MOBILITY CHALLENGES AND POSSIBLE SOLUTIONS FOR LOW-GRAVITY PLANETARY BODY EXPLORATION

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Motivation

> Exploration of small bodies is challenging
  > Microgravity
  > Environmental conditions
  > Deep space missions

> Testing of microgravity mobility systems is impossible on earth
  > Simulation (not valid without any tests)
  > Alternative tests (mock-up)
  > Microgravity tests

> Hardware development
  > Test-rigs
  > Breadboard
  > Flight model

> Electronics and controller development for
  > Deep space mission requirements
  > High miniaturization
  > Simulation support
Small bodies environment

Microgravity
- Gravitational force depends on
  - mass distribution/density
  - distance of body centre
  - position on target body

Undefined soil conditions
- Ground shape
- Material
- Behaviour while interacting
Mobility system requirements

- Provide measurements on different locations
  - Maximise science possibilities
- Robust concept
  - Simple but effective
  - Controllable & adaptive
  - Independent from soil characteristics
- Deep space qualified
  - Survival of cruise phase
    - radiation
    - temperatures

(1999 JU3)
Finding a solution

- Multi body system (MBS) simulation model
  - Small body (or representative) environment
  - Mobile system
- Gravitation model of the target body
  - Simple (mostly sufficient)
  - Sophisticated (if needed)
- Contact models
  - Polygonal contact model PCM
  - Soil contact model SCM (DLR developed)
- Parameter variations
  - Test out suitable model parameters
  - Sensitivity analysis to environment parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
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<tbody>
<tr>
<td>Young’s modulus</td>
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<td>Poisson ratio</td>
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<td>Layer depth</td>
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<td>Areal damping</td>
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<tr>
<td>Damping depth</td>
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<tr>
<td>Friction coefficient μ</td>
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<table>
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<th>MRS-C</th>
<th>MRS-D</th>
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<tr>
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<td>Coarse</td>
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<td>Grain size dist</td>
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<td>-</td>
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<td>Bulk density</td>
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<td>1400</td>
<td>1800</td>
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<td>Internal friction angle</td>
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<td>Cohesion</td>
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<tr>
<td>Scaling coefficient k*</td>
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<td>10³ - 2*10⁵</td>
<td>10⁵</td>
<td>10⁵ - 10⁶</td>
<td>10⁵ - 10⁶</td>
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</tbody>
</table>

- MOBILITY CHALLENGES AND POSSIBLE SOLUTIONS FOR LOW-GRAVITY PLANETARY BODY EXPLORATION
- Florian Herrmann > 14.04.2011
Simulation: Wheeled rover in microgravity (1)

- Example model
  - 6-wheeled rover
  - ExoMars (breadboard) kinematics
  - Mass of 102 kg reproduce ground loads of a 300 kg rover on Mars
  - Rover behaviour covered by hardware test experience

- Scenario 1
  - Earth gravity
  - Ascending slope of 11 deg
  - Crossing an obstacle
Simulation: Wheeled rover in microgravity (2)

- Test: Reducing gravity step by step
  - Scenario 2: 10 % of earth gravity
  - Scenario 3: 2.5 % of earth gravity

- Not considered
  - Possible change of soil behaviour due to microgravity
  - Microgravity-specific modification possibilities
Simulation: Wheeled rover in microgravity (3)

- Scenario 4: 1.0 % of earth gravity
  - Still 1000 x higher gravity than usually on small bodies!
- Results
  - Great impact of microgravity on traction performance
  - Conventional kinematics do not work in this environment
  - Less wheel loads mean less applicable torque
  - Disturbances can lead to uncontrollable dynamics, e.g. wheel lift-off
  - Very slow reaction due to microgravity
Hopping mechanisms

- Previous missions
  - Phobos hopper (43 kg)
    - spring-driven brackets
    - 10 hops
    - 20 meters each
  - MINERVA I & II (0.6 kg)
    - Flywheel driven
    - Lifetime: 36 hrs
- Both were lost before operating on the target’s surface
Trade off: Definition of a hopper concept (1)

- Requirements: MASCOT (DLR-RY)
  - 10 kg lander package
  - Target body 1999 JU3
    - surface gravity: 1.7e-5 g
- Example: Only two concepts
  - Arm concept
  - Excenter driven concept
- Other tested concepts
  - Spring driven concepts
  - Flywheel
- Important parameters
  - Robustness of motion
  - Estimated power consumption
  - Mechanical issues
    - bearing & mounting design
    - complexity
Trade off: Definition of a hopper concept (2)

- Example scenario
  - Gravity: $1.7 \times 10^{-5}$ g
  - Different soil characteristics left/right
  - PCM
  - $v_0 = 0.5 \times v_{esc} = 0.16$ m/s
- Lever arm concept
Trade off: Definition of a hopper concept (3)

- Example scenario
  - Gravity: 1.7 * 10^{-5} g
  - Different soil characteristics left/right
  - PCM
    - \( v_0 = 0.5 \times v_{esc} = 0.16 \text{ m/s} \)
  - Excenter driven concept
Trade off: Definition of a hopper concept (4)

- Reasons for simulation-supported trade-off
  - Concept decision in early phase (A)
  - Not yet all information available
    - target properties
    - final system parameters (mass..)
  - Many open questions
  - It is easy with parameter variation to compare concepts

- Results of the trade-off
  - Excenter tappet concept is the most promising for given mission requirements
Parameter Variation: Deviation of mass moment inertia (1)

- When concept is fixed
  - Get information about system behaviour
  - Improve dynamics
  - Support design process
  - Component selection

- Parameter variation example
  - Hopping scenario
  - Variation of the inertia tensor (4x)
  - Observe impact on dynamic behaviour

- Desired results
  - Specification of acceptable inertia deviation

- Other possible variations
  - Position of CoM
  - Drive control strategies
Parameter Variation: Deviation of mass moment inertia (2)

- Note: Slow motions due to microgravity
  - Realtime duration of this action: 400 s / 6:40 min

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Parameter Variation: Deviation of mass moment inertia (3)

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<td>0,015</td>
<td>0</td>
<td>0,1505</td>
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Component development (1)

- Goal of the ParVar: identify required drive speed for small hop
- Parameter variation
  - $4 \times K_L$ (proportional gain for position control): 5…20
  - $45 \times T$ (time constant for drive action): 0.1 … 1 sec
  - 180 variations
Component development (2)

- Results
  - Height (z-position)
  - Required motor torque

![Graph showing z-position and motor torque over time](image)
Component development (3)

➤ Best result
  ➤ K_L = 5
  ➤ T = 0.445 s

➤ Motor
  ➤ Less than 5 mNm without margins and security
  ➤ Runs less than 0.5 s
  ➤ Maximum drive speed: 820 rad/s or 7830 rpm
  ➤ Relocation distance: 0.79 m
  ➤ Estimated motor current: 0.55 A
Component development (4)

- Results are used for calculating
  - Input & output speed of the gear
  - Required current
- This leads to suitable components
  - Motor
  - Gear
  - Controller / power electronics
- Resulting action
  - Small hop
  - Duration: 130 s (low gravity!)
DLR RM activities overview

- MBS model
  - Simulation
- Mock-up
  - Tests under earth gravity
- Breadboard
  - Microgravity tests
- Flight model
  - Asteroid
DLR-RM test facility: Mock-up (1)

- Testing on earth
  - Impossible without modifications
- Mock-up: Highly scaled test model
  - Off-the-shelf components
  - Less mass
  - More power
  - Increased excenter masses
  - Different mass distribution
  - Gravity compensation: pendulum
  - Simulation verification
DLR-RM test facility: Mock-up (2)

- First test results
  - Pendulum: 2 m
- Comparison
  - Test
  - Simulation

![Graph showing angular velocity over time](image-url)
Outlook

- More mock-up tests
  - Improved test modes
  - pendulum length: up to 10 m
  - Control strategies
  - start & stop position
  - drive speed
  - Different ground conditions
- Breadboard microgravity tests
  - Drop tower
  - Parabolic flight
- Simulation support
  - Mock-up tests
  - Microgravity tests
  - Flight model

MASCOT is under the lead of DLR-RY (Bremen) and proposed for the Hayabusa-2 mission of JAXA