Model Predictive Traction and Steering Control of Planetary Rovers

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DLR

Model Predictive Control (MPC) - User Point of View

- Well-known from process control of plants
  - Large number of states $\mathbf{x}$ and algebraic variables $\mathbf{z}$
  - Small number of controls $\mathbf{u}$
  - Slow system reaction, long latency
- Idea: Model based prediction of process evolution and selection of optimal control inputs
  - Goals
    - Min. process time
    - Min. energy consumption, etc.
  - Constraints
    - Limitations of control inputs
    - Safety issues
    - Product quality (terminal constraint)


Source: BASF, Press Release

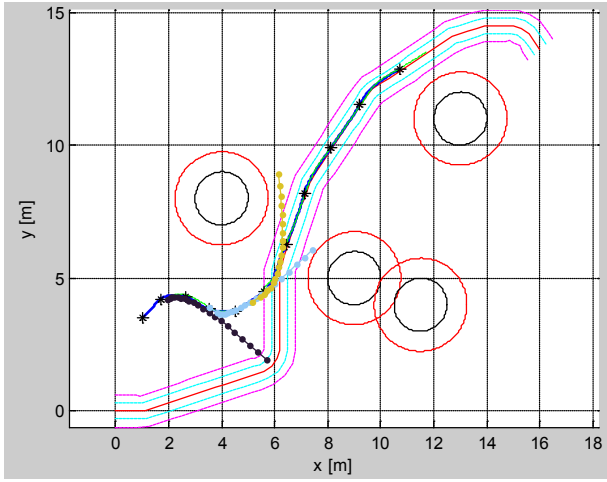

Source: ESA

ORCSAT S/C Rendezvous Application	Ts	Prediction Horizon
Orbit Synchronization TG	10min	<250min
Impulsive Nominal TG	5min	<100min
Forced Terminal TG	3s	45s

RobMPC* – Planetary Rover Locomotion Application

- MPC control solutions for rover control hierarchy
  - Guidance
    - Off-line generated collision free reference path
    - Computation of collision free contingency path, if the rover has left the safety corridor
  - Trajectory control
    - Generation of rover trajectory (velocity domain)
  - Traction and steering control
    - Wheel velocity and steering angle coordination
    - Actuator control inputs
- Verification with functional engineering simulator (FES)
- Results:
  - Better control performance w.r.t. classical reference controllers
  - Seamless interaction within control hierarchy


Source: ESA, EGP Rover

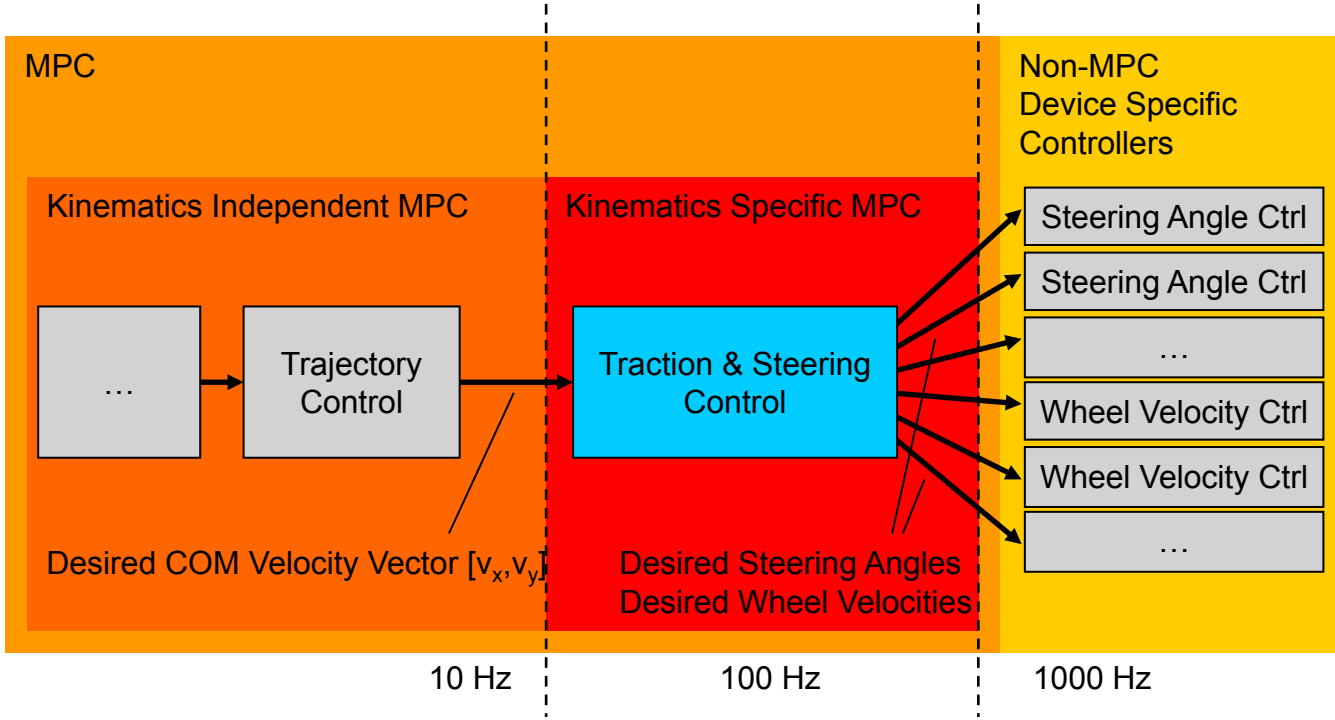


* ESA Contract ESTEC/ITT AO/1-5979/09/NL/JK; S. Bennani, E. Bornschlegl

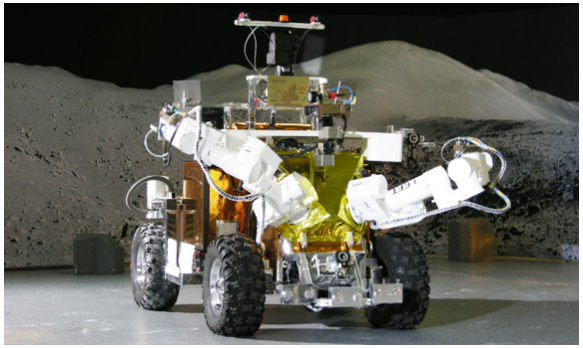
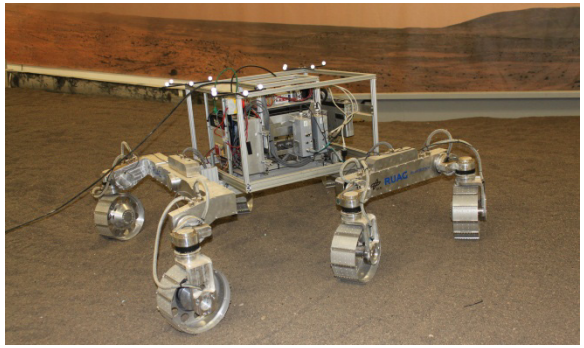
* G. Binet, R. Krenn, A. Bemporad; *MPC for Planetary Rovers*; iSAIRAS 2012

Traction and Steering Control with MPC
Outline

1. MPCSofT
2. User Model
   - Prediction model
   - Optimization goals
   - Constraints
3. RobMPC Test Results
   - Nominal tests
   - Robustness tests
4. ExoMars BB Test Results



MPC Traction & Steering Control Implementations

Parameter	EGP Rover (RobMPC)	ExoMars Breadboard Rover
Rover		
Environment	Functional Engineering Simulator	Planetary Exploration Lab (DLR)
Bounding box volume (L/W/H)	2246 / 1580 /1505 mm	1600 / 1370 / ~800 mm
Total weight	880 kg	90 kg
Track width (front/rear)	1041 / 1330 mm	1200 / 1200 / 1200 mm
Axle distance	1511 mm	640 / 720 mm
Steering axle	rear wheel steering	all wheel steering
Maximum velocity	0.35 m/s	0.03 m/s
Navigation sensor	IMU model	Camera based 3D pose tracking

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MPCSofT – QP Builder and QP Solver of User Model

- At each time t: Solve an optimal control problem over a finite future horizon of N steps
- Apply the first optimal move: u_t
- At each time $t+1$: Get feedback and repeat optimization

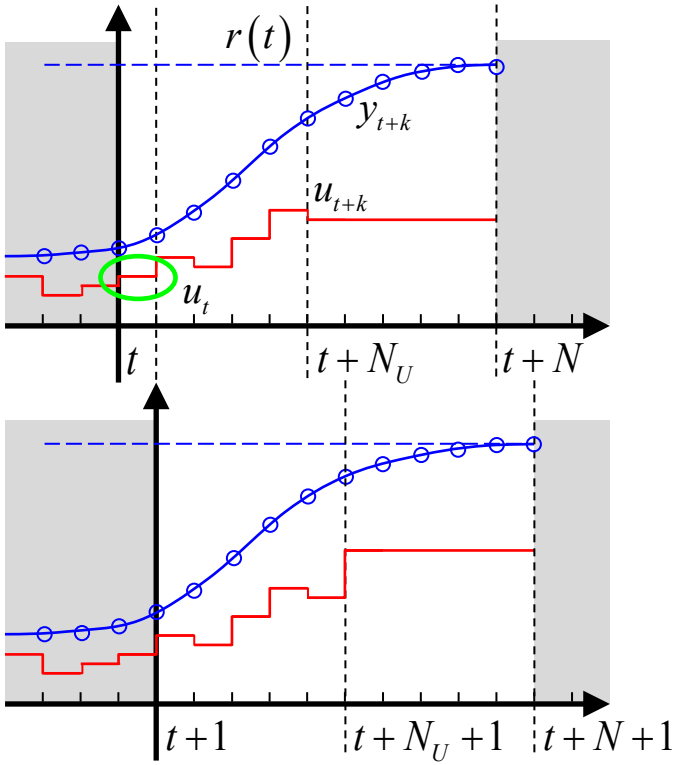
$$\min \sum_{k=0}^{N(t)-1} \left\| y_{t+k} - r(t) \right\|^2 + \rho \left\| u_{t+k} \right\|^2 \quad \text{Quadratic costs}$$

$$\text{s.t.} \quad \left.\begin{aligned} x_{t+k+1} &= f\left(x_{t+k}, u_{t+k}\right) && \text{States} \\ y_{t+k} &= g\left(x_{t+k}\right) && \text{Outputs} \end{aligned}\right\} \text{Linear model}$$

$$u_{min} \le u_{t+k} \le u_{max} \quad \text{Constraints on inputs}$$

$$y_{min} \le y_{t+k} \le y_{max} \quad \text{Constraints on outputs}$$

$\triangleq$ Solve a convex QP problem for all $x(t)$ w.r.t. Δu_k



- User model: Prediction model (state space model, LTV)

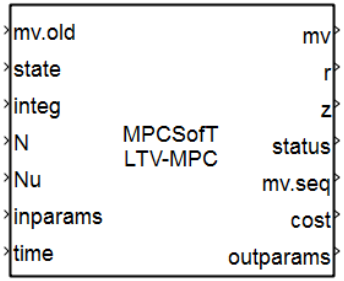
$$\mathbf{x}_{k+1} = \mathbf{A}\left(t,k,\mathbf{x}(t)\right)\mathbf{x}_k + \mathbf{B}\left(t,k,\mathbf{x}(t)\right)\mathbf{u}_k$$

- User model: Goals and constraints

$$\mathbf{r}_k \quad \Rightarrow \quad \mathbf{z}_k = \mathbf{E}_z\left(t,k,\mathbf{x}(t)\right)\mathbf{x}_k + \mathbf{H}_z\left(t,k,\mathbf{x}(t)\right)\mathbf{u}_k + \mathbf{P}_z\left(t,k,\mathbf{x}(t)\right)\Delta\mathbf{u}_k$$

$$\mathbf{c}_{max} \quad \Rightarrow \quad \mathbf{c}_k = \mathbf{E}_c\left(t,k,\mathbf{x}(t)\right)\mathbf{x}_k + \mathbf{H}_c\left(t,k,\mathbf{x}(t)\right)\mathbf{u}_k + \mathbf{P}_c\left(t,k,\mathbf{x}(t)\right)\Delta\mathbf{u}_k$$

$$\mathbf{d}_N \quad \Rightarrow \quad \mathbf{d} = \mathbf{C}_N\left(t,\mathbf{x}(t)\right)\mathbf{x}_{N(t)}$$



MPCSofT LTV-MPC

MPC Prediction Model: Equations of Motion

- Vehicle states:

$$\mathbf{x} = \begin{pmatrix} v_{long} & v_{lat} & \omega_z \end{pmatrix}^T$$

- Control inputs:

$$\mathbf{u} = \begin{pmatrix} \beta_1 & \beta_2 & \dots & \beta_{nSteering} & \omega_1 & \omega_2 & \dots & \omega_{nWheel} \end{pmatrix}^T$$

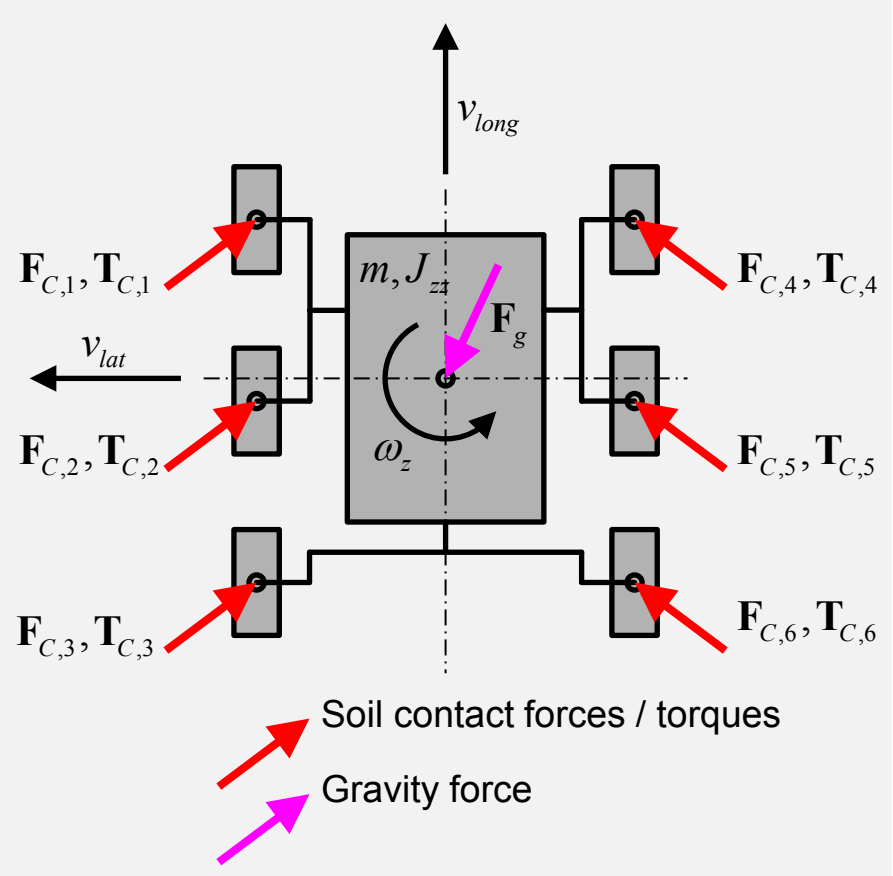
- Equations of planar motion:

$$m\dot{v}_{long} = mg_{long} + \sum_{i=1}^{n_{Wheel}} F_{C,long,i}$$

$$m\dot{v}_{lat} = mg_{lat} + \sum_{i=1}^{n_{Wheel}} F_{C,lat,i}$$

$$J_{zz}\dot{\omega}_z = \sum_{i=1}^{n_{Wheel}} \left(r_{long,i} F_{C,lat,i} + r_{lat,i} F_{C,long,i} + T_{C,z,i} \right)$$

- $F_C, T_C \rightarrow$ Highly non-linear model,
  $\mathbf{A}$ and $\mathbf{B}$ by numerical linearization
- Prediction horizon $N \leq 10$ (sample rate ratio)



- Contact forces / torques are functions of
  - Chassis kinematics, wheel shape
  - Soil parameters
  - Vehicle mass, gravity conditions
  - States of controlled actuators
  - Vehicle states, vehicle attitude

MPC Prediction Model: Contact Dynamics Model

- Load-sinkage relationship for soft soil proposed by Bekker

$$\sigma = \left(\frac{k_c}{b} + k_\varphi\right) z^n \cdot \left(1 + dv_{Normal}\right)$$

- Mohr-Coulomb soil failure criterion

$$\tau_{max} = c + \sigma \tan\varphi$$

- Formulation for shear stress by Janosi-Hanamoto

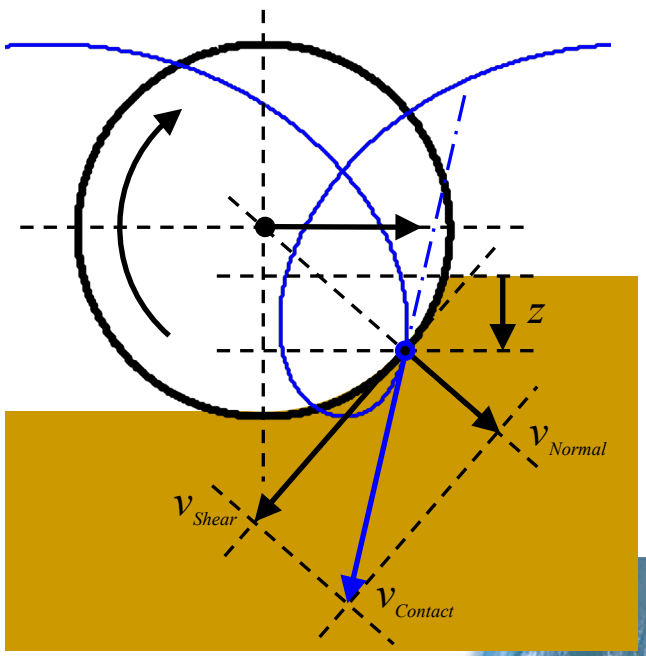
$$\tau = \tau_{max}\left(1 - e^{-j/k_j}\right); \quad j = \int v_{Shear}\, dt_{Contact}$$

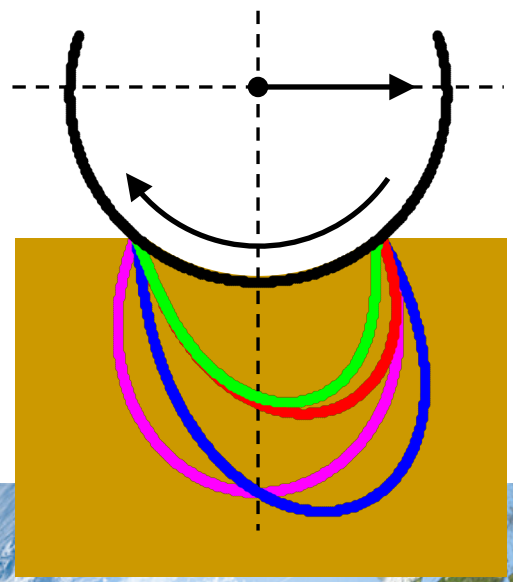
σ: Contact normal stress
τ: Contact shear stress

z: Vertical sinkage
j: Shear deformation

k_c: Cohesive modulus
k_φ: Frictional modulus
k_j: Deformation modulus
n: Exponent of sinkage
c: Soil cohesion
φ: Angle of internal soil friction
d: Soil damping coefficient

b: Contact patch width





MPC Optimization Goals

- Primary goals on states $\mathbf{x}$
  - Achieve desired trajectory velocity

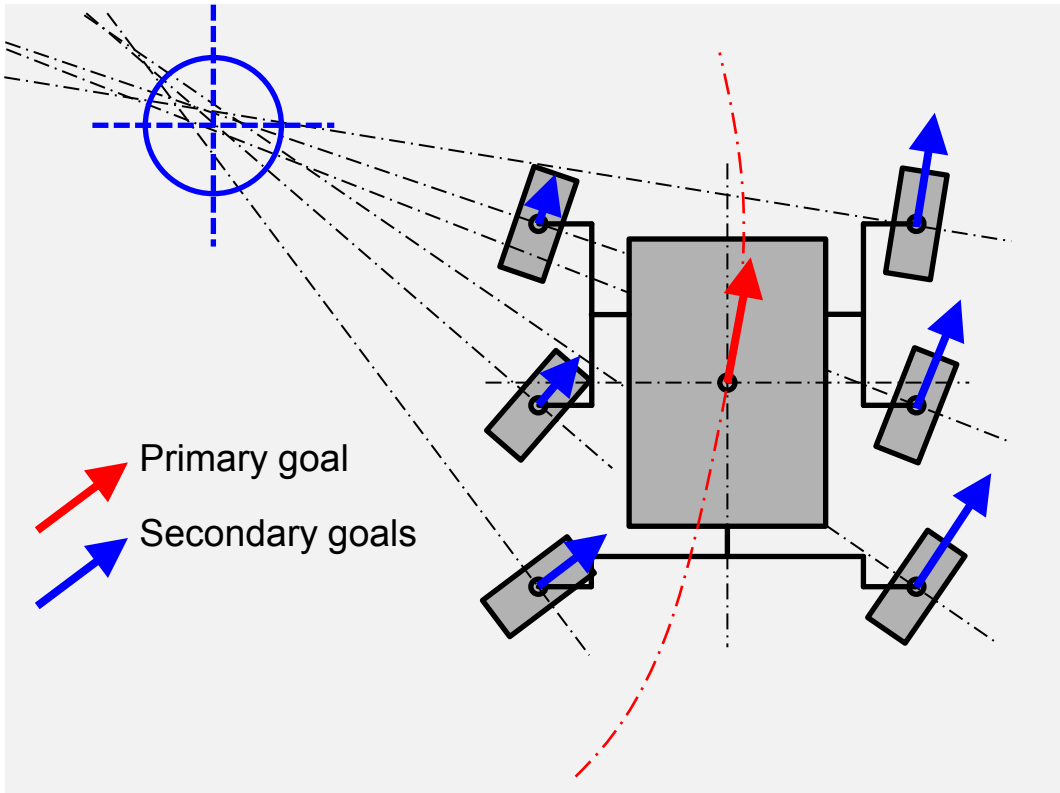
$$\begin{pmatrix} v_{long} \\ v_{lat} \end{pmatrix} \rightarrow \mathbf{v}_{traj} = \begin{pmatrix} v_{long} \\ v_{lat} \end{pmatrix}_{traj}$$

  - 2 DOF, heading angle not defined
- Secondary goals on control inputs $\mathbf{u}$
  - Keep rover in rolling configuration

$$\mathbf{u} \rightarrow \mathbf{u}_{roll} = \mathbf{u}\left(Ackermann\right)$$

  - Avoid sliding if not required
  - Avoid fancy configurations
- Controller tuning by goal weights

$$\mathbf{r} = \begin{pmatrix} \mathbf{r}_{pri} \\ \mathbf{r}_{sec} \end{pmatrix} = \begin{pmatrix} \mathbf{W}_{pri}\mathbf{v}_{traj} \\ \mathbf{W}_{sec}\mathbf{u}_{roll} \end{pmatrix}$$



MPC Constraints

- Steering drive limits
  - Static steering angle limit due to end stops

$$\boldsymbol{\beta}_{min} \leq \boldsymbol{\beta} \leq \boldsymbol{\beta}_{max}$$

  - Dynamic steering angle rate limit due steering torque

$$\boldsymbol{\omega}_{Steering,min}\left(\mathbf{T}_{\beta}\right) \leq \boldsymbol{\omega}_{Steering} \leq \boldsymbol{\omega}_{Steering,max}\left(\mathbf{T}_{\beta}\right)$$

- Wheel drive limits
  - Dynamic velocity limit due to wheel torque

$$\boldsymbol{\omega}_{Wheel,min}\left(\mathbf{T}_{\omega}\right) \leq \boldsymbol{\omega}_{Wheel} \leq \boldsymbol{\omega}_{Wheel,max}\left(\mathbf{T}_{\omega}\right)$$

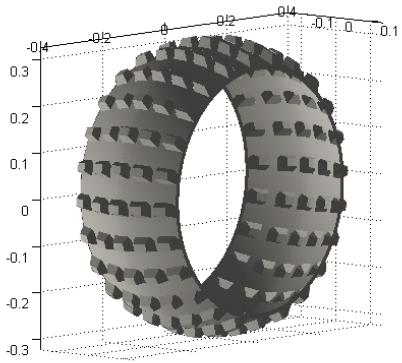
  - Dynamic acceleration limit due to wheel torque at current velocity

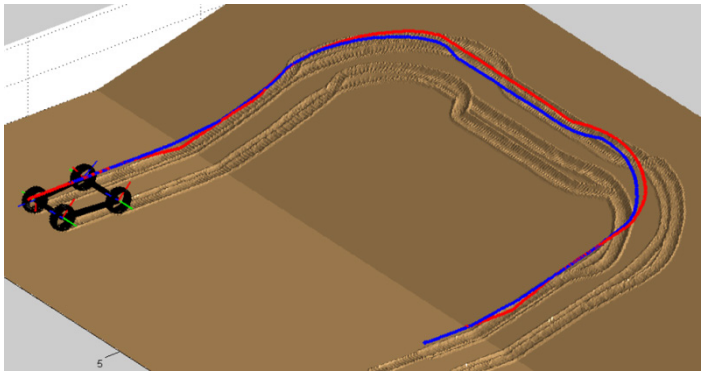
$$\dot{\boldsymbol{\omega}}_{Wheel,min}\left(\mathbf{T}_{\omega},\boldsymbol{\omega}_{Wheel}\right) \leq \dot{\boldsymbol{\omega}}_{Wheel} \leq \dot{\boldsymbol{\omega}}_{Wheel,max}\left(\mathbf{T}_{\omega},\boldsymbol{\omega}_{Wheel}\right)$$

RobMPC: Dynamic and Kinematic Environment (DKE) for Nominal Tests and Robustness Tests

- Multi-body dynamics model of EGP rover
  - Vehicle kinematics and dynamics
  - Actuator dynamics model
- SCM* (Soil Contact Model)
  - 3D soil contact model for MBS applications
  - Terrain topology DEM
  - Tire profile
- Sensor models
  - Vehicle attitude
  - Vehicle states
- MPC and reference controllers

Parameter	Nominal	Min	Max
Vehicle Parameters			
Total rover mass	880 kg	810	950
4x wheel mounting misalignment	0°	-0.5°	0.5°
2x steering drive time constant	0.19 s	0.17	0.21
4x wheel drive time constant	0.3 s	0.1	0.59
Terrain Parameters			
Terrain inclination	0°	0°	15°
Environmental gravity	3.71 m/s^2	3.24	4.08
Frictional modulus	1.0e7	1.0e6	1.0e7
Cohesive modulus	0	0	1.0e4
Shear def. modulus	0.1	0.1	0.5
Exponent of sinkage	1	1	1.2
Cohesion of soil	0 Pa	0	30
Internal friction angle	30°	20°	35°

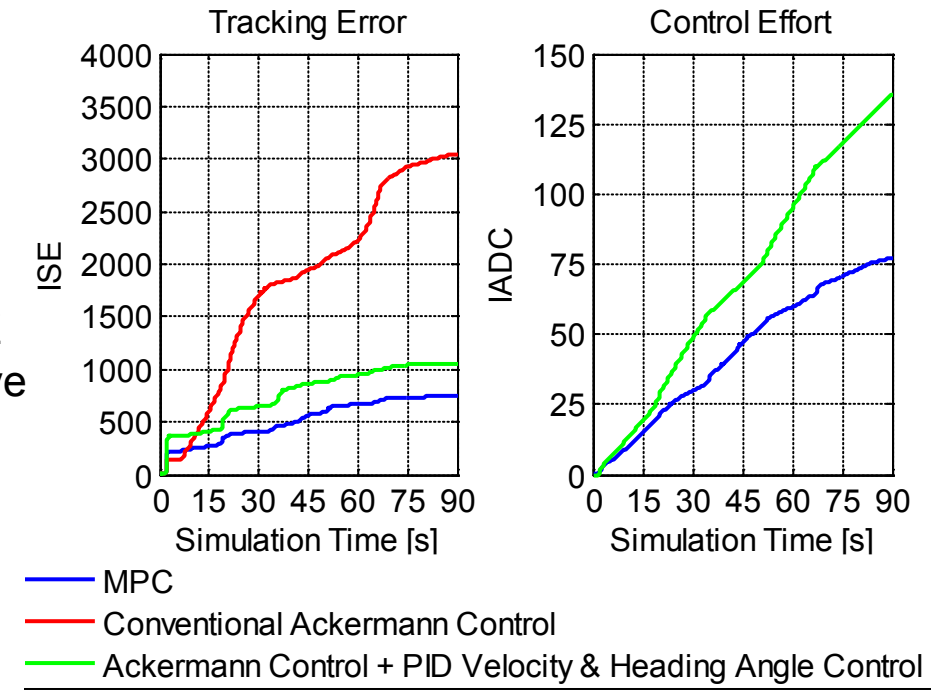


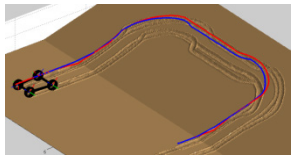


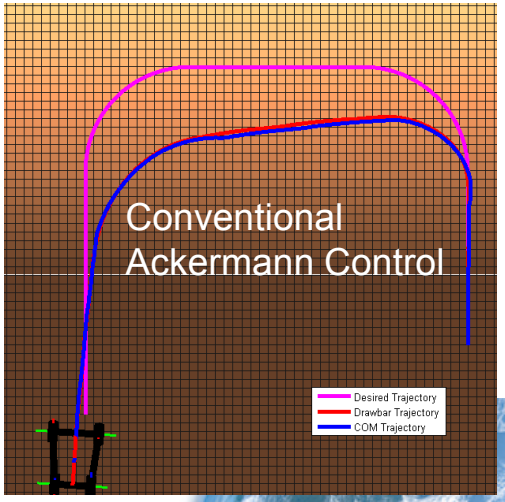
* R. Krenn; G. Hirzinger; *Simulation of Rover Locomotion on Sandy Terrain - Modeling, Verification and Validation*; ASTRA 2008

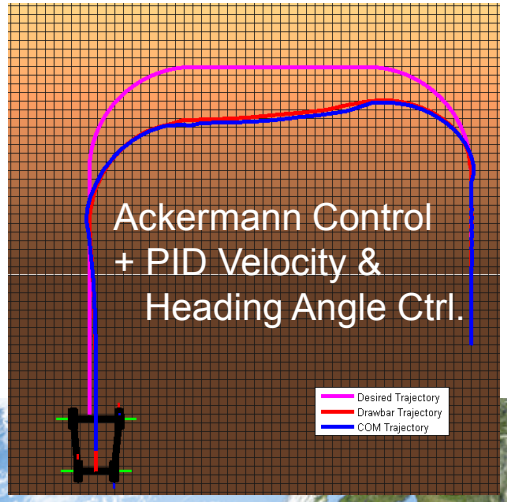
RobMPC: Results of Nominal Tests

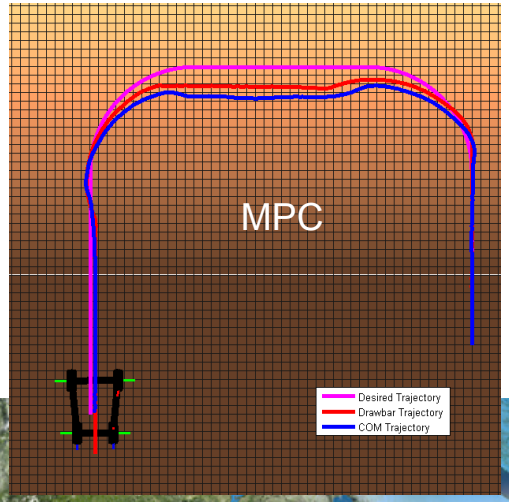
- Verification against reference controllers
  1. Conventional Ackermann control
  2. Ackermann control with PID velocity and heading angle control
- Control performance estimation using indicators
  1. Tracking error: Integral of square error ISE
  2. Control effort: Integral of absolute derivative of control signal
- Best performance achieved with MPC
  - Independent control of each actuator (6 controls vs. 2 for Ackermann control)
  - Optimal actuator coordination → Sliding





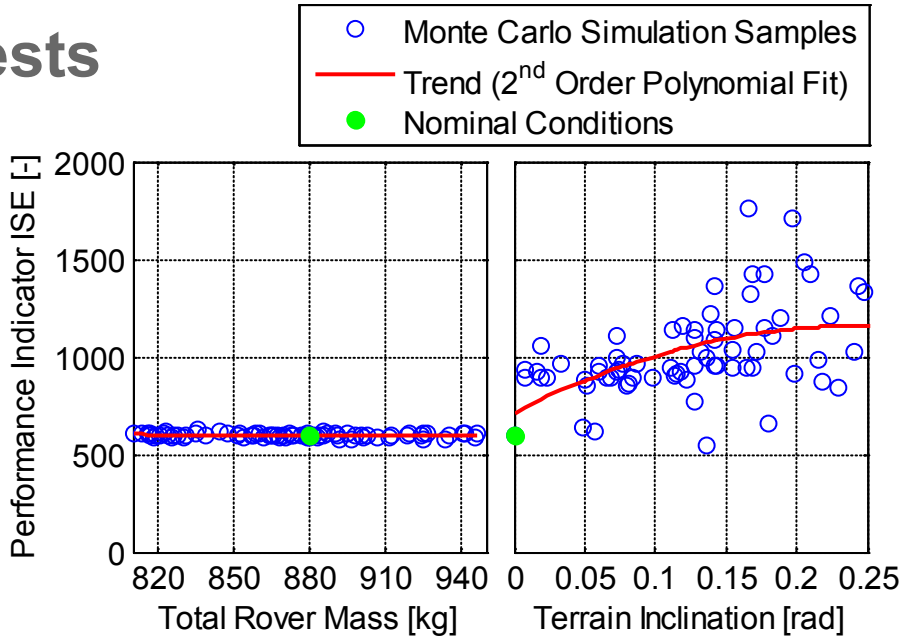






RobMPC: Robustness Tests

- Monte Carlo Simulations
  - Controller parameters: Nominal
  - DKE parameters: Varied
  - 100 simulation runs per campaign
  - Outputs used: Performance indicator values at end of each simulation
- 2 Monte Carlo campaigns
  - Random variation of vehicle parameters
  - Random variation of terrain parameters
- Evaluation:
  - Sorting of results by single parameter
  - Identifying trend → sensitivity w.r.t. single parameter used for sorting
- Results:
  - Low sensitivity w.r.t. vehicle params
  - Moderate sensitivity w.r.t. terrain params
  - Always better than conventional Ackermann control



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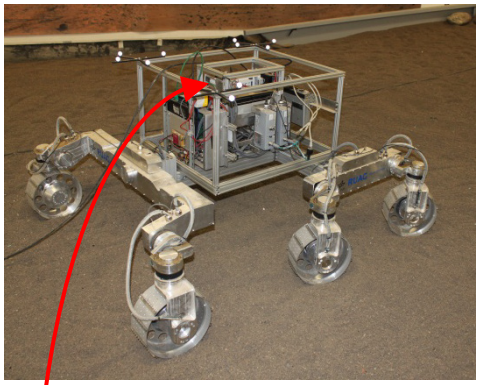
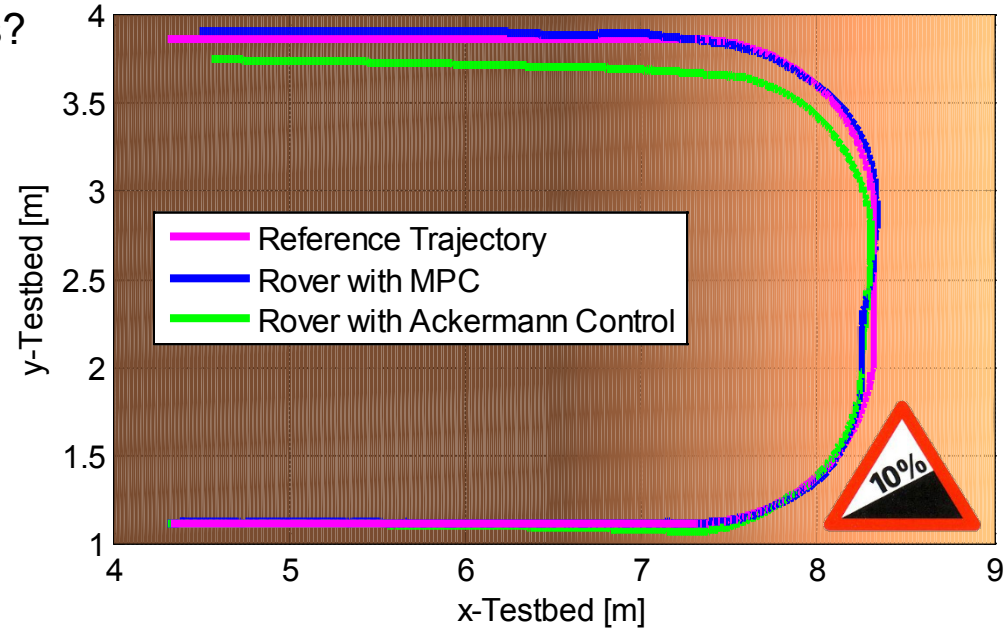
ExoMars Breadboard Rover Tests



- Is MPC approach applicable to real rover system?
  - ExoMars breadboard rover
  - Planetary exploration testbed DLR-RMC

Parameter	Value
CPU	INTEL Core2Duo T9600, 2.8GHz
RAM	4 GB, 1066 MHz
OS	QNX 6.5 Neutrino

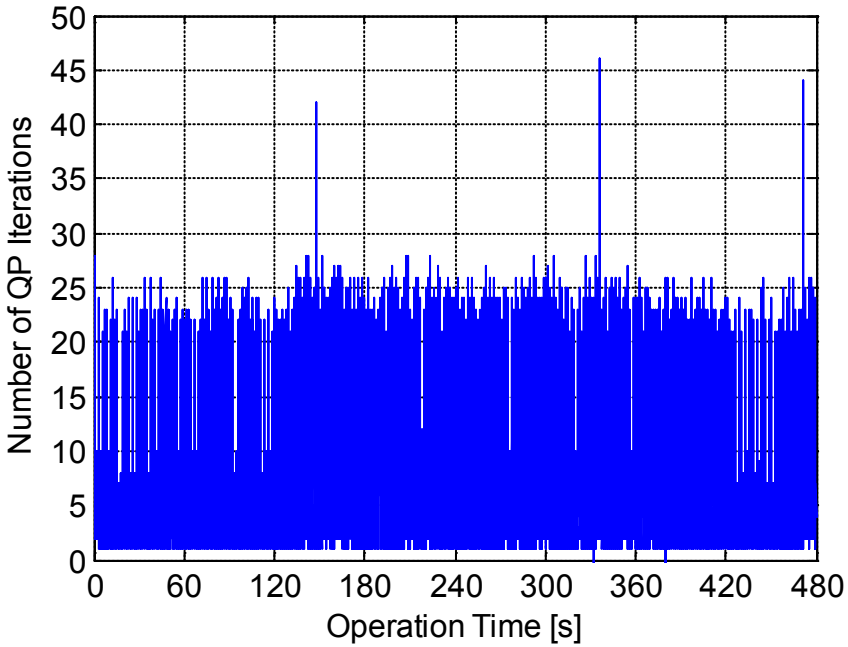
- Is the MPC prediction model descriptive enough to capture the dynamics of the real system?
- Is the MPC prediction model simple enough to work under real-time operation conditions?
  - 100 Hz
- Is controller robust enough to deal with parameter uncertainties?
  - Actuator performance uncertainties
  - Soil parameter uncertainties
- Is controller robust enough to work with real sensor feedback?
  - Time derivative of pose tracking sensor signal

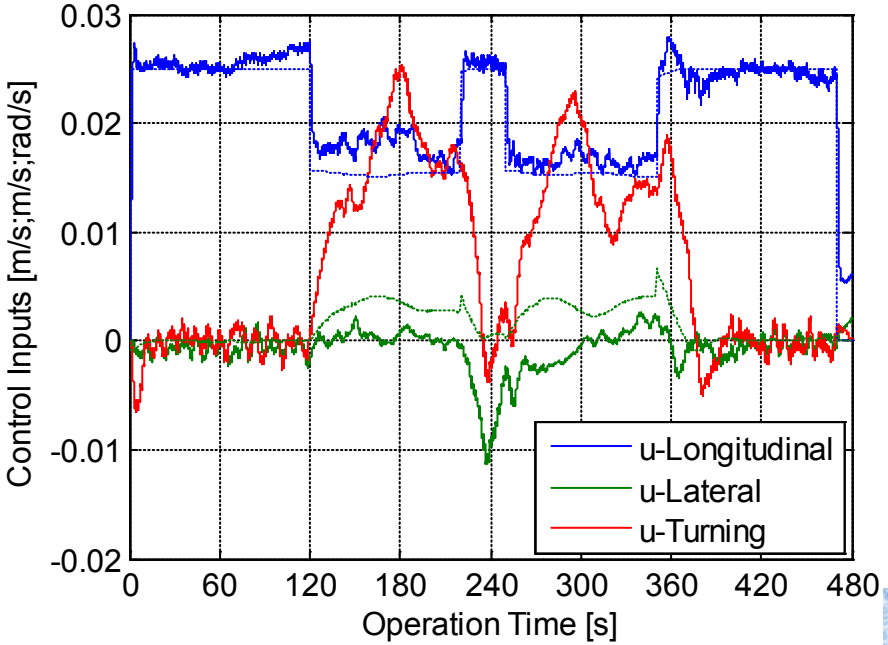


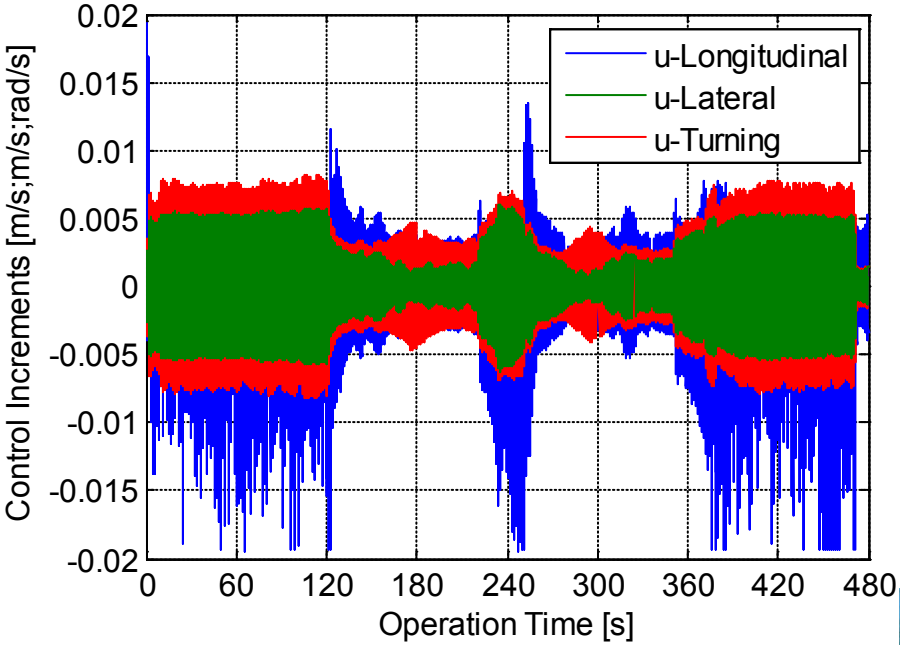
Answer: YES!

ExoMars BB Rover Tests … More Results

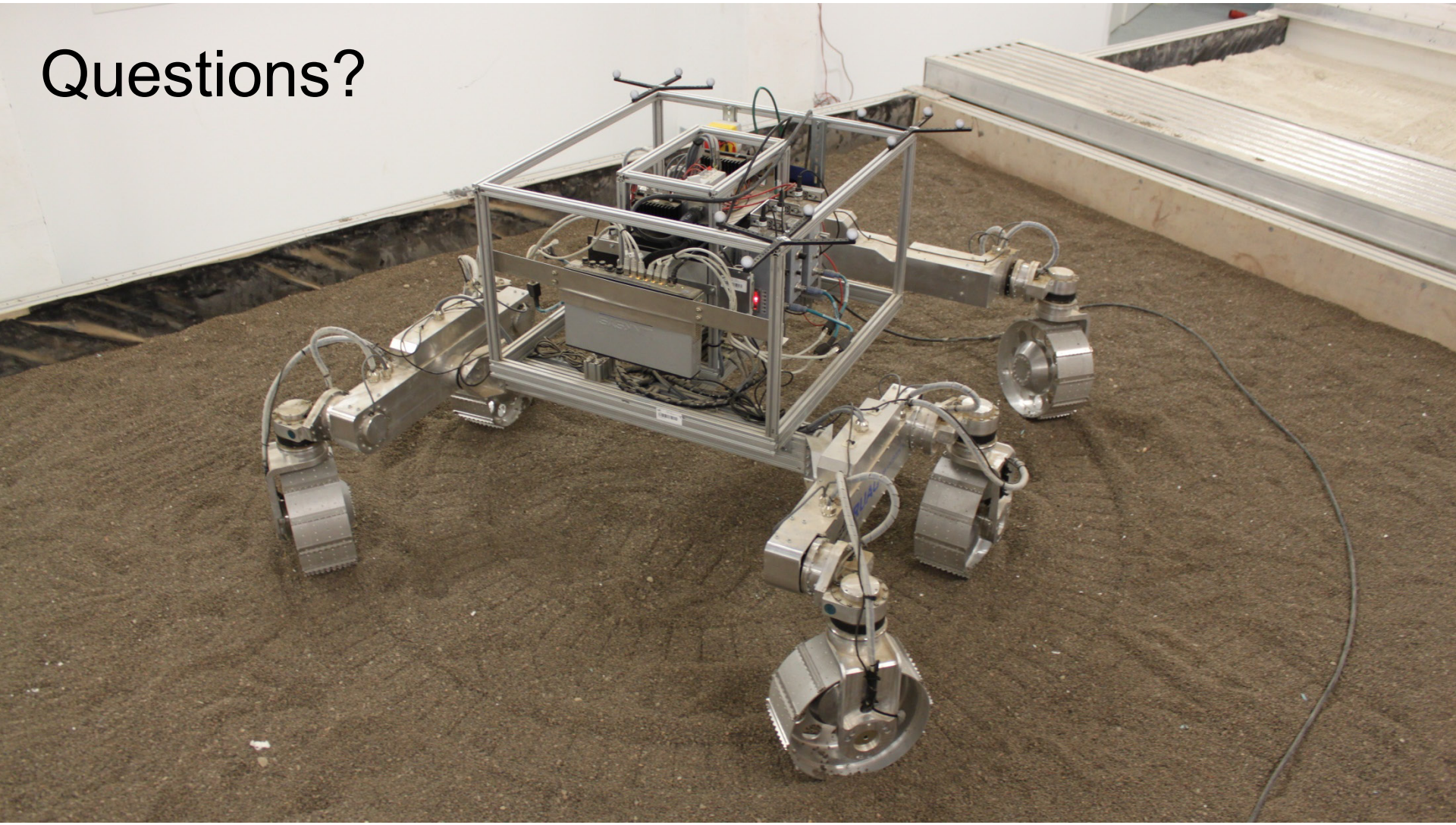
- CPU time: ~2600 ns (< 0.01 %)
- Deterministic process: QP < 50
- Transferability of results to space qualified computers?







Questions?



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