Evaluation of Mobility Concepts for a Martian Rover

IEEE International Conference on Robotics and Automation, 2008

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Outline

• Rover Comparison

• Controller

• CRAB Model

• Simulations

• Tactile Wheel

• Conclusion
• **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.

- 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.

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

  where \( \vartheta_{ref} \) = velocity of reference wheel,
  \( \vartheta_{opt_i} \) = optimal velocity of wheel \( i \),
  \( n \) = number of wheels.

• **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

<table>
<thead>
<tr>
<th>Breadboard</th>
<th>Schematic view</th>
<th>Kinematic model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MER</strong> by NASA (rocker-bogie type)</td>
<td><img src="image1" alt="Schematic view of MER" /></td>
<td><img src="image2" alt="Kinematic model of MER" /></td>
</tr>
<tr>
<td><strong>CRAB</strong> by ASL (symmetric structure based on four parallel bogies)</td>
<td><img src="image3" alt="Schematic view of CRAB" /></td>
<td><img src="image4" alt="Kinematic model of CRAB" /></td>
</tr>
<tr>
<td><strong>RCL-E</strong> by RCL (three parallel bogies, no differential mechanism)</td>
<td><img src="image5" alt="Schematic view of RCL-E" /></td>
<td><img src="image6" alt="Kinematic model of RCL-E" /></td>
</tr>
</tbody>
</table>
Kinematic Models

• **Kinematic modeling**

\[
\begin{align*}
\vartheta_{DA} & := \vartheta_D = \vartheta_A + \omega_1 \times 0 \frac{1}{1} R(\alpha) \frac{1}{AD} \\
\vartheta_{DB} & := \vartheta_D = \vartheta_B + \omega_2 \times 0 \frac{2}{2} R(\beta) \frac{2}{DB} \\
\vartheta_{DC} & := \vartheta_D = \vartheta_C + \omega_2 \times 0 \frac{2}{2} R(\beta) \frac{2}{DC}
\end{align*}
\]

• **Simulation setup: Working Model 2D interfaced with Matlab**
Rover Comparison: Simulation Results

<table>
<thead>
<tr>
<th>Rover</th>
<th>Ref. wheel</th>
<th>Test</th>
<th>$\sum (\Delta vel_{opt})$ [m/s]</th>
<th>Test</th>
<th>$\sum (\Delta vel_{opt})$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MER</td>
<td>1</td>
<td>1</td>
<td>27.87</td>
<td>7</td>
<td>93.71</td>
</tr>
<tr>
<td>CRAB</td>
<td>1</td>
<td>1</td>
<td>12.17</td>
<td>7</td>
<td>37.53</td>
</tr>
<tr>
<td>RCL-E</td>
<td>1</td>
<td>1</td>
<td>12.72</td>
<td>7</td>
<td>35.69</td>
</tr>
<tr>
<td>MER</td>
<td>2</td>
<td>2</td>
<td>15.87</td>
<td>8</td>
<td>55.46</td>
</tr>
<tr>
<td>CRAB</td>
<td>2</td>
<td>2</td>
<td>10.00</td>
<td>8</td>
<td>28.00</td>
</tr>
<tr>
<td>RCL-E</td>
<td>2</td>
<td>2</td>
<td>11.12</td>
<td>8</td>
<td>29.96</td>
</tr>
<tr>
<td>MER</td>
<td>3</td>
<td>3</td>
<td>17.25</td>
<td>9</td>
<td>55.20</td>
</tr>
<tr>
<td>CRAB</td>
<td>3</td>
<td>3</td>
<td>12.02</td>
<td>9</td>
<td>37.87</td>
</tr>
<tr>
<td>RCL-E</td>
<td>3</td>
<td>3</td>
<td>11.69</td>
<td>9</td>
<td>33.70</td>
</tr>
</tbody>
</table>

Performance regarding metric $\Delta vel_{opt}$

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

• **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
• **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
- **CRAB Rover**

- **Passive Structure**
• **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
• **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
• Optimization
  
  - MO = 1  =>  single motor needed for control
  - All wheels motorized:  system under constrained
  - Missing equations:  \( n_{\text{wheel}} - 1 \)

• Heuristic
  
  - With:
    \[ G_i = \frac{R_i}{N_i} \]

  - The optimal set of torques is found as follows:
    \[ H = \min \left( \sum_i \left( G_i - \bar{G} \right)^2 \right) \]
- Performed with ODE (Open Dynamics Engine)
- 3 test terrains
- 3 different $\mu$
• **Test**
  
  - Torque control compared with wheel synchronization algorithm

  [E.T. Baumgartner 2001]

<table>
<thead>
<tr>
<th>Terrain</th>
<th>$\mu$</th>
<th>Distance Tot.</th>
<th>Control Type</th>
<th>Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Torque</td>
<td>Velocity</td>
</tr>
<tr>
<td>1</td>
<td>0.4</td>
<td>25 m</td>
<td>1.41 m</td>
<td>2.41 m</td>
</tr>
<tr>
<td>2</td>
<td>0.4</td>
<td>25 m</td>
<td>1.02 m</td>
<td>1.60 m</td>
</tr>
<tr>
<td>3</td>
<td>0.4</td>
<td>25 m</td>
<td>1.97 m</td>
<td>2.56 m</td>
</tr>
</tbody>
</table>

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

- 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

ETH Zürich, Autonomous Systems Lab – Towards Torque Control of the CRAB rover
Static stability
Static stability
Static stability
Questions ?