Model Predictive Traction and Steering Control of Planetary Rovers

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Model Predictive Control (MPC) - User Point of View

- Well-known from process control of plants
  - Large number of states $x$ and algebraic variables $z$
  - Small number of controls $u$
  - 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)

<table>
<thead>
<tr>
<th>ORCSAT S/C Rendezvous Application</th>
<th>$T_s$</th>
<th>Prediction Horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit Synchronization TG</td>
<td>10min</td>
<td>&lt;250min</td>
</tr>
<tr>
<td>Impulsive Nominal TG</td>
<td>5min</td>
<td>&lt;100min</td>
</tr>
<tr>
<td>Forced Terminal TG</td>
<td>3s</td>
<td>45s</td>
</tr>
</tbody>
</table>

Source: BASF, Press Release

Source: ESA
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

* 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

- Kinematics Independent MPC
- Trajectory Control
- Desired COM Velocity Vector $[v_x, v_y]$

Kinematics Specific MPC

- Traction & Steering Control
- Desired Steering Angles
- Desired Wheel Velocities

Non-MPC Device Specific Controllers

- Steering Angle Ctrl
- Wheel Velocity Ctrl

Frequencies:
- 10 Hz
- 100 Hz
- 1000 Hz
MPC Traction & Steering Control Implementations

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

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

s.t. $x_{t+k+1} = f(x_{t+k}, u_{t+k})$ States

$y_{t+k} = g(x_{t+k})$ Outputs

$u_{\min} \leq u_{t+k} \leq u_{\max}$ Constraints on inputs

$y_{\min} \leq y_{t+k} \leq y_{\max}$ Constraints on outputs

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

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

$$x_{k+1} = A(t,k,x(t))x_k + B(t,k,x(t))u_k$$

- User model: Goals and constraints

$$r_k \Rightarrow z_k = E_z(t,k,x(t))x_k + H_z(t,k,x(t))u_k + P_z(t,k,x(t))\Delta u_k$$

$$c_{\max} \Rightarrow c_k = E_c(t,k,x(t))x_k + H_c(t,k,x(t))u_k + P_c(t,k,x(t))\Delta u_k$$

$$d_N \Rightarrow d = C_N(t,x(t))x_{N(t)}$$
MPC Prediction Model: Equations of Motion

- Vehicle states:
  \[ \mathbf{x} = \begin{pmatrix} v_{\text{long}} & v_{\text{lat}} & \omega_z \end{pmatrix}^T \]

- Control inputs:
  \[ \mathbf{u} = \begin{pmatrix} \beta_1 & \beta_2 & \ldots & \beta_{n\text{Steering}} & \omega_1 & \omega_2 & \ldots & \omega_{n\text{Wheel}} \end{pmatrix}^T \]

- Equations of planar motion:
  \[
  m\ddot{v}_{\text{long}} = mg_{\text{long}} + \sum_{i=1}^{n_{\text{Wheel}}} F_{C,\text{long},i} \\
  m\ddot{v}_{\text{lat}} = mg_{\text{lat}} + \sum_{i=1}^{n_{\text{Wheel}}} F_{C,\text{lat},i} \\
  J_{zz}\ddot{\omega}_z = \sum_{i=1}^{n_{\text{Wheel}}} \left( r_{\text{long},i} F_{C,\text{lat},i} + r_{\text{lat},i} F_{C,\text{long},i} + T_{C,z,i} \right)
  \]

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

- Highly non-linear model, \( A \) and \( B \) by numerical linearization

- Prediction horizon \( N \leq 10 \) (sample rate ratio)
MPC Prediction Model: Contact Dynamics Model

- Load-sinkage relationship for soft soil proposed by Bekker
  \[
  \sigma = \left( \frac{k_c}{b} + k_\phi \right) z^n \cdot (1 + d v_{\text{Normal}})
  \]

- Mohr-Coulomb soil failure criterion
  \[
  \tau_{\text{max}} = \frac{c + \sigma \tan \varphi}{1 + \sigma}
  \]

- Formulation for shear stress by Janosi-Hanamoto
  \[
  \tau = \tau_{\text{max}} \left(1 - e^{-j/k_j}\right); \quad j = \int v_{\text{Shear}} \, dt_{\text{Contact}}
  \]

\[\sigma: \text{Contact normal stress}\]
\[\tau: \text{Contact shear stress}\]
\[z: \text{Vertical sinkage}\]
\[j: \text{Shear deformation}\]
\[k_c: \text{Cohesive modulus}\]
\[k_\phi: \text{Frictional modulus}\]
\[k_j: \text{Deformation modulus}\]
\[n: \text{Exponent of sinkage}\]
\[c: \text{Soil cohesion}\]
\[\varphi: \text{Angle of internal soil friction}\]
\[d: \text{Soil damping coefficient}\]
\[b: \text{Contact patch width}\]
MPC Optimization Goals

• Primary goals on states $x$
  • Achieve desired trajectory velocity
    $$\begin{pmatrix} v_{\text{long}} \\ v_{\text{lat}} \end{pmatrix} \rightarrow v_{\text{traj}} = \begin{pmatrix} v_{\text{long}} \\ v_{\text{lat}} \end{pmatrix}_{\text{traj}}$$
  • 2 DOF, heading angle not defined

• Secondary goals on control inputs $u$
  • Keep rover in rolling configuration
    $$u \rightarrow u_{\text{roll}} = u(\text{Ackermann})$$
  • Avoid sliding if not required
  • Avoid fancy configurations

• Controller tuning by goal weights
    $$\mathbf{r} = \begin{pmatrix} r_{\text{pri}} \\ r_{\text{sec}} \end{pmatrix} = \begin{pmatrix} W_{\text{pri}} v_{\text{traj}} \\ W_{\text{sec}} u_{\text{roll}} \end{pmatrix}$$
MPC Constraints

- Steering drive limits
  - Static steering angle limit due to end stops
    \[ \beta_{\text{min}} \leq \beta \leq \beta_{\text{max}} \]
  - Dynamic steering angle rate limit due steering torque
    \[ \omega_{\text{Steering, min}}(T_{\beta}) \leq \omega_{\text{Steering}} \leq \omega_{\text{Steering, max}}(T_{\beta}) \]

- Wheel drive limits
  - Dynamic velocity limit due to wheel torque
    \[ \omega_{\text{Wheel, min}}(T_{\omega}) \leq \omega_{\text{Wheel}} \leq \omega_{\text{Wheel, max}}(T_{\omega}) \]
  - Dynamic acceleration limit due to wheel torque at current velocity
    \[ \dot{\omega}_{\text{Wheel, min}}(T_{\omega}, \omega_{\text{Wheel}}) \leq \dot{\omega}_{\text{Wheel}} \leq \dot{\omega}_{\text{Wheel, max}}(T_{\omega}, \omega_{\text{Wheel}}) \]
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

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal</th>
<th>Min</th>
<th>Max</th>
</tr>
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<tbody>
<tr>
<td><strong>Vehicle Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total rover mass</td>
<td>880 kg</td>
<td>810</td>
<td>950</td>
</tr>
<tr>
<td>4x wheel mounting misalignment</td>
<td>0°</td>
<td>-0.5°</td>
<td>0.5°</td>
</tr>
<tr>
<td>2x steering drive time constant</td>
<td>0.19 s</td>
<td>0.17</td>
<td>0.21</td>
</tr>
<tr>
<td>4x wheel drive time constant</td>
<td>0.3 s</td>
<td>0.1</td>
<td>0.59</td>
</tr>
<tr>
<td><strong>Terrain Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terrain inclination</td>
<td>0°</td>
<td>0°</td>
<td>15°</td>
</tr>
<tr>
<td>Environmental gravity</td>
<td>3.71 m/s²</td>
<td>3.24</td>
<td>4.08</td>
</tr>
<tr>
<td>Frictional modulus</td>
<td>1.0e7</td>
<td>1.0e6</td>
<td>1.0e7</td>
</tr>
<tr>
<td>Cohesive modulus</td>
<td>0</td>
<td>0</td>
<td>1.0e4</td>
</tr>
<tr>
<td>Shear def. modulus</td>
<td>0.1</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Exponent of sinkage</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Cohesion of soil</td>
<td>0 Pa</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Internal friction angle</td>
<td>30°</td>
<td>20°</td>
<td>35°</td>
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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 $\rightarrow$ 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

### Parameter Values

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<td>1.2</td>
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ExoMars Breadboard Rover Tests

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

- 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: $\sim 2600$ ns ($< 0.01 \%$)
- Deterministic process: QP $< 50$
- Transferability of results to space qualified computers?
Questions?