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

ESA/ESTEC, NOORDWIJK, THE NETHERLANDS / 12 – 14 APRIL 2011

F. Herrmann [(1)], S. Kuß [(1)], B. Schäfer [(1)]

[(1)] DLR, Institute of Robotics and Mechatronics, Münchner Str. 20, 82234 Weßling, Germany, florian.herrmann@dlr.de

ABSTRACT

Currently, a number of missions in the field of small bodies exploration, e.g. to asteroids, are ongoing or planned (amongst others Hayabusa 2 by JAXA or the follow-on of Marco Polo by ESA). Several of these missions foresee a lander package for in-situ science (e.g. proposed MASCOT for Hayabusa 2). To enhance functional safety as well as science possibilities, the provision of mobility on the target body is widely appreciated. However, due to the very low gravity influence, possible solutions are different from present ones for larger gravity planets and moons such as Mars and the Earth's Moon. The paper gives an overview about simulation and testing activities which lead to promising mobility concepts for microgravity environment.

1. INTRODUCTION

To provide mobility on an asteroid's surface, the special conditions there have to be taken into account. The lander system has to function reliable under microgravity as well as on the widely unknown underground, which includes hard, rocky terrain and soft soil.

These uncertainties make it reasonable to investigate the possibilities of mobility there by detailed dynamic multibody simulations, which can give an understanding of sensitive influences, for example by parameter variations. Of course, simulation results have to be verified. Therefore hardware tests are performed or adequate test rigs are in preparation.

1.1. Target Bodies: Asteroids

A typical low gravity body is the asteroid 1999 JU3, the target of Hayabusa 2 (Figure 1). The published properties of all known asteroids can be found in databases such as [1]. The asteroid, in first approach with spherical shape, has an estimated radius r_{Ast} of up to 460 m, a density ρ of 1300 kg/m³ and a spin period of 7.63 h.

From dimension and density data, estimated as homogeneous, the mean gravitation can easily be calculated for the asteroid's surface as:

$$g_{Ast} = G \cdot \frac{m_{Ast}}{r_{Ast}^2} = G \cdot \frac{4}{3} \cdot r_{Ast} \cdot \pi \cdot \rho \approx 1.672 \cdot 10^{-4} \frac{m}{s^2} \approx 1.705 \cdot 10^{-5} g_{Earth} \qquad (1)$$

where G means Newton's gravitational constant. This very low gravity leads to extremely low contact forces between an asteroid lander and the surface and to a very low escape velocity v_{esc}, which can be approached for by:

$$v_{esc} = \sqrt{\frac{2 \cdot G \cdot m_{Ast}}{r_{Ast}}} = \sqrt{\frac{8}{3} \cdot G \cdot \pi \cdot \rho \cdot r_{Ast}} \approx 0.392 \frac{m}{s} \qquad (2)$$

The exact value for each surface position depends on the real distance between the spacecraft and the center of the asteroid. A conclusion from these conditions is that the principles of movement have to be reconsidered for this environment.

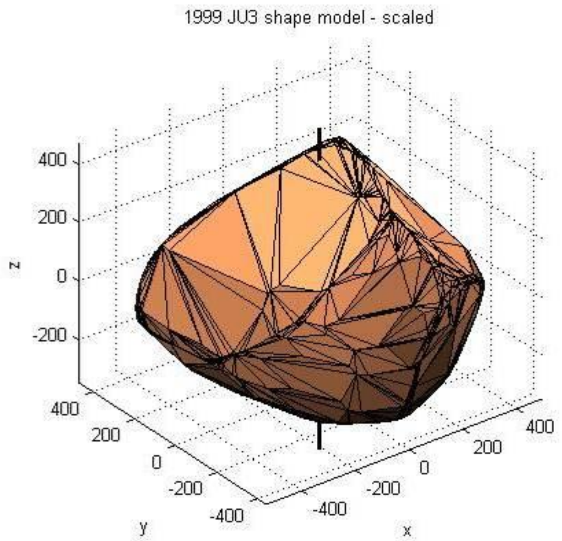

Figure 1. Model of the asteroid 1999 JU3 [2]

1.2. Previous missions

Several missions to small bodies were launched in the past and are planned in near future. For example, Phobos 2 was started by USSR in 1988, including a hopper of 67 kg to explore the surface of the Mars' moon Phobos. Unfortunately, this part of the mission was not successful.

In 2003, the Hayabusa sample-return mission was launched by JAXA (Japan), towards the asteroid Itokawa, shown in Figure 2. The mission included MINERVA, a small hopper with a mass of 591 g [3]. Although the overall mission was a great success including the first sample return from an asteroid in June 2010, the landing of the asteroid hopper was not successful. MINERVA was lost during descent due to the very low gravity of Itokawa.

Figure 2. Photo of the asteroid Itokawa (JAXA)

ESA operates the mission ROSETTA from launch in 2004, which is intended to meet the comet Churyumov-Gerasimenko in 2014. Rosetta will release the non-mobile lander Philae with a mass of 96 kg on the object's surface [4].

Hayabusa 2 is the follow-on mission of Hayabusa and intended to be launched by JAXA in 2014 to the target asteroid 1999 JU3. During the mission, the hopper MINERVA-II with similar dimensions as MINERVA is planned to operate on the asteroid. The 10 kg lander package MASCOT is also proposed for Hayabusa 2 [5].

Since until now, it never was crowned with success to place a robot on a small body's surface and autonomously operate on it, particularly including mobility. One of these two hoppers potentially could be the first one in this field.

1.3. Mobility System Requirements

A mobility system for a small body, e.g. an asteroid, has to provide the possibility to change the location on the surface. Therefore, some requirements have to be considered. It has to manage a highly robust motion with respect to uncertain and different soil properties including, rocks and diverse soils. This can be achieved by finding a system which is as independent as possible from surface interaction. Additionally, the rectangular speed must be strictly limited due to the very low escape velocity of a small body. Therefore controllability or adjustability to different scenarios has to be implemented to ensure a secure motion.

The mechanical construction must on the one hand be simple enough for overall mass and power-budget reasons. On the other hand it must be sealed against mechanical stress from dust and sand on the asteroid. Moving parts and electronics must be insensitive to the vibration and radiation conditions during start and cruise phase and functionality must be ensured after a period of several years.

1.4. Motivation for this work

Our engagement in this area is focused on alternative concept studies as well as mobility subsystem design support by extensive dynamic analysis and hardware tests. The systems shall consider known or estimated target properties and provide functionality within given parameter ranges. Due to the very low gravity, system testing close to reality is very tedious, if not impossible on earth. Therefore extensive multibody simulations are the only reasonable choice to arrive at a realizable solution. Reasonable soil and system parameter estimations are assumed, and their influence on mobility is investigated within a given parameter range.

The development of a hopping subsystem for MASCOT is described. The results of simulated mission scenarios help to select and dimension the design and optimize subsystem components. Hardware tests are in preparation by way of highly scaled mock-up systems or sensor testing strategies, as well as a proposal for parabolic flight tests, and they are used to ensure the simulation validity.

2. MBS SIMULATION

Multi-Body-System (MBS) simulation is used to analyse the dynamic behaviour of the mobility systems. The simulations shown here are performed with the MBS software tool SIMPACK [6].

The development and design process of hardware components, especially the drive mechanism including motor dimensions, are supported by simulations as well. This includes calculations of energy consumption and possible weight reductions (optimization).

2.1. Contact models

Two contact models are used for dynamic analysis: The Polygonal Contact Model (PCM) for rigid contact and the Soil Contact Model (SCM) for contact on soft, sandy terrain. Both contact models can work parallel in one model, if needed.

<u>PCM</u>

A set of parameters of the PCM is listed in Table 1. The given standard values can vary for different scenarios and soil behaviour. For the asteroid, adequate parameters are estimated. PCM is implemented as force element in SIMPACK. The contact bodies are defined as polygons and the forces are computed by analyzing the virtual intersection of the bodies. Multiple contacts between user-defined shaped bodies are possible. Although the asteroid's soil properties are hardly known, PCM is suitable for most analyses of dynamic behaviour.

Table 1. PCM 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

SCM

The SCM contact model offers the possibility to apply the terramechanics theory of Bekker and Wong with MBS simulations. The contact model has been developed by DLR-RM for planetary rover dynamic wheel-soil interaction calculation [7]. It is implemented in SIMPACK as user routine and used to analyze special scenarios on soft soil and sandy terrain.
The Bekker parameters, which describe the soil behaviour, are needed for SCM. The values for different soils are identified by Bevameter (Bekker value meter) tests [8]. For unknown environments, Bekker parameters are estimated in dependence on properties of known, similar soils.

Table 2. Parameters of MASCOT reference soils [5]

Parameter	Unit	MRS-A	MRS-B
Soil class	[-]	Fine	Inter-mediate
Bulk density	[kg/m³]	1300-2300	1400
Internal friction angle	[deg]	30-32	31-33
Cohesion	[kPa]	1.0	0.0
Deformation coefficient n	[-]	1.1 – 1.8	0.8 – 1.5
Scaling co-efficient k*	[kN/m^{n+2}]	1e3 – 2e5	1e3 – 1e5

For 1999 JU3, a set of four reference soils with different properties from fine to pebbly were defined [5]. The (Bekker) parameters of two of these soils are shown in Table 2.

2.2. Environment model

For the MBS simulation, the asteroid is modelled as a homogeneous sphere, with the properties taken from [1], as described in section 1.1. According to Figure 1, this simplification is acceptable. The gravitational force applied on a moving system on the asteroid is computed for every numerical integration step from the asteroid's mass and the distance to its center of mass. Therefore it is paid attention to the decrease of gravitational force during a hop dependent on the hopping height.
In another grade of simplification, for basic investigations and comparison between different concepts, the ground is simulated as a plane with constant gravity. This simplification is only reasonable for motions near the surface, like a driving rover or an upright action, but not for hopping.

3. WHEELED ROVER IN LOW GRAVITY

Several principles of movement are imaginable for exploration. On planets or moons with high gravity, wheeled rovers are used with great success (e.g. the MER rover of NASA). Hoppers using mechanical propulsion systems would not be suitable there considering energy consumption aspects, required mechanical loads and payload to weight ratio.
For low-gravity bodies, physical conditions are completely different. It can be shown, that wheeled rovers do not work properly in low gravity environment. As the mass constraints are very strict for asteroid missions due to long range cruises, asteroid lander usually have to be small (MASCOT: 10 kg). Small rover's payload to overall mass ratio is usually not advantageous, because relatively complex drives have to be implemented for each wheel.
As an example for a wheeled rover, the model of the 6-wheeled ExoMars breadboard was simulated in microgravity environment. Reality tests with this breadboard were performed in our institute [9], and there is access to some experience of real behaviour of this model and how to simulate it. The breadboard has a mass of 102 kg, to represent the real wheel forces under mars gravity.
The scenario setup is shown in Figure 3. The rover drives up- and downhill a slope of 11 degrees, crossing a cuboids-shaped rock. This has been investigated under earth-gravity (1.0 g) and lower gravity values of 0.1 g, 0.025 g and 0.01 g with constant soil properties.
As the power transmission between wheel and ground depends on friction, the soil properties and the wheel contact forces have a great impact on the transferable forces. At least two problems or imponderables are determined for wheeled locomotion in low gravity:

- the behaviour of the soil and
- the contact between wheel and ground.

The first means, that due to microgravity presumably uncompacted and therefore very soft soil is not appropriate to transform wheel rotation into a forward motion without losses. The latter one means, that a majority of the wheels must be in ground contact to assure locomotion. While driving forward (if possible), every disturbance of the trajectory, e.g. a rock or gap, can lead to a lift-off of one or more wheels. The lower the gravity is, the longer it lasts for each body to fall down to ground afterwards. For example, it is imaginable that all wheels of one side are lift up simultaneously. In this case, the rover cannot go on driving and has to wait for the wheels to come to contact again.

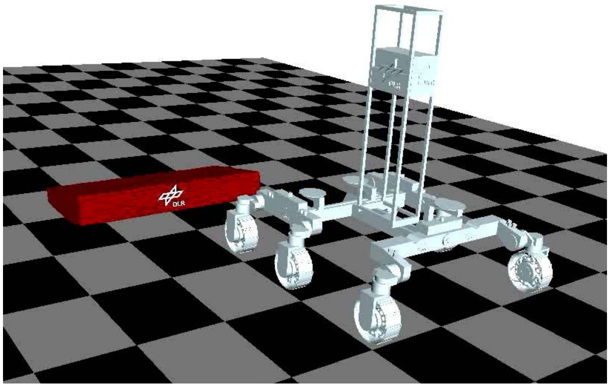

Figure 3. Simulation model setup: wheeled rover

This dynamic behaviour can make it impossible to pass over some obstacles in microgravity. Simulations were only performed down to 1 % of earth-gravity, because even then an expedient locomotion becomes complicated. On the asteroids presented in section 1.1, the gravity is even 1000 times lower. Therefore, wheeled rovers do not work on asteroids of this size. This conclusion is confirmed by the results of [10].

4. HOPPING: A PROMISING MOBILE MODE IN LOW GRAVITY

For multiple reasons, hopping is a suitable and adequate way of moving in microgravity environment. The very low applied forces empower small, simple and lightweight mechanical systems to move the lander, including a comparatively high load capacity for science (MASCOT: 3kg payload of 10kg overall mass).

4.1. Concept Trade-offs

Several concepts were proposed in the past, for example a rotating flywheel as in JAXA's Minerva [3] or a push-off actuator in form of so called whiskers in [11]. Performing a trade-off study in Phase A of the MASCOT project, six different concepts of hopping mechanisms were investigated. The main goals were to define a system that provides a robust motion in terms of being as independent as possible from (the hardly known) soil characteristics. This can only be achieved by using a maximised area for push-off the ground. Therefore, mechanical actuators that hit the ground on small contact areas, such as arms or whiskers, were not investigated any more.
The defined system therefore consists of an inertia based excenter tappet concept as shown in Figure 4. It is favoured because of its simple mechanics with only one actuator drive system (motor and gear) which provides sufficient power for uprighting and hopping. As the whole system is integrated inside the MASCOT structure, it is sealed against environmental influences on the asteroid.

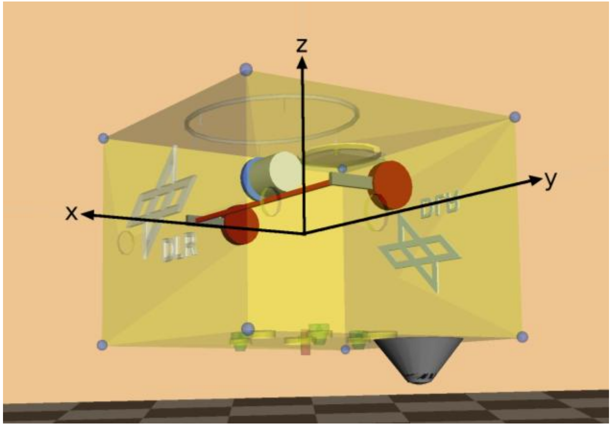

Figure 4. Simulation model setup: MASCOT

The system is used for self-uprighting and hopping. It works inertia-driven, but in comparison to the Minerva system not by accelerating an inclined flywheel but by the acceleration and deceleration of excentric masses in a controlled way. While accelerating the masses, the MASCOT structure is slightly pressed into the ground. This acceleration is absorbed in the elastic structure-soil contact and does not cause any turnaround motion.
While moving, the excenter masses transfer an impulse based on their inertia to the excenter axis. This momentum applies a force to the structure, whose moving vector depends on the tangential velocity profile of the excenter masses, and therefore indicates a motion sequence. A variation of the applied power in combination with defined start and stop angles allows an adjustment of the resulting movement.

4.2. Simulation results

To analyze the functionality of the proposed mobility system, a multitude of scenarios with different configurations and varied input parameter sets are simulated and evaluated. As examples, results of parameter variations for two scenarios are presented:

- inhomogeneous surface properties in the push-off area and
- sensitivity to the deviation of mass moment of inertia.

The first one is a safety issue and reflects an imaginable situation on the asteroid, where the mobility system should work robust enough to provide functionality in spite of adverse conditions. The latter one targets system parameters such as the inertia tensor of the complete MASCOT system.

<u>Inhomogeneous surface properties:</u>
Certainly MASCOT does not only have to move from even, uniform ground. It is imaginable that it has to push off over loose in combination with compacted sand and even rocks.

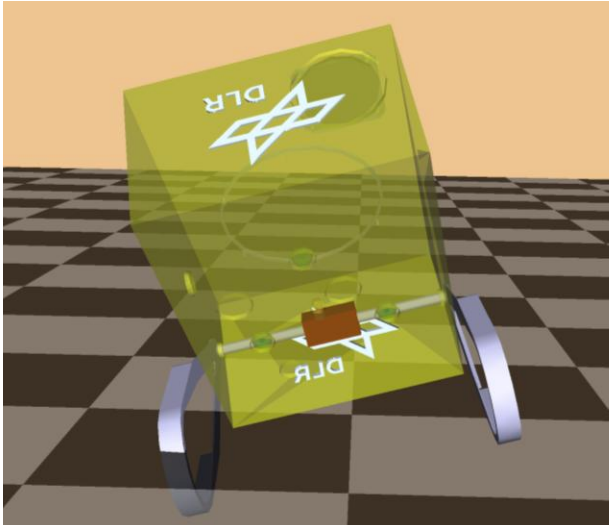

Figure 5. Two arms concept on inhomogeneous surface

If different conditions appear on each side of the structure, it is important to use a preferably robust mobility system. This typical situation is shown using the example of a two-arm concept (Figure 5) and the proposed inertia driven concept, shown in Figure 6.

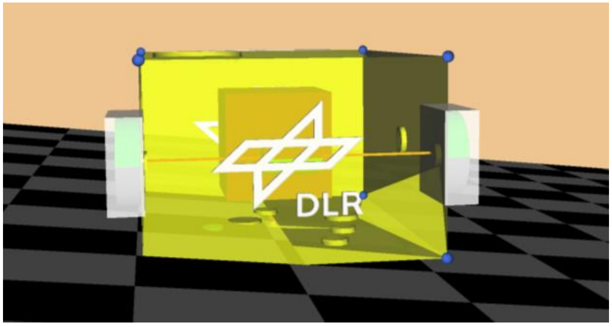

Figure 6. Inertia concept on inhomogeneous surface

It can be shown, that the excenter system is more robust due to the fact that it uses the whole structure as push-off area. The resulting pressure distribution can partly compensate the inhomogeneous surface. In contrast, the arm-system performance highly depends on the ground conditions right in the relatively small arm/ground contact areas. If one of the arms sinks into soft soil or gets stuck inside gaps between rocks, different forces are applied to each side of the MASCOT structure which leads to an unpredictable and therefore uncontrollable dynamic.

Deviation of mass moment of inertia:

MASCOT carries several scientific instruments [12] and system components, for example electronic boards and batteries. The arrangement of these components of different masses leads to non-ideal dynamic parameters concerning the position of the center of mass (CoM) and the mass distribution. To investigate the impact of the latter one on the dynamic behaviour, a varied deviation of the inertia tensor was tested in simulation with the excenter driven mobility system. The body-fixed coordinate system with the major axes x, y and z is shown in Figure 4, the accordant rotation angles are defined as alpha, beta and gamma. In Table 3, the four investigated tensors are listed: dev01 (a) is the standard inertial tensor with the given values for the major axes and no product of inertia. dev02 (b) has a product of inertia of 0.015 kgm² about the x-axis, dev03 (c) about the y-axis and dev04 (d) about the z-axis.

Table 3. Inertia tensors, all values in [kgm²]

a) dev01

	x	y	z
x	0.0784	0	0
y	0	0.1152	0
z	0	0	0.1505

b) dev02

	x	y	z
x	0.0784	0.015	0
y	0.015	0.1152	0
z	0	0	0.1505

c) dev03

	x	y	z
x	0.0784	0	0
y	0	0.1152	0.015
z	0	0.015	0.1505

d) dev04

	x	y	z
x	0.0784	0	0.015
y	0	0.1152	0
z	0.015	0	0.1505

As reaction on the command for a hopping action such as a drive speed sequence as shown in Figure 8, changed dynamic behaviour can be observed for the resulting motion of MASCOT. The influence can be shown with the help of rotation angles, for example the rotation about the y-axis, beta, may be used here (Figure 7). This represents the forward rotation during the hop. And, due to the fact that around the major axis b the medial inertia value occurs, between x- and z-axis, the rotation about beta is a gyroscopic instable motion. Nevertheless, for the shown hop without external disturbances, the dev01-model (black line in Figure 7), basically rotates during flight phase between t=100 s and t=500 s. The dev03-model (red line), with a deviation of the inertia tensor about the y-axis, naturally shows a very similar behaviour, since this deviation does not affect the inertia about the main rotation y-axis. In contrast, if there is an inertia deviation about the x-axis (dev02) and especially about the z-axis (blue respectively green line), then the effective inertia about the y-axis is increased and therefore a changed rotational behaviour can be observed. The effect can analogical be reconstructed for the other rotations and combinations of rotational motion and differing inertia tensors. This results shows, that the impact of the mass distribution on the dynamic behaviour can not be neglected. On the other hand, the real effective inertia tensor of MASCOT becomes known while constructing.

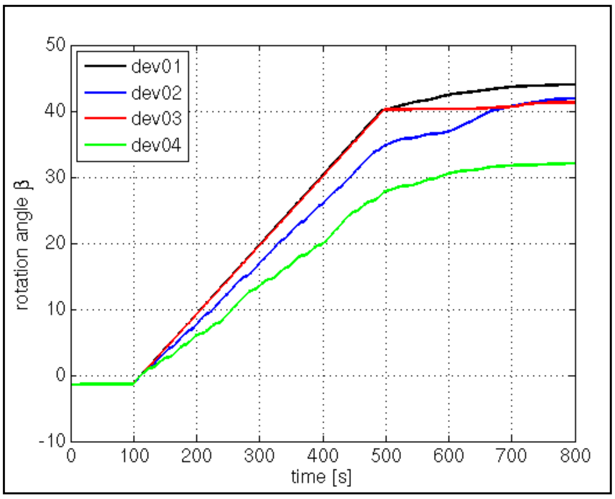

Figure 7. Rotation angle beta for different inertia tensors

Using the proposed inertia driven mobility system, the dynamic behaviour can therefore be adapted to the given system parameters. After all, this mobility system acts robust enough to provide satisfactory hopping possibilities even with the products of inertia of 10% of the maximum major axis inertia (around z-axis). Other investigations show an adequate insensitivity of the uprighting mode against these deviations.

5. DESIGN PROCESS OF A HOPPING MECHANISM

While designing and arranging the mobility system (phase A), simulation results are used to configure the dimensions of the hardware as well as to define the motor and electronics requirements. Components have to be specified that fit the requirement profile. This chapter describes the selection process from the mechanical point of view with respect to the mission requirements, regardless all parts have to tolerate extensive radiation and mechanical loads during the start and cruise phase of several years. The qualification of each component for deep space missions is performed in separated tests and not discussed here.
Phase B is used to optimize the resulting system regarding mass and functionality issues, still using simulation as well as first hardware tests to prove the simulation outputs. It is also used to develop all subsystems that are needed for test and flight. These steps are described in the following.

5.1. Component selection

Based on a variety of simulated scenarios, requirements regarding drive speed and applied torque as well as needed mechanical properties are defined. Figure 8 shows a requested motor drive speed (gear input) for one uprighting action (detailed time span from t=99 s to t=101 s). The motor has to accelerate from zero to about 350 rad/s (3340 rpm) in about 0.4 s.

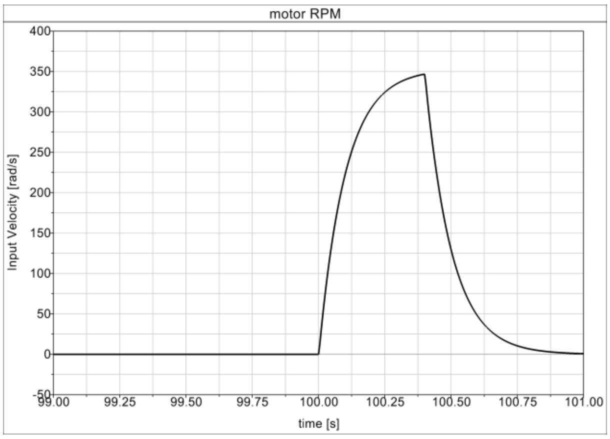

Figure 8. Motor drive speed (simulation result)

This motor activity leads - in combination with a gear stage and two excenter masses of 60 grams each (120 g total mass) - to the desired effect on the lander structure. Figure 9 shows the z-coordinate of the CoM of MASCOT while moving. A jump of about 0.275 m can be identified, which indicates a successful turnaround.

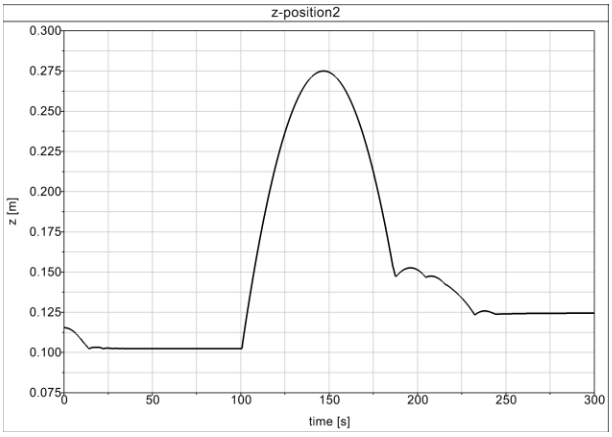

Figure 9. Resulting jump profile (simulation result)

A suitable motor for MASCOT based on its power and control specifications as well as its sensor system is the RoboDrive ILM25 [13]. It is a three-phase brushless DC motor using three Hall sensors for commutation. One example for an appropriate gear is the Harmonic Drive HFUC 8 [14]. A ratio of 30:1 with an output torque of up to 1.0 Nm is adequate for the needs of MASCOT.

5.2. Electronics development

Controller and power electronics, that fit the requirements concerning accuracy and radiation as well as mechanical loads, have to be redeveloped. The design of the controller system is based on DLR-RM's long-term experience with the ROKVISS actuator arm experiment on the outer surface of the ISS [15] and several robotic hands using miniature drives. The power electronic is designed to be mounted inside MASCOT's shielded common e-box.

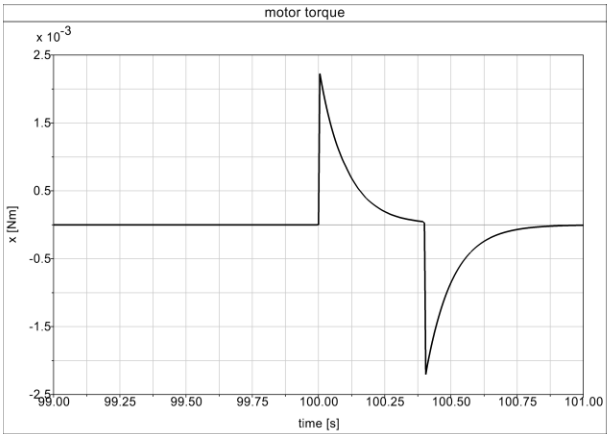

Figure 10. Estimated motor torque (simulation result)

The parameters of the electronics design are also based on simulation results, such ass the estimated motor torque, shown in Figure 10. For the upright action on the asteroid, a motor torque of less than 2.5 mNm is needed. The current that have to be provided by the electronics is proportional to the torque; for this action, 0.28 A is required.

5.3. MASCOT mock-up

For first hardware tests under earth gravity, a mock-up is built, which consists of a highly scaled model – shown in Figure 11 - in terms of mass distribution and motor power, but using the microgravity mobility concept, in combination with strategies for partial gravity compensation.

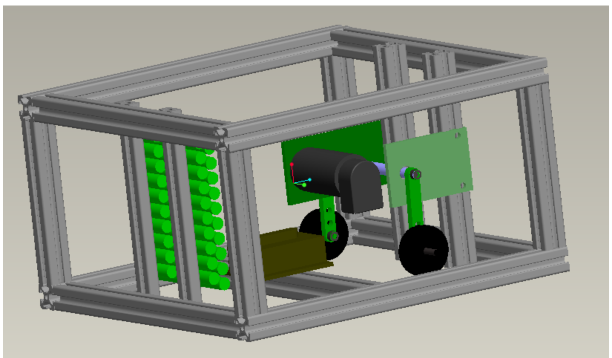
Figure 11. The MASCOT mock-up model (CAD)

The mock-up consists of an open aluminium frame which represents the MASCOT structure and an off-the-shelve drive system including controller and motor-gear-unit with a gear ratio of 1:4. Excenter masses of 100 g and 200 g can be mounted on each side; the excentricity is adjustable between 40 mm and 60 mm. The electric system operates on a voltage of 24 V with a 20 cells onboard battery. To avoid disturbances while moving, the control signal is transmitted by a short-distance wireless system (not yet implemented in Figure 12).

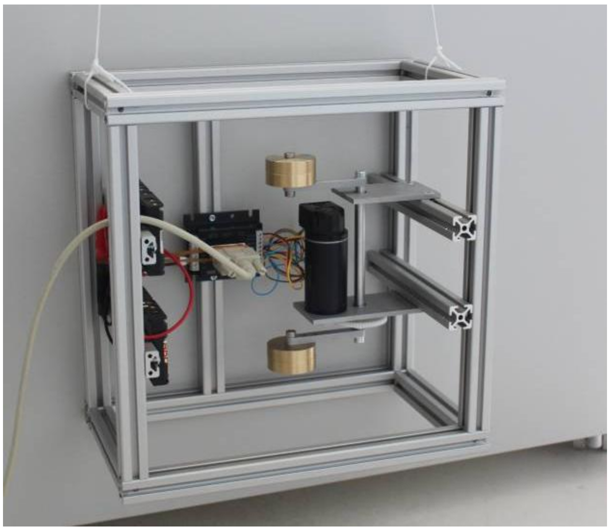
Figure 12. The MASCOT mock-up

The mock-up model is used to show the principle of the inertia driven mobility system. It has reduced mass but higher motor power as well as different mechanical properties, and therefore a changed mass distribution and dynamic behaviour in comparison to the estimated flight model. The mock-up is designed with the help of dynamic simulation as well; therefore simulation results can be evaluated for the specific environment which leads to a partly validated simulation.
Strategies for gravity compensation on earth always include simplifications and constraints. For example, a suitable pendulum system only allows rotation about one axis and implies interfering forces from the attachment while moving. Nevertheless, the tests are useful and the results lead to enhanced simulation models and results.

6. OUTLOOK: DROP TOWER AND PARABOLIC FLIGHT TESTS

The dynamic behaviour and functionality of the unscaled microgravity mobility system can only be tested in microgravity environment. One possibility is to perform drop tower tests. As lower gravity means slower dynamics, a certain time is needed to assure accurate functionality. Hence the test time provided in drop towers is only up to 9.3 seconds [16], only the early phase of motion can be observed in these kinds of tests.
Furthermore it is desired to attend parabolic flights, which provide microgravity test periods of 22 seconds for each parabola [17]. For the flights a special test rig is

designed (Figure 13). The test preparation is accompanied by particular simulations to generate a specific data pool to be verified during the parabolic flight tests.

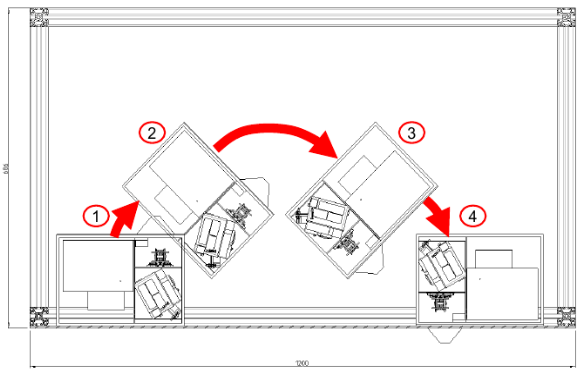

Figure 13. Parabolic flight test rig set-up and motion sequence (upright)

The test results ideally will lead to a deeper understanding of the interaction between the mechatronics components and software in microgravity environment. Therefore, besides the demonstration of concept functionality and simulation validity, a noticeable performance improvement and refinement of the system properties is expected to be achievable with the test experience.

7. ACKNOWLEDGEMENTS

The MASCOT project is under the lead of the DLR Institute of Space Systems, Bremen (DLR-RY). The DLR Institute of Robotics and Mechatronics (DLR-RM) is responsible for the development of the mobility subsystem. The authors highly appreciate the support of the MASCOT team (DLR, CNES, JAXA) for providing the basic conditions to the work described in this paper. And specifically, we would like to thank for the most valuable support in electronics and motor design given by Hans-Jürgen Sedlmayr, Nikolaus Seitz, Maximilian Maier and Josef Reill from our institute.

8. REFERENCES

1. The Near-Earth Asteroids Data Base, DLR, request March 2011, http://earn.dlr.de/nea/.

2. Abe, M., Kawakami, K. & Hasegawa, S. et al. (2008), *COSPAR Scientific Assembly*, B04-0061-08.

3. Yoshimitsu, T. et al. (2003). Micro-hopping robot for asteroid exploration, *Acta Astronautica 52*, pp. 441-446.

4. Ulamec, S. & Biele, J. (2007). Surface elements and landing strategies for small bodies missions – Philae and beyond, *Advances in Space Research 44*, pp. 847-858.

5. Dietze, C., Herrmann, F., Kuß, S., Lange, C., Scharringhausen, M., Witte, L., van Zoest, T. & Yano, H. (2010). Landing and mobility concept for the small asteroid lander MASCOT on asteroid 1999 JU3. 61st International Astronautical Congress, IAC Prague, Czech Republic.

6. SIMPACK AG, request March 2011, http://www.simpack.de.

7. Gibbesch, A., Krenn, R., Herrmann, F., Schäfer, B., Rebele, B., Allouis, E. & Diedrich, Thomas (2010). Multi-Body System and Contact Simulation within the Design Development of Planetary Surface Exploration Systems. Proceedings. ISAIRAS 2010, Sapporo, Japan.

8. Apfelbeck, M., Kuß, S., Rebele, B & Schäfer, B. (2010). A systematic approach to reliably characterize soils based on Bevameter testing. 9th Asia-Pacific ISTVS Conference and Annual Meeting of Japanese Society for Terramechanics, Sapporo, Japan

9. Apfelbeck, M., Kuß, S., Wedler, A., Gibbesch, A., Rebele, B. & Schäfer, Bernd (2009) A novel Terramechanics testbed setup for planetary Rover wheel-soil Interaction. 11th European Regional Conference of the ISTVS, Bremen, Germany.

10. Takashi K. & Testuo Y. (2005). Asteroid Exploration Rover, IEEE ICRA 2005, Planetary Rover Workshop.

11. Ulamec, S., Kucherenko, V., Biele, J., Bogatchev, A., Makurin, A. & Matrossov, S. (2010). Hopper concepts for small body landers. *Advances in Space Research*. ELSEVIER, September 2010.

12. Lange, C. et al. (2010). Baseline Design of a Mobile Asteroid Surface Scout (MASCOT) for theHayabusa-2 Mission, 7th International Planetary Probe Workshop, Barcelona, Spain.

13. RoboDrive, request March 2011, http://www.robodrive.de/670/?L=2

14. Harmonic Drive, request March 2011, http://www.harmonicdrive.de/cms/front_content.php?idart=2&idcat=2&changelang=3

15. Landzettel, K., Preusche, C., Albu-Schäffer, A., Reintsema, D., Rebele, B., & Hirzinger, G. (2006). Robotic On-Orbit Servicing - DLR's Experience and Perspective. International Conference on Intelligent Robots and Systems (IROS), Peking, China.

16. Center of Applied Space Technology and Microgravity (ZARM), request March 2011, http://www.zarm.uni-bremen.de/

17. Novespace, request March 2011, http://www.novespace.fr/