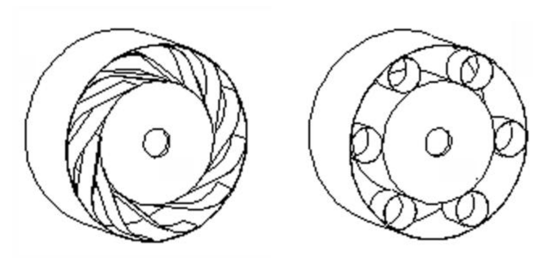


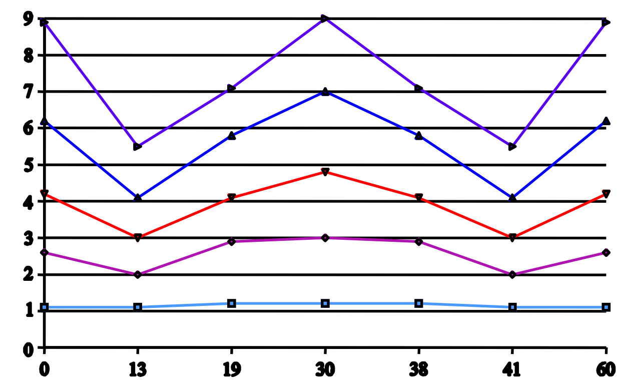


Tactile Wheel
Measuring Deformation

- Final Mechanical Design

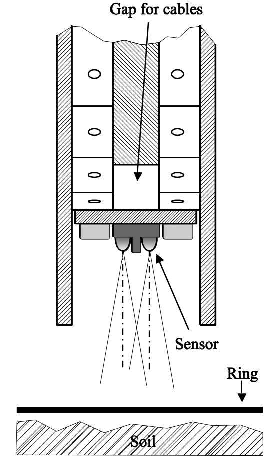






20[N] 40[N] 60[N] 80[N] 100[N]

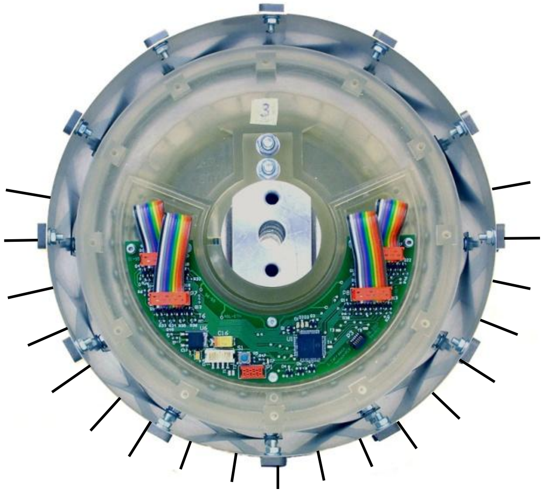
- Sensing Concept
  - IR sensor measuring the distance
  - Sensors placed on the stator



Tactile Wheel

Results

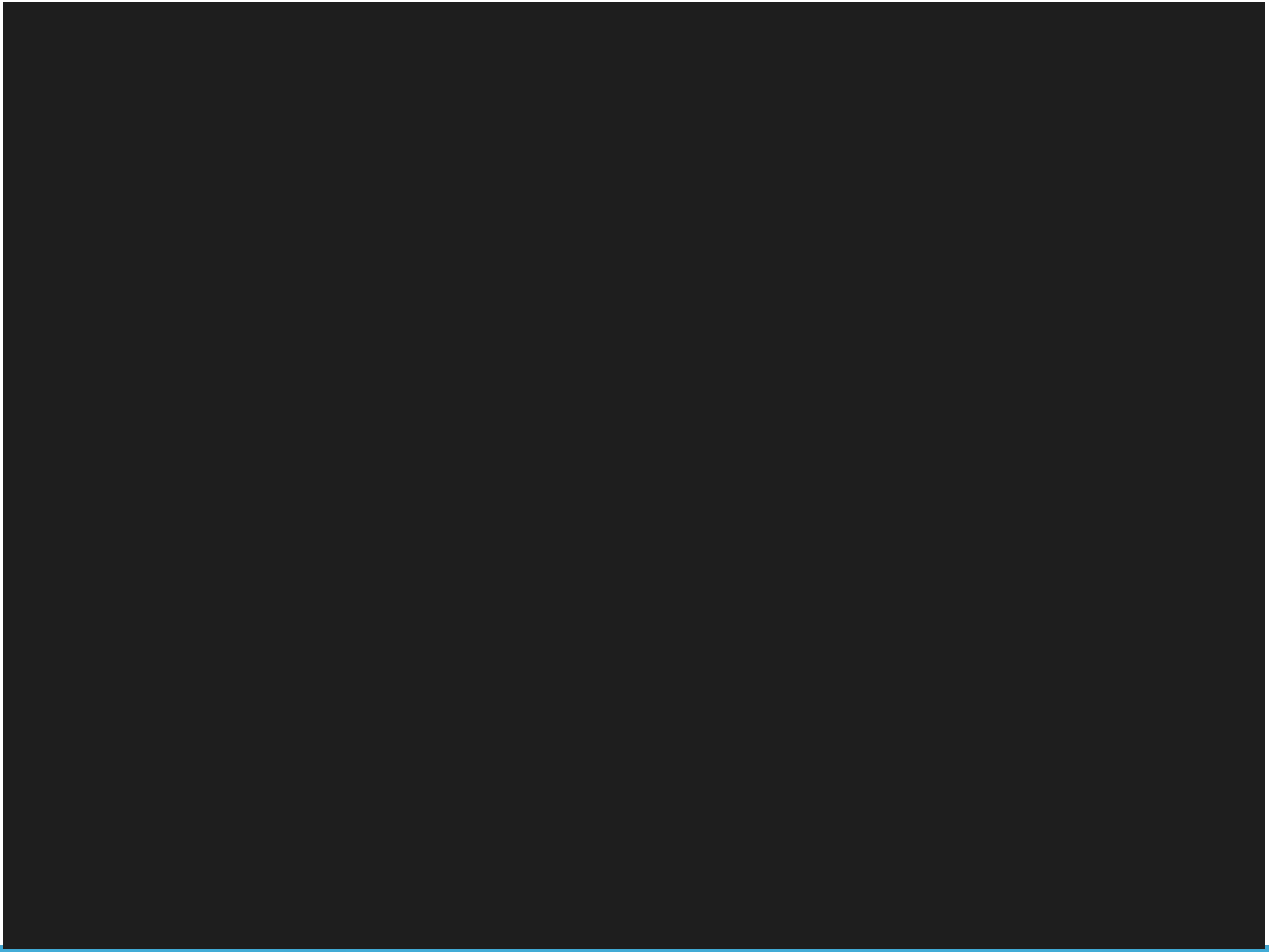
- **Radial deformation:** 0.05 mm/N
- **Angular displacement:** 0.09 °/Nm
- **Axial displacement:** negligible
- **System weight:** 1.21 Kg
- **IR Sensors:** 19
- **Resolution:** 11.25°
- **Frequency:** 20 Hz



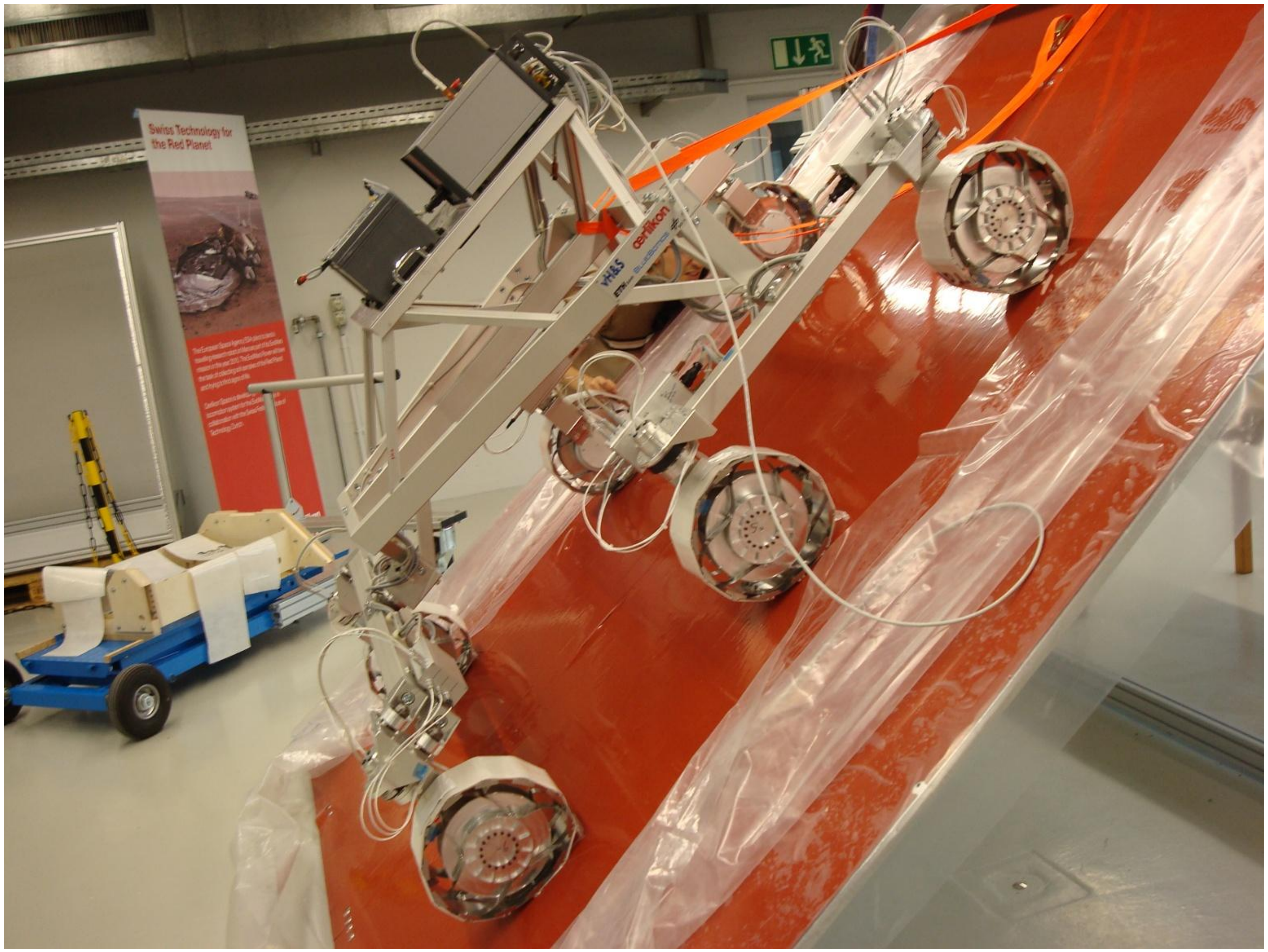
Conclusion

- Torque Control
  - Controller implemented and tested in simulation
  - Shows encouraging results
- Tactile Wheels
  - Realized and tested
  - Meet specifications
- Future Work
  - Integration of tactile wheels needs to be finished
  - Test of torque control in reality

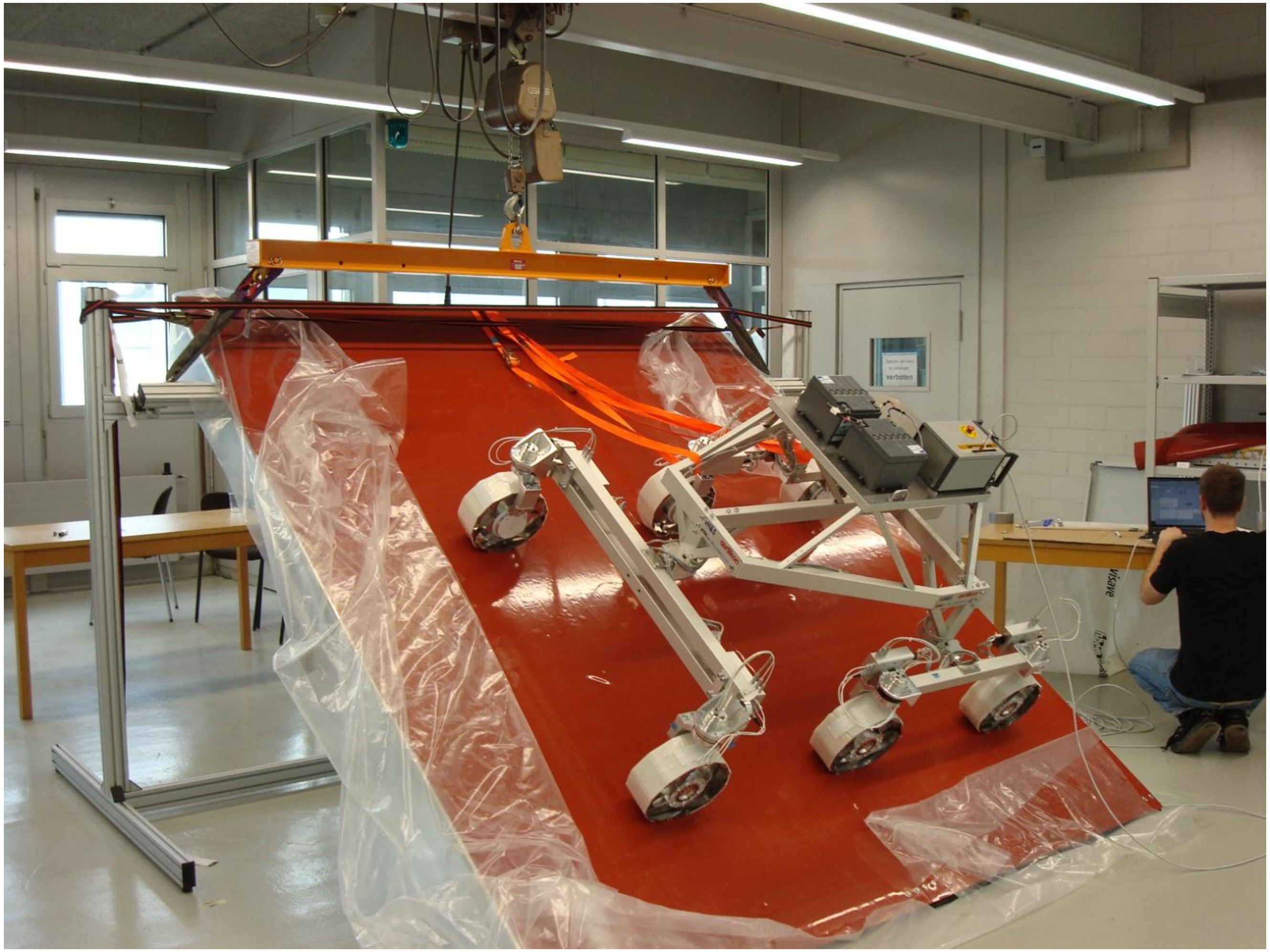
ICRA WS Premiere: First test of the ExoMars BreadBoard



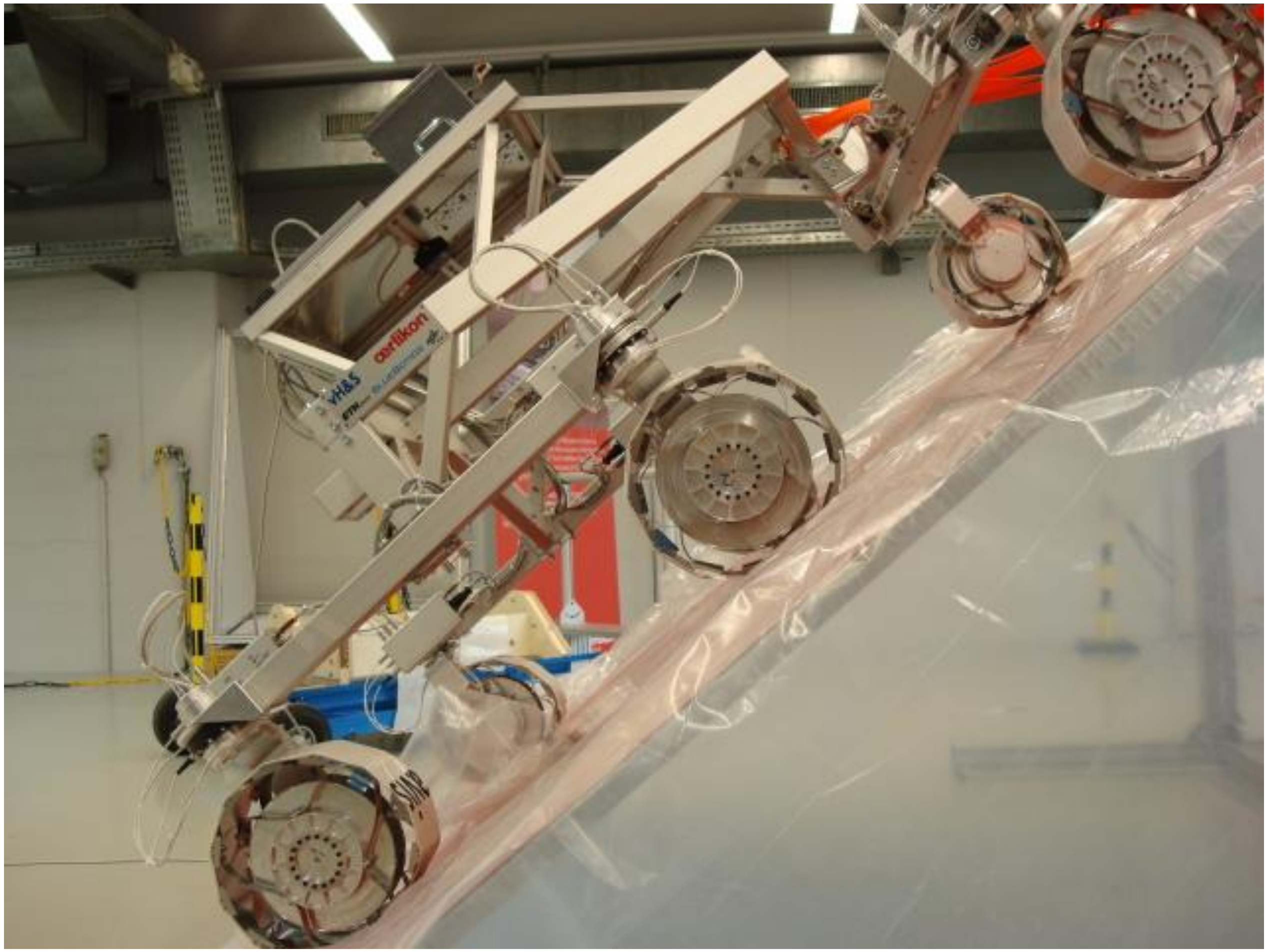
Static stability

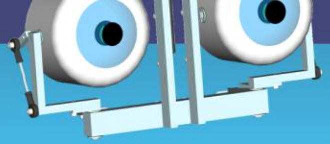


Static stability



Static stability





Questions ?

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