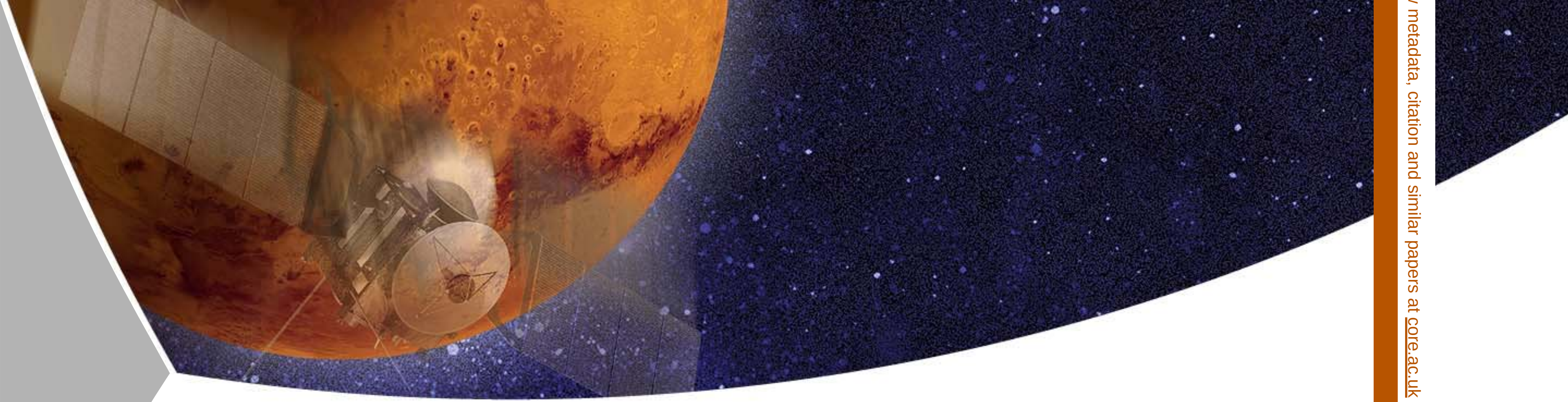

MOBILITY CHALLENGES AND POSSIBLE SOLUTIONS FOR LOW-GRAVITY PLANETARY BODY EXPLORATION

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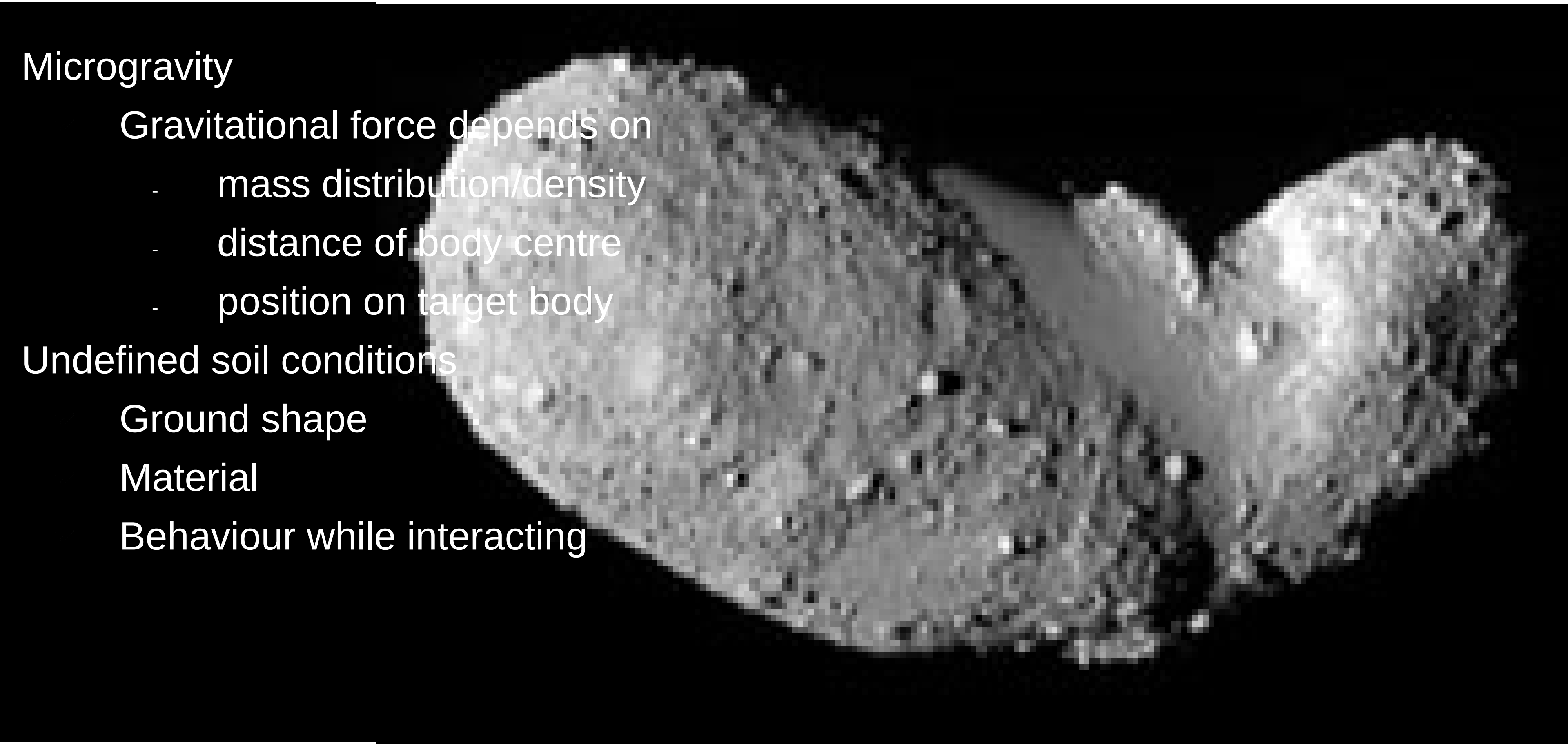
Motivation

- 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



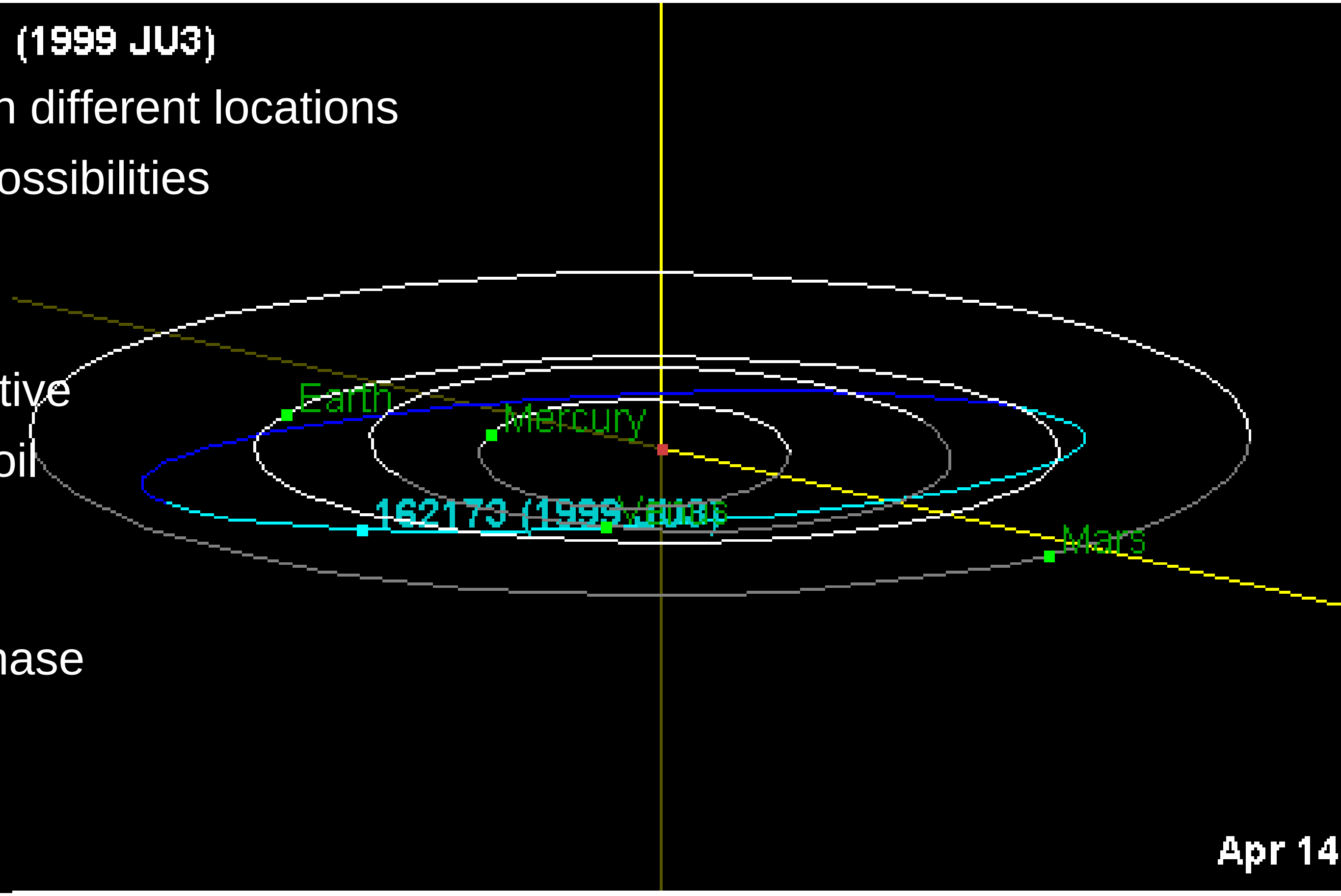
Microgravity

- 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



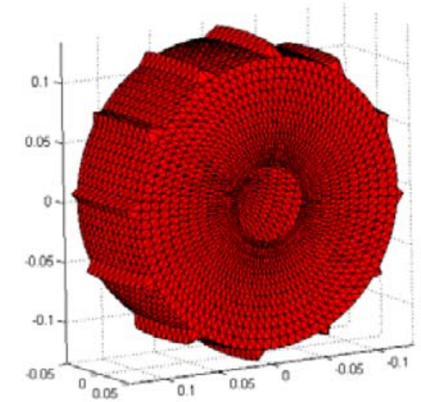
Provide measurements on different locations
- Maximise science possibilities

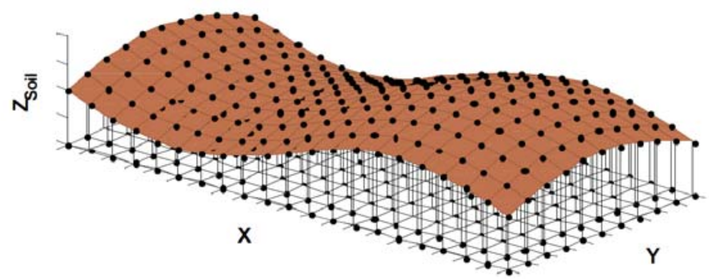
Robust concept
- Simple but effective
- Controllable & adaptive
- Independent from soil characteristics

Deep space qualified
- Survival of cruise phase
  - radiation
  - temperatures

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

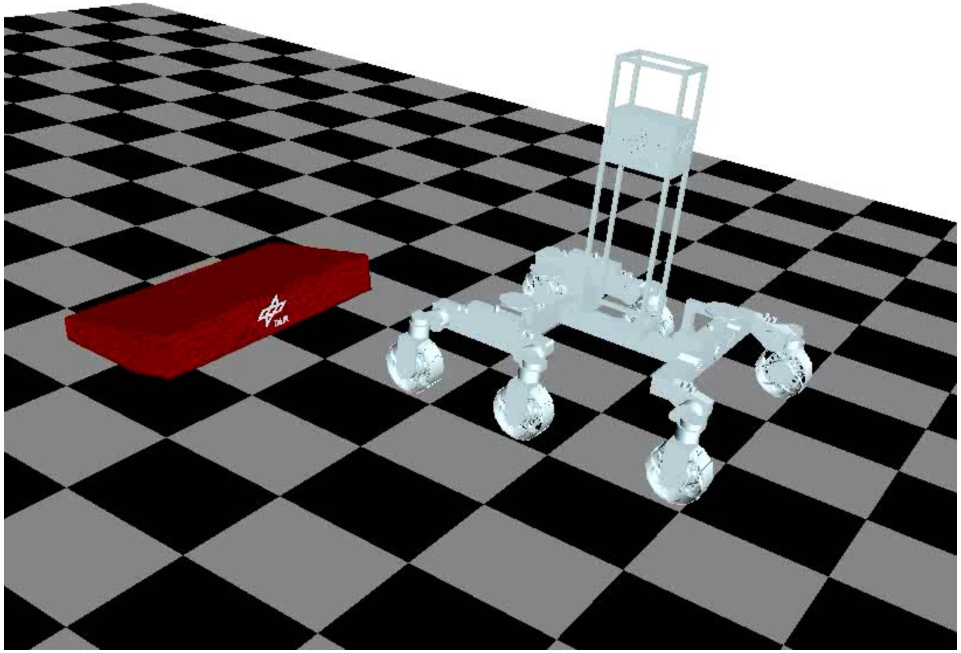




Parameter	Unit	Value
Young's modulus	[N/m²]	4.72e5
Poisson ratio	[-]	0.4
Layer depth	[m]	0.02
Areal damping	[Ns/m³]	1.0e8
Damping depth	[m]	0.02
Friction coefficient μ	[-]	0.45

Parameter	Unit	MRS-A	MRS-B	MRS-C	MRS-D
Soil class	[-]	Fine	Intermediate	Coarse	pebbly
Grain size dist	[mm]	-	-	0.7 – 1.5	8-12
Bulk density	[kg/m³]	1300-2300	1400	1800	1800
Internal friction angle	[deg]	30-32	31-33	30-39	20-30
Cohesion	[kPa]	1.0	0.0	0.0	0.0
Deformation coefficient n	[-]	1.1 – 1.8	0.8 – 1.5	1	1
Scaling coefficient k*	[kN/m^{n+2}]	10^3 - 2*10^5	10^3 - 10^5	10^3 - 10^5	10^3 - 10^5

Simulation: Wheeled rover in microgravity (1)

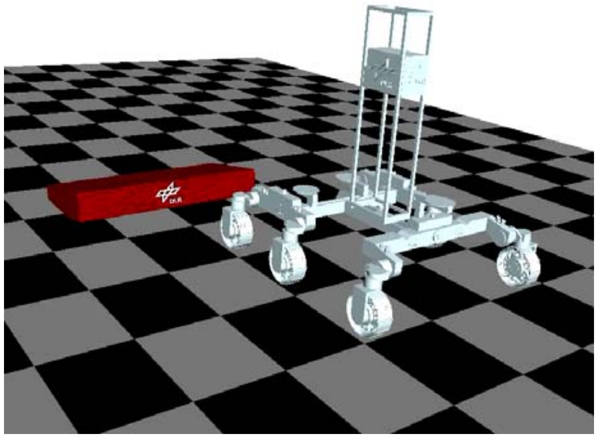


- Example model
  - 6-wheeled rover
  - ExoMars (breadboard) kinematics
  - Mass of 102 kg reproduce ground loads of a 300 kg rover on Mars
  - Rover behaviour covered by hardware test experience
- Scenario 1
  - Earth gravity
  - Ascending slope of 11 deg
  - Crossing an obstacle

Simulation: Wheeled rover in microgravity (2)

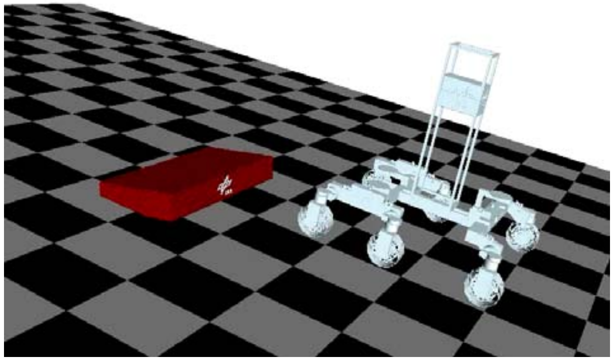
- Test: Reducing gravity step by step
  - Scenario 2: 10 % of earth gravity
  - Scenario 3: 2.5 % of earth gravity

10 % of g



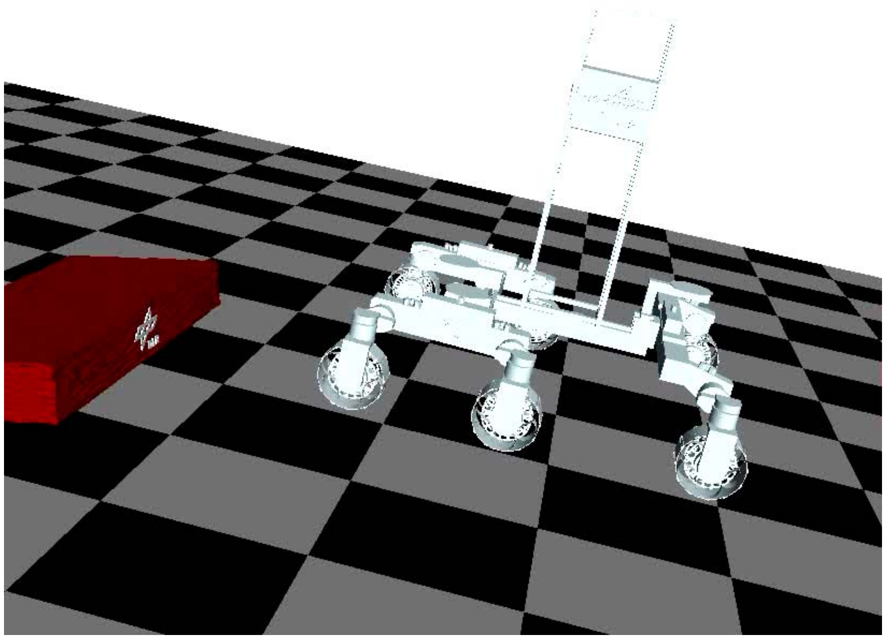
- Not considered
  - Possible change of soil behaviour due to microgravity
  - Microgravity-specific modification possibilities

2.5 % of g



Simulation: Wheeled rover in microgravity (3)

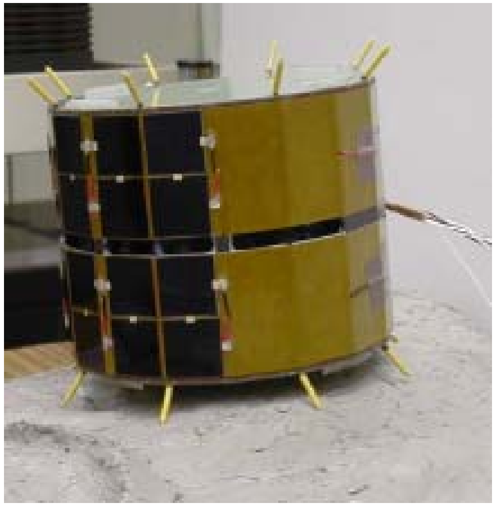
1.0 % of g



- 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

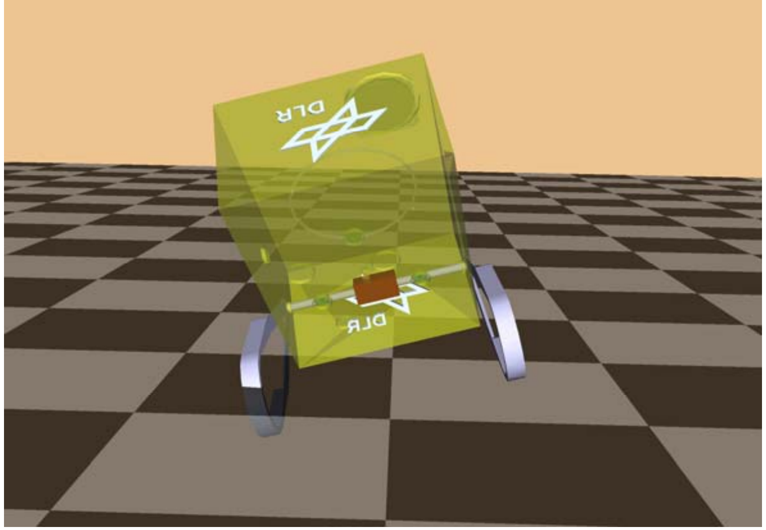
Hopping mechanisms

- 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



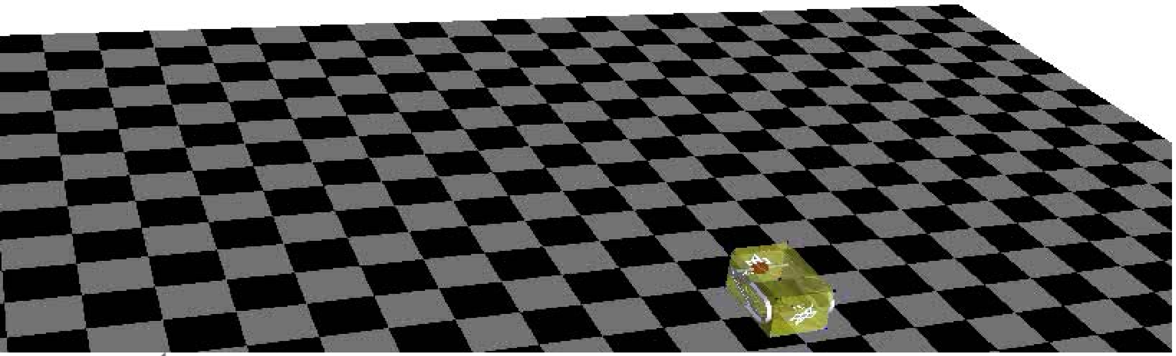
Trade off: Definition of a hopper concept (1)

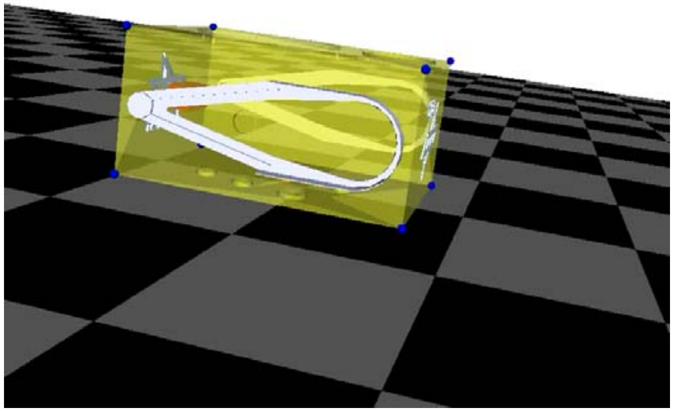
- Requirements: MASCOT (DLR-RY)
  - 10 kg lander package
  - Target body 1999 JU3
    - surface gravity: 1.7e-5 g
- Example: Only two concepts
  - Arm concept
  - Excenter driven concept
- Other tested concepts
  - Spring driven concepts
  - Flywheel
- Important parameters
  - Robustness of motion
 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



Trade off: Definition of a hopper concept (2)

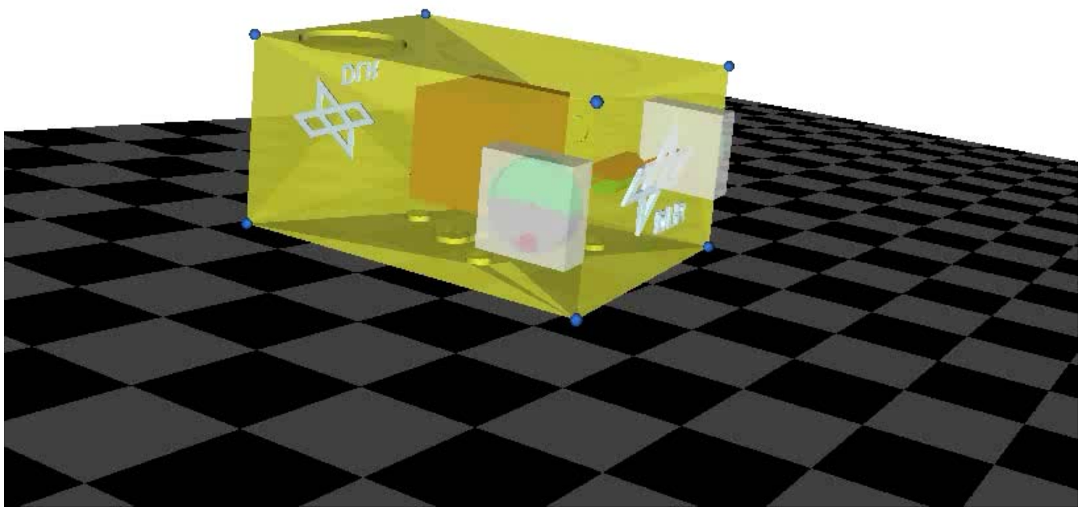
- Example scenario
  - Gravity: $1.7 * 10^{-5}$ g
  - Different soil characteristics left/right
  - PCM
  - $v_0 = 0.5 * v_{esc} = 0.16$ m/s
- Lever arm concept

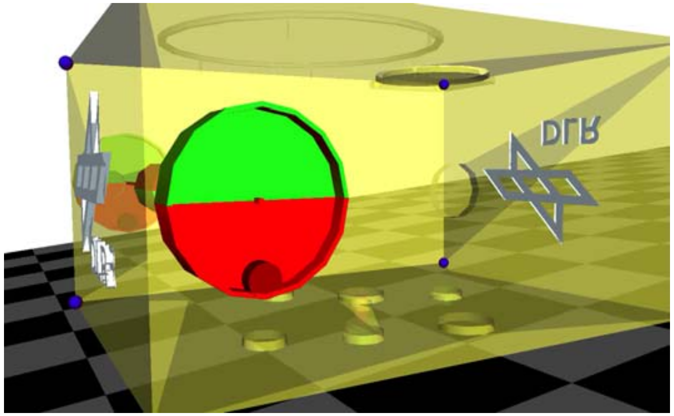




Trade off: Definition of a hopper concept (3)

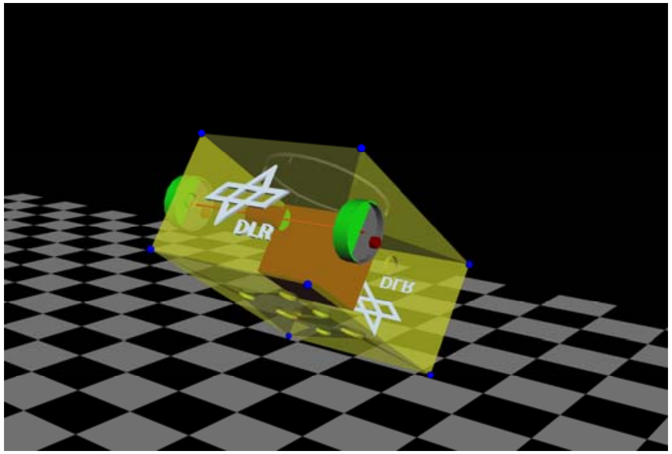
- Example scenario
  - Gravity: $1.7 * 10^{-5}$ g
  - Different soil characteristics left/right
  - PCM
  - $v_0 = 0.5 * v_{esc} = 0.16$ m/s
- Excenter driven concept





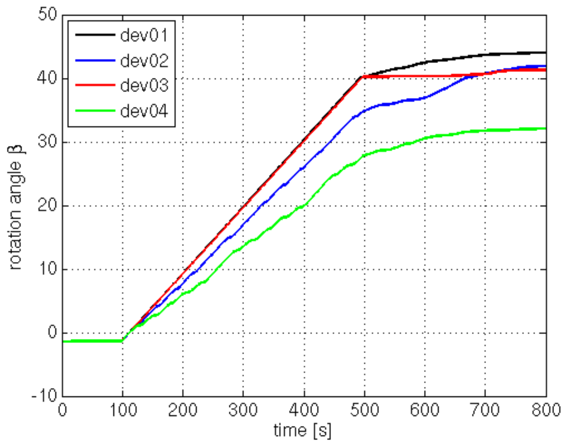
Trade off: Definition of a hopper concept (4)

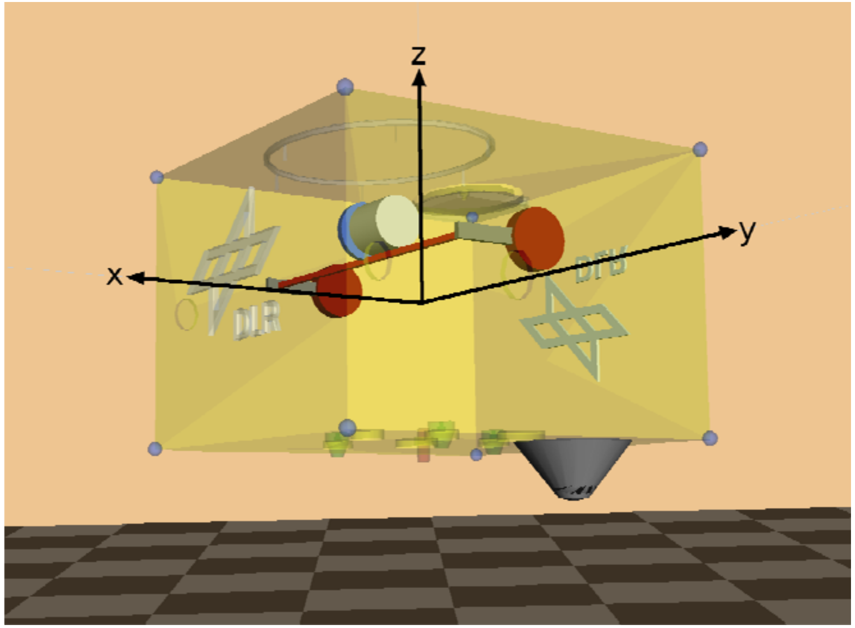
- Reasons for simulation-supported trade-off
  - Concept decision in early phase (A)
  - Not yet all information available
    - target properties
    - final system parameters (mass..)
  - Many open questions
  - It is easy with parameter variation to compare concepts
- Results of the trade-off
  -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

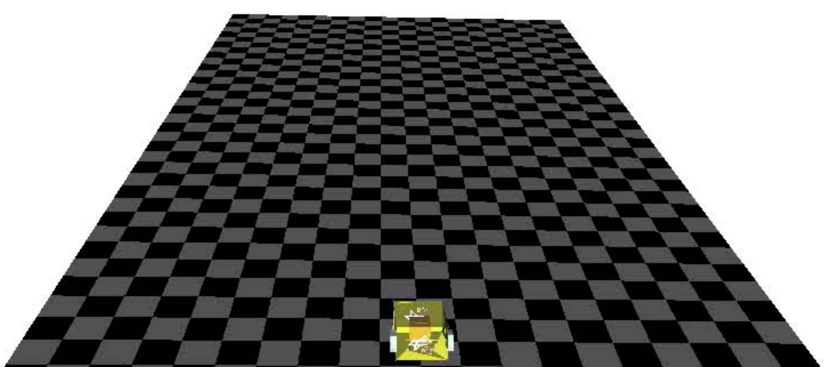
- Note: Slow motions due to microgravity
  - Realtime duration of this action: 400 s / 6:40 min

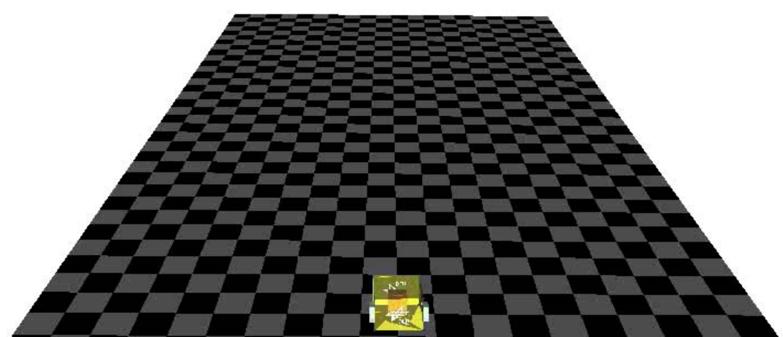
dev01

	x	y	z
x	**0,0784**	0	0
y	0	**0,1152**	0
z	0	0	**0,1505**

dev02

	x	Y	z
x	**0,0784**	**0,015**	0
y	**0,015**	**0,1152**	0
z	0	0	**0,1505**

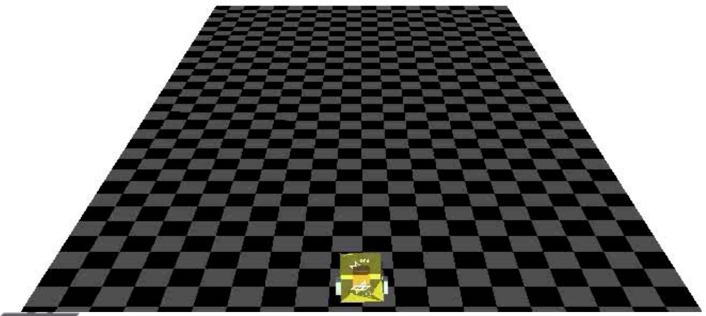




Parameter Variation: Deviation of mass moment inertia (3)

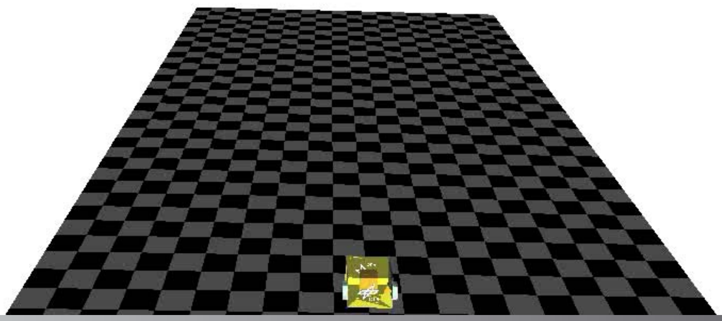
dev03

	x	y	z
x	**0,0784**	0	0
y	0	**0,1152**	**0,015**
z	0	**0,015**	**0,1505**



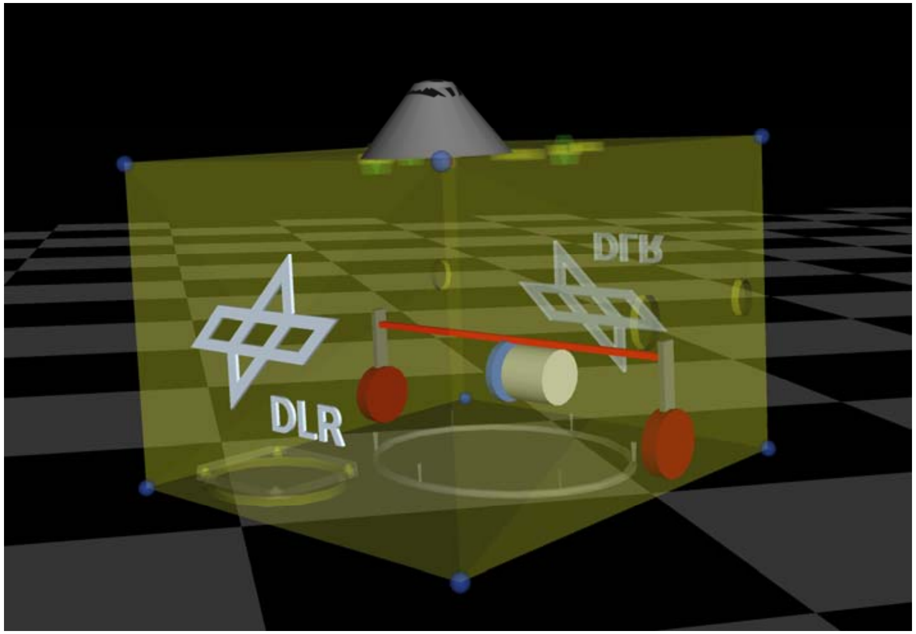
dev04

	x	y	z
x	**0,0784**	**0**	**0,015**
y	**0**	**0,1152**	0
z	**0,015**	0	**0,1505**



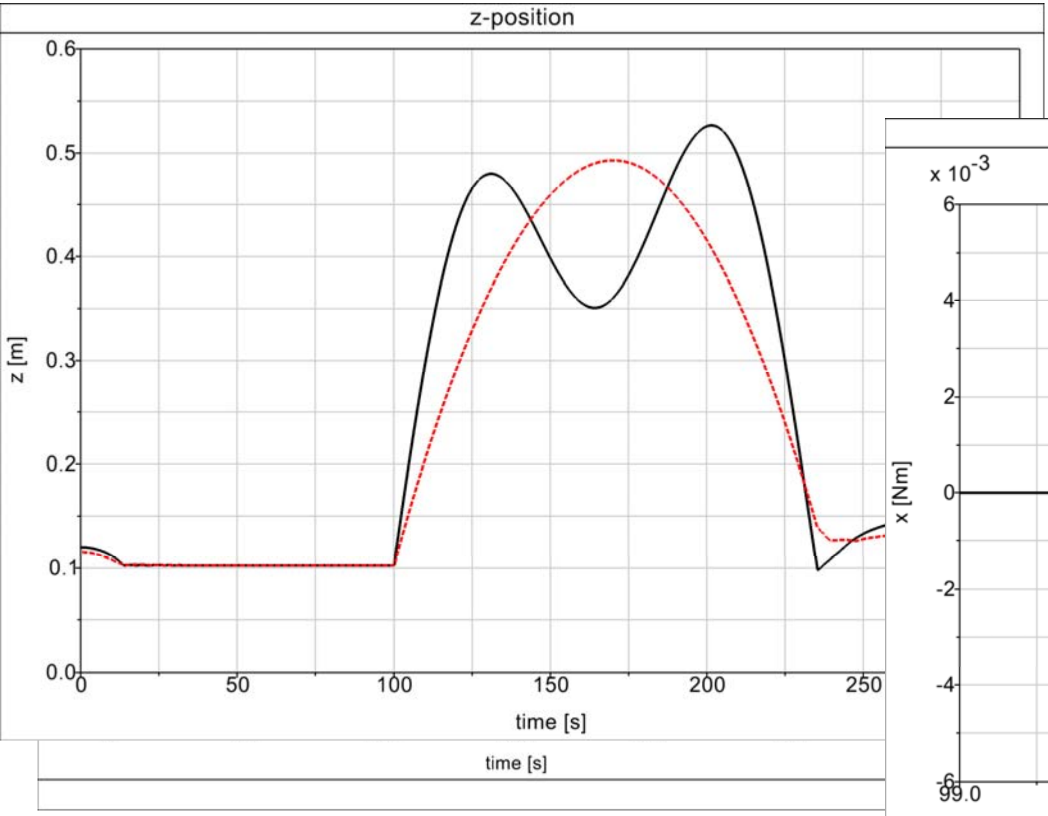
Component development (1)

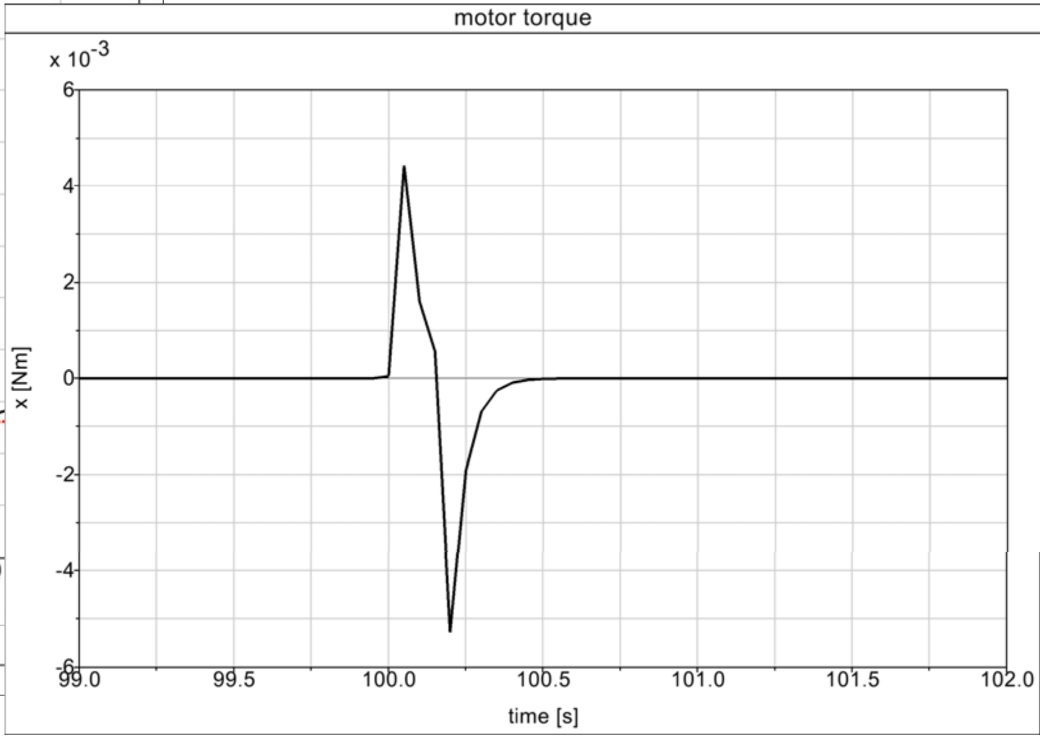
- Goal of the ParVar: identify required drive speed for small hop
- Parameter variation
  - 4 x K_L (proportional gain for position control): 5…20
  - 45 x T (time constant for drive action): 0.1 … 1sec
  - 180 variations



Component development (2)

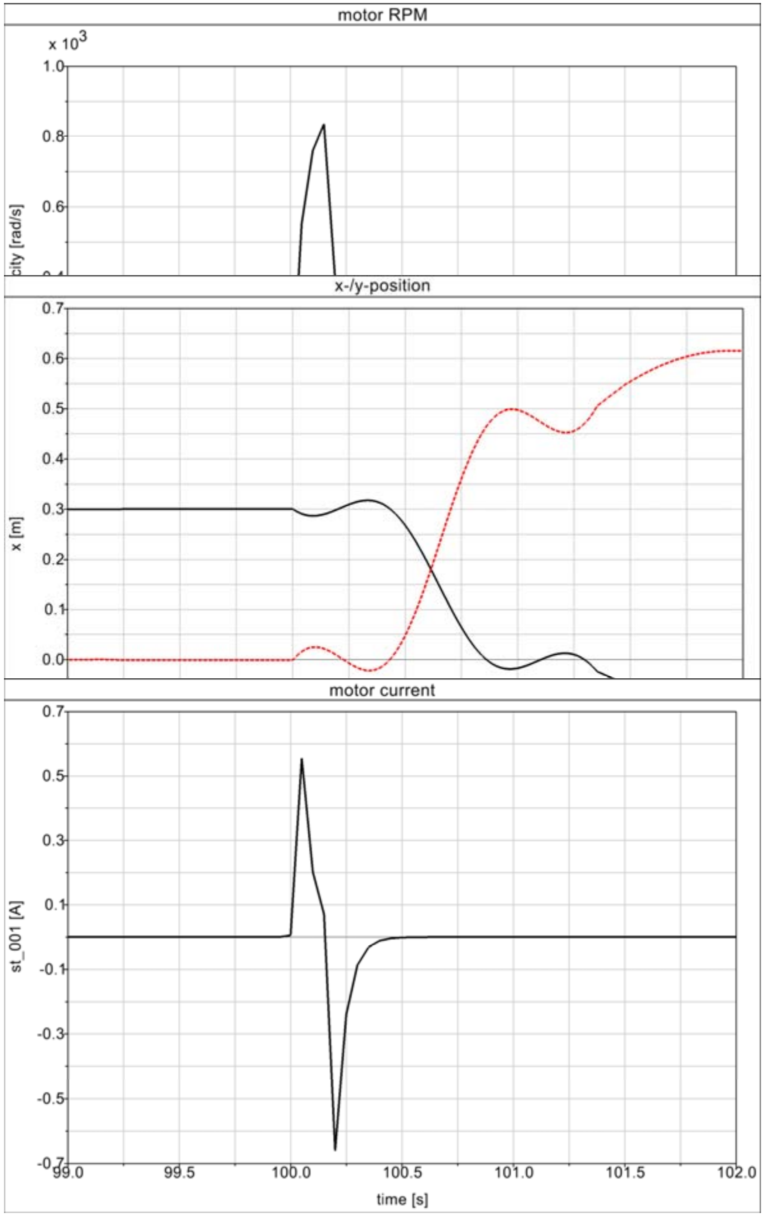
- Results
  - Height (z-position)
  - Required motor torque





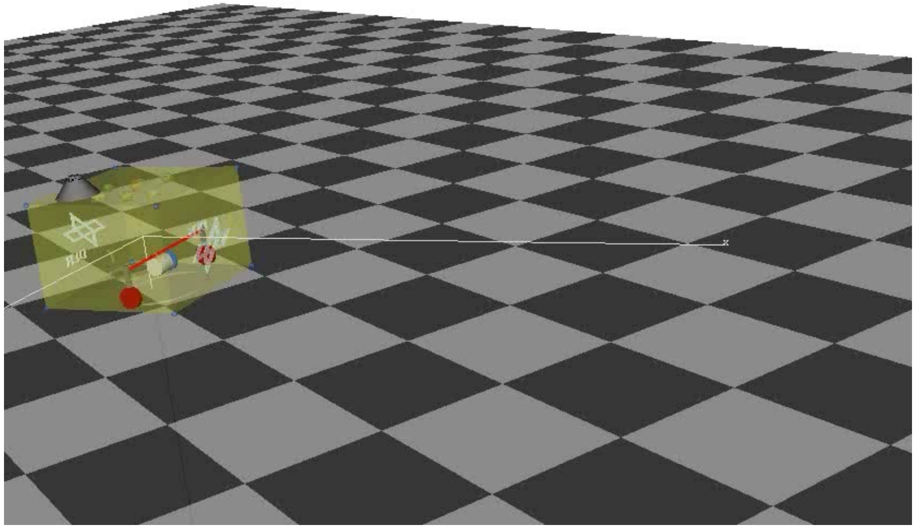
Component development (3)

- 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

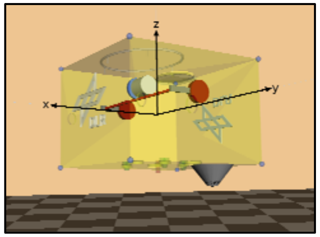


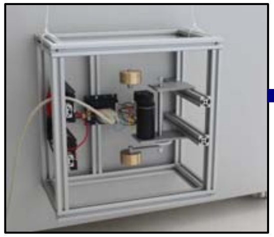
Component development (4)

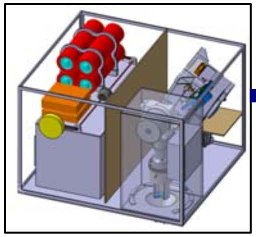
- Results are used for calculating
  - Input & output speed of the gear
  - Required current
- This leads to suitable components
  - Motor
  - Gear
  - Controller / power electronics
- Resulting action
  - Small hop
  - Duration: 130 s (low gravity!)



DLR RM activities overview







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MBS model

- Simulation

Mock-up

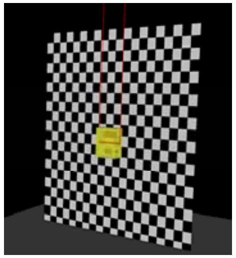
- Tests under earth gravity

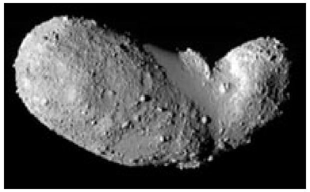
Breadboard

- Microgravity tests

Flight model

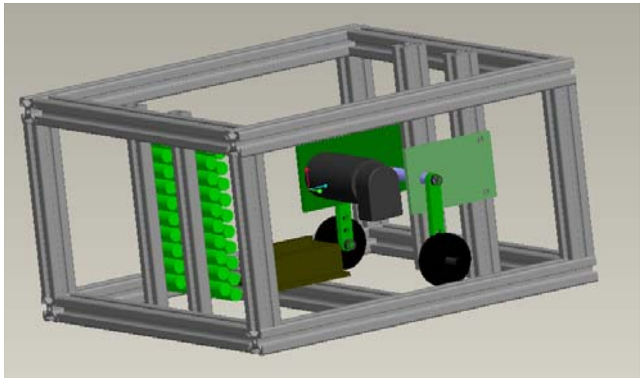
- Asteroid

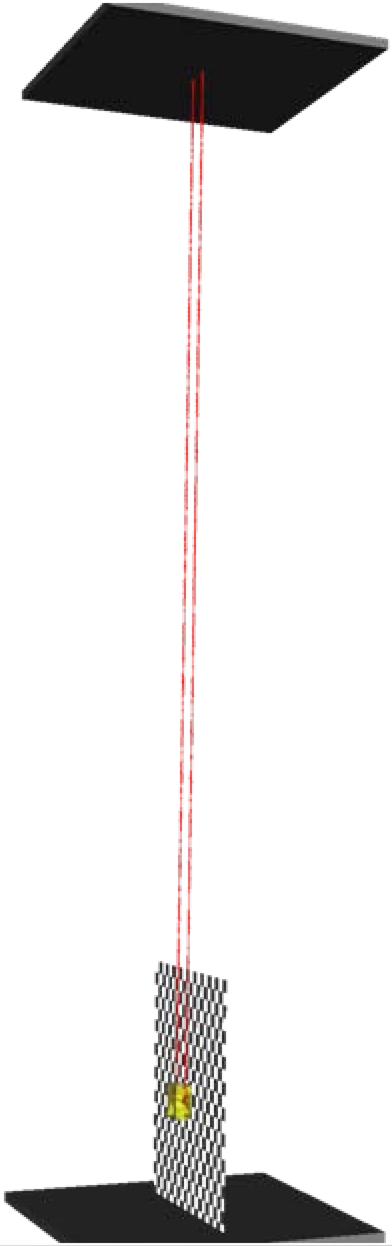




DLR-RM test facility: Mock-up (1)

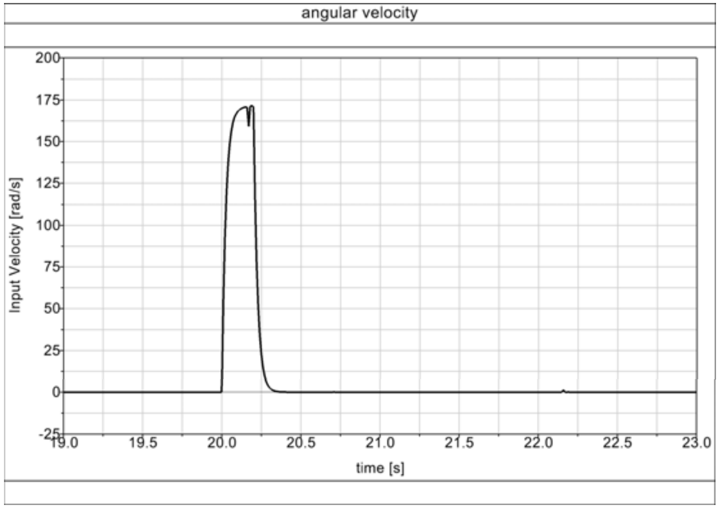
- Testing on earth
  - Impossible without modifications
- Mock-up: Highly scaled test model
  - Off-the-shelve components
  - Less mass
  - More power
  - Increased excenter masses
  - Different mass distribution
  - Gravity compensation: pendulum
  - Simulation verification

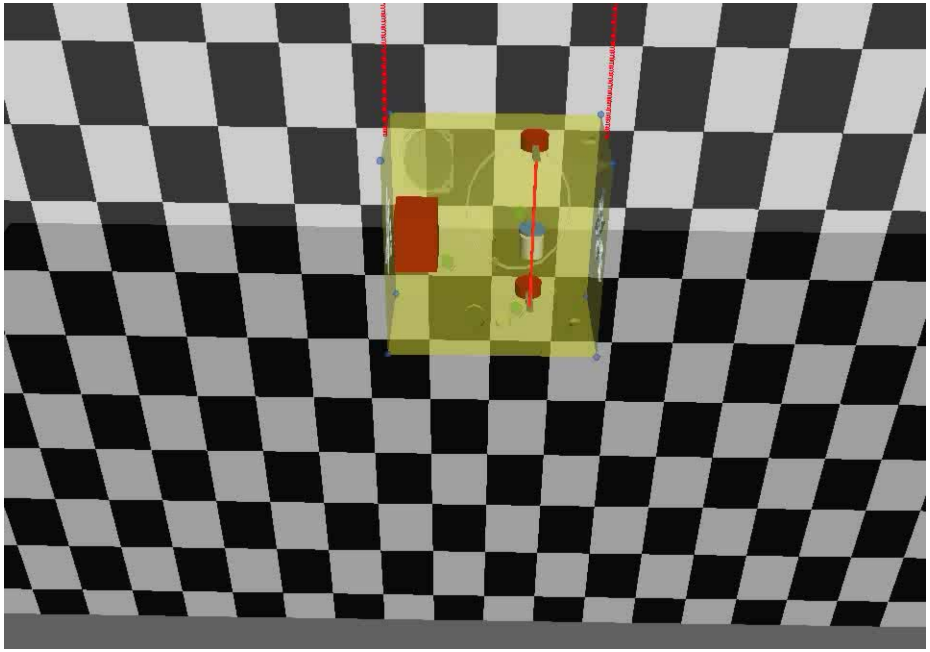




DLR-RM test facility: Mock-up (2)

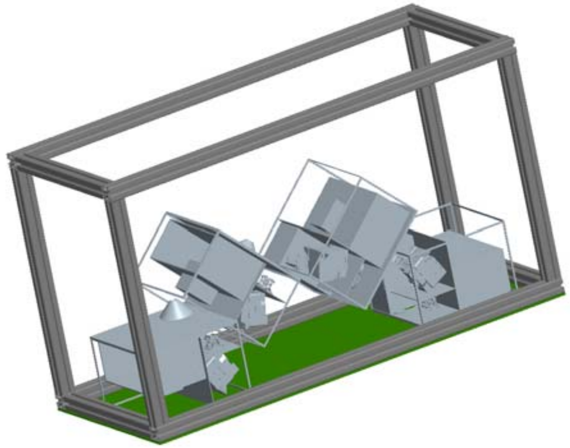
- First test results
  - Pendulum: 2 m
- Comparison
  - Test
  - Simulation

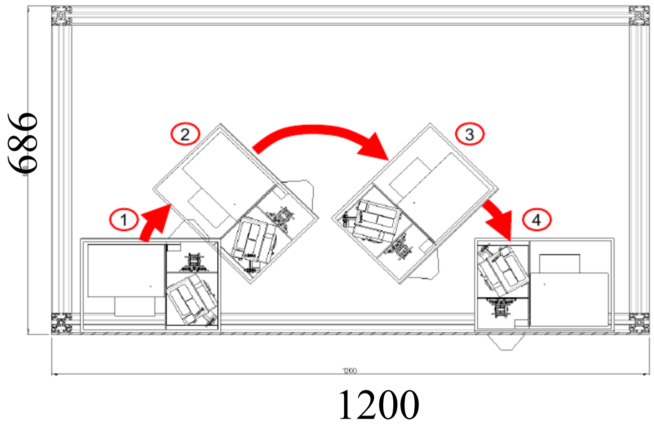




Outlook

- 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