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MOBILE ASTEROID SURFACE SCOUT (MASCOT) – DESIGN, DEVELOPMENT
AND DELIVERY OF A SMALL ASTEROID LANDER ABOARD HAYABUSA2

Jan Thimo Grundmann^(1,2), Uli Auster^(16,17), Volodymyr Baturkin^(1,3), Anthony Bellion^(20,21), Jean-Pierre Bibring^(29,30), Jens Biele^(33,34), Ralf Boden^(1,23), Olivier Bompis^(20,22), Belinda Borgs^(39,40), Pierre Bousquet⁽²⁰⁾, Elisabet Canalias^(20,24), Luca Celotti⁽³⁷⁾, Céline Cenac-Morthe^(20,25), Federico Cordero⁽³⁸⁾, Muriel Deleuze^(20,26), Corinne Evesque^(29,31), Ross Findlay^(1,4), Stéphane Fredon^(20,27), Karl-Heinz Glaßmeier^(16,18), David Granena^(20,28), Christian D. Grimm^(1,5), Matthias Grott^(39,41), Vincent Hamm^(29,32), Jeffrey Hendrikse⁽⁴⁴⁾, David Hercík^(16,19), Tra-Mi Ho^(1,6), Ralf Jaumann^(39,42), Christian Krause^(33,34), Ronald Kroth⁽⁴⁵⁾, Eugen Ksenik^(1,7), Caroline Lange^(1,8), Michael Lange^(46,47), Olaf Mierheim^(46,48), Tatsuaki Okada^(49,50), Josef Reill^(52,53), Kaname Sasaki^(1,9), Nicole Schmitz^(39,43), Hans-Jürgen Sedlmayr^(52,54), Maria Talapina^(1,10), Sirinart Tangruamsub^(1,11), Nawarat Termtanasombat^(1,12), Stephan Ulamec^(33,36), Elisabet Wejmo^(1,13), Michael Wrasmann^(1,14), Tetsuo Yoshimitsu^(49,51), Christian Ziach^(1,15), and the MASCOT Team⁽⁶⁾

⁽¹⁾DLR Institute of Space Systems, Robert-Hooke-Str. 7, 28359 Bremen, Germany

⁽²⁾+49-(0)421-24420-1107, jan.grundmann@dlr.de

⁽³⁾+49-(0)421-24420-1610, Volodymyr.Baturkin@dlr.de

⁽⁴⁾+49-(0)228-447-231, ross.findlay@dlr.de

⁽⁵⁾+49-(0)421-24420-1266, christian.grimm@dlr.de

⁽⁶⁾+49-(0)421-24420-1171, Tra-Mi.Ho@dlr.de

⁽⁷⁾+49-(0)421-24420-1247, eugen.ksenik@dlr.de

⁽⁸⁾+49-(0)421-24420-1159, caroline.lange@dlr.de

⁽⁹⁾+49-(0)421-24420-1150, Kaname.Sasaki@dlr.de

⁽¹⁰⁾+49-(0)421-24420-1305, Maria.Talapina@dlr.de

⁽¹¹⁾Sirinart.Tangruamsub@dlr.de

⁽¹²⁾+49-(0)421-24420-1210, nawarat.termtanasantombat@dlr.de

⁽¹³⁾+49-(0)421-24420-1107, Elisabet.Wejmo@dlr.de

⁽¹⁴⁾+49-(0)421-24420-1278, Michael.Wrasmann@dlr.de

⁽¹⁵⁾+49-(0)421-24420-1181, Christian.Ziach@dlr.de

⁽¹⁶⁾Institute for Geophysics and Extraterrestrial Physics, Technical University Braunschweig, Germany

⁽¹⁷⁾uli.auster@tu-bs.de

⁽¹⁸⁾kh.glassmeier@tu-bs.de

⁽¹⁹⁾d.hercik@tu-braunschweig.de

⁽²⁰⁾Centre National d'Etudes Spatiales CNES, 18 avenue Edouard Belin, 31401 - Toulouse Cedex 9, France

⁽²¹⁾DCT/RF/AN, Service Antennes, BPi 3602, +33 (0)5 61 27 47 94, anthony.bellion@cnes.fr

⁽²²⁾CNES DCT/RF/ITP, +33 (0)5 61 27 36 54, Olivier.Bompis@cnes.fr

⁽²³⁾Department of Aeronautics and Astronautics, The University of Tokyo, Tokyo, Japan, +81-(0)50-336-23042, boden.ralf@ac.jaxa.jp

Institute of Astronautics (LRT), Technische Universität München (TUM), Boltzmannstr. 15, 85748 Garching, Germany, ralf.boden@tum.de

- (24) *Elisabet.Canalias@cnes.fr*
- (25) *DCT/TV/EL, +33 5 61 28 21 94, celine.cenac-morthe@cnes.fr*
- (26) *+33 561 274 847, Muriel.Deleuze@cnes.fr*
- (27) *+33 5 61 28 30 21, Stephane.Fredon@cnes.fr*
- (28) *DCT/TV/EL, BPi: 2213, +33 5 61 28 34 08, David.Granena@cnes.fr*
- (29) *IAS - Institut d'Astrophysique Spatiale, Université Paris Sud - Bat 121, 91405
ORSAY CEDEX, France*
- (30) *bibring@ias.u-psud.fr*
- (31) *+33 (0)1 69 85 85 24, corinne.evesque@ias.u-psud.fr*
- (32) *+33 (0)1 69858684, vincent.hamm@ias.u-psud.fr*
- (33) *DLR Space Operations and Astronaut Training – MUSC, 51147 Köln, Germany,*
- (34) *+49-2203-601-4563, Jens.Biele@dlr.de*
- (35) *+49-2203-601-3048, Christian.Krause@dlr.de*
- (36) *+49-2203-601-4567, Stephan.Ulamec@dlr.de*
- (37) *Active Space Technologies, Rudower Chaussee 29, 12489 Berlin, Germany,
luca.celotti@activespacetech.eu*
- (38) *Telespazio-VEGA, Darmstadt, Germany, federico.cordero@telespazio-vega.de*
- (39) *DLR Institute of Planetary Research, Rutherfordstr. 2, 12489 Berlin*
- (40) *+49-(0)30 67055-658, Belinda.Borgs@dlr.de*
- (41) *+49-(0)30 67055-419, matthias.grott@dlr.de*
- (42) *+49-(0)30-67055-400, ralf.jaumann@dlr.de*
- (43) *+49-(0)30 67055-456, Nicole.Schmitz@dlr.de*
- (44) *EADS Astrium, Friedrichshafen, Germany, Jeffrey.Hendrikse@astrium.eads.net*
- (45) *MAGSON GmbH, Carl-Scheele-Str. 14, 12489 Berlin, Germany,
ronald.kroth@magson.de*
- (46) *DLR Institute of Composite Structures and Adaptive Systems – Composite
Design, Lilienthalplatz 7, 38108 Braunschweig, Germany*
- (47) *+49-(0)531-295-3223, m.lange@dlr.de*
- (48) *+49-(0)531-295-3224, olaf.mierheim@dlr.de*
- (49) *Japan Aerospace Exploration Agency (JAXA), Institute of Space and Astronautical
Science (ISAS), 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210,
JAPAN*
- (50) *ISAS & JSPEC, okada@planeta.sci.isas.jaxa.jp*
- (51) *+81 4 27 59 80 69, kikko@nnl.isas.jaxa.jp*
- (52) *DLR Robotics and Mechatronics Center, 82234 Wessling, Germany*
- (53) *+49-(0)8153-28-3563, Josef.Reill@dlr.de*
- (54) *+49-(0)8153-28-3532, Hans-Juergen.Sedlmayr@dlr.de*

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ABSTRACT

MASCOT is a small asteroid lander launched on December 3rd, 2014, aboard the Japanese HAYABUSA2 asteroid sample-return mission towards the 980 m diameter C-type near-Earth asteroid (162173) 1999 JU₃.

MASCOT carries four full-scale asteroid science instruments and an uprighting and relocation device within a shoebox-sized 10 kg spacecraft; a complete lander comparable in mass and volume to a medium-sized science instrument on interplanetary missions.

Asteroid surface science will be obtained by: MicrOmega, a hyperspectral near- to mid-infrared soil microscope provided by IAS; MASCAM, a wide-angle Si CMOS camera with multicolour LED illumination unit; MARA, a multichannel thermal infrared surface radiometer; the magnetometer, MASMAG, provided by the Technical University of Braunschweig. Further information on the conditions at or near the lander's surfaces is generated as a byproduct of attitude sensors and other system sensors.

MASCOT uses a highly integrated, ultra-lightweight truss-frame structure made from a CFRP-foam sandwich. It has three internal mechanisms: a preload release mechanism, to release the structural preload applied for launch across the separation mechanism interface; a separation mechanism, to realize the ejection of MASCOT from the semi-recessed stowed position within HAYABUSA2; and the mobility mechanism, for uprighting and hopping. MASCOT uses semi-passive thermal control with Multi-Layer Insulation, two heatpipes and a radiator for heat rejection during operational phases, and heaters for thermal control of the battery and the main electronics during cruise. MASCOT is powered by a primary battery during its on-asteroid operational phase, but supplied by HAYABUSA2 during cruise for check-out and calibration operations as well as thermal control. All housekeeping and scientific data is transmitted to Earth via a relay link with the HAYABUSA2 main-spacecraft, also during cruise operations. The link uses redundant omnidirectional UHF-Band transceivers and patch antennae on the lander. The MASCOT On-Board Computer is a redundant system providing data storage, instrument interfacing, command and data handling, as well as autonomous surface operation functions. Knowledge of the lander's attitude on the asteroid is key to the success of its uprighting and hopping function. The attitude is determined by a threefold set of sensors: optical distance sensors, photo electric cells and thermal sensors. A range of experimental sensors is also carried.

MASCOT was built by the German Aerospace Center, DLR, with contributions from the French space agency, CNES.

The system design, science instruments, and operational concept of MASCOT will be presented, with sidenotes on the development of the mission and its integration with HAYABUSA2.

INTRODUCTION

During the 63rd International Astronautical Congress (IAC) in Naples in 2012, a Memorandum of Understanding was signed between the Japanese Aerospace Exploration Agency (JAXA) and the German Aerospace Centre (DLR), paving the way for the Mobile Asteroid Surface Scout (MASCOT) participation in JAXA's HAYABUSA2 mission.

Like its famous predecessor HAYABUSA which returned the first samples from an asteroid, (25143) Itokawa, HAYABUSA2 is foreseen to study and return samples from a Near-Earth Asteroid (NEA). As a new addition to the previous mission, HAYABUSA2 also includes an array of small lander packages. One of these, MASCOT, was developed by DLR and the Centre National d'Etudes Spatiales (CNES). MASCOT is a shoebox-sized 10 kg mobile planetary lander equipped with four science instruments:

- MARA, a multispectral radiometer to measure surface thermal properties (DLR);

- CAM, a surface and in-flight imaging wide angle camera with LED illumination unit (DLR);
- MAG, a fluxgate magnetometer (IGEP, Technical University of Braunschweig); and
- MicrOmega, a hyperspectral IR soil-imaging microscope (IAS, Université de Paris Sud, Orsay).

The spacecraft bus of MASCOT includes an internal mobility mechanism, a GNC sensor package and on-board autonomy software that enable MASCOT to upright itself and to perform relocation leaps on the asteroid surface. A redundant on-board computer (OBC) provides autonomous control, command and data handling, and pre-processing power. Power is supplied by primary battery via a redundant power subsystem (PCDU). The design goal is to operate during two asteroid days on the surface and to perform at least one relocation. [1][2][3]

Following its launch on December 3rd, 2014, HAYABUSA2 will take 4 years of interplanetary cruise to arrive at (162173) 1999JU₃, a 980 m diameter C-type asteroid. After a period of initial remote sensing operations, MASCOT will be released to the surface and perform a comprehensive sequence of science operations after settling at its first location. Once this is complete, MASCOT will be able to 'hop' from one measurement site to the next.

Realizing MASCOT's mission is difficult due to the strict mission requirements, the harsh landing environment and a short development time for a piggyback deep space mission. Aiming for high performance and reliability requires creative design solutions and novel developments in order to meet all challenges and to stay inside the mass limit of 11 kg including the support mechanism aboard HAYABUSA2. The results obtained in the final stage of development and testing before flight model (FM) delivery have shown the strict limits of the structure and thermal design, and highlighted risks inherent in such a fast-paced project development. Lessons have also been learned regarding margin policy for such small spacecraft. Despite these challenges, the project remained on-track, with all delivery milestones met in the end.

DEVELOPMENT OF THE MASCOT PROJECT

From Study to Project

The JAXA HAYABUSA mission achieved success in returning the first samples of an Near-Earth asteroid to Earth in June 2010.[4]

HAYABUSA2 is an advanced and further developed follow on of a successful mission which enjoyed the benefit of all lessons learned during its predecessor. Taking advantage of a previous concept for the ESA MARCO POLO mission, DLR was invited to develop a small lander package to complement the main mission. Originally conceived for the MARCO POLO study in 2008, MASCOT had developed from a PHILAE-like lander into a lightweight and compact design with 40% payload mass fraction. After the deselection of MARCO POLO in 2009, the JAXA invitation to join HAYABUSA2 provided the chance to realize MASCOT. Since then MASCOT is being developed at DLR in close collaboration with CNES and JAXA.

From Timelines to Timeline – Project Realization

HAYABUSA2 is a mission that is based on limited modifications of a highly successful predecessor with maximum applicability of all lessons learned due to the similarity of the core of the new mission objectives; in interplanetary spaceflight a today become rare case of efficient knowledge re-use and sustaining capabilities once built up with great effort. MASCOT was selected when its final conceptual design including science payload selection had not yet been fully defined. This necessarily led to a situation of decoupled schedules, compounded for MASCOT with the need to catch up with its smoothly advancing and already much more advanced mothership. Since the design of HAYABUSA2 was already much more advanced, MASCOT had to fit into a firmly defined envelope, and it entered at a level of detail of design on the mothership side at which there already is a strict margins policy in place and interfaces had to be fixed. These were challenges during development of MASCOT at all levels. Science instruments and bus subsystem units, even the overall system design had to be derived as much as possible from what was available off the shelf, in the lab or in the design bureaux. Contributions of the project partners were thus at first entering the project at very heterogeneous maturity levels ranging from concept study to flight heritage hardware which all had to converge with the progress of MASCOT towards flight readiness of the integrated system.

MASCOT hardware assembly began with the first unit breadboarding start on June, 6th, 2011, over half a year before formal go-ahead. It passed HAYABUSA2 subsystem CDR in December 2011, the MASCOT-internal system PDR in July 2012, and, after a series of subsystem midterm reviews, the internal system CDR was passed in April 2013. The flight model was delivered to JAXA in June 2014, to be integrated in HAYABUSA2 for the launch ultimately planned for November 30th, 2014, at the beginning of a brief launch window of just a few days. The launch window had been set years ahead because it was tied to the target asteroid 1999 JU₃ and therefore firmly determined by celestial mechanics and the capabilities of the launcher and mothership on-board propulsion. In the end, after minor delays due to weather, the launch occurred on December 3rd, 2014, 04:22 UT.

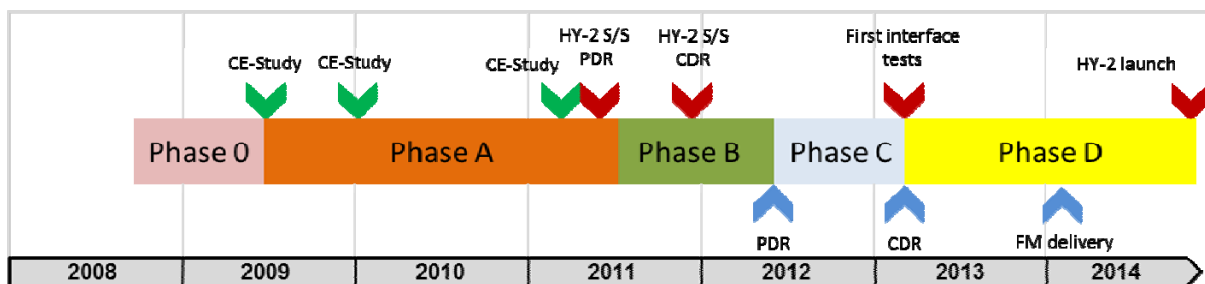


Figure 1 – MASCOT’s time on Earth: from MARCO POLO to HAYABUSA2

Mission Timeline

After its launch from Tanegashima Space Center HAYABUSA2 is scheduled to arrive at 1999JU₃ in June 2018. In interplanetary cruise until then and during target reconnaissance, MASCOT is mostly inactive and carried aboard HAYABUSA2 which provides thermal control and occasional power supply for cruise check-outs. This allows MASCOT to rely on a non-rechargeable primary battery which only powers MASCOT’s science mission after separation. MASCOT is carried semi-recessed on the –Y side panel of its mothership.

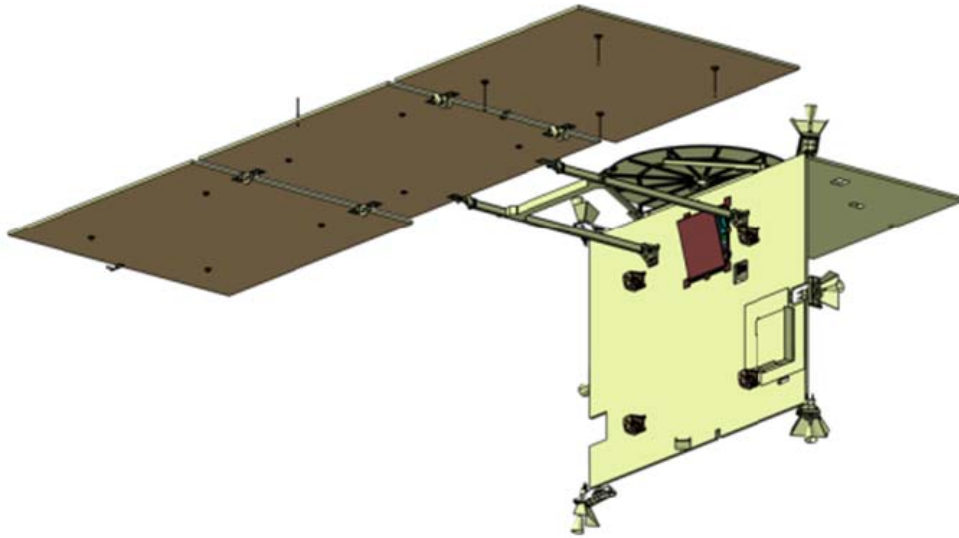


Figure 2 – MASCOT aboard HAYABUSA2 in the –Y panel

HAYABUSA2 is scheduled to accompany 1999 JU₃ for more than one asteroid year, till the end of 2019 before departing with the collected samples for Earth:

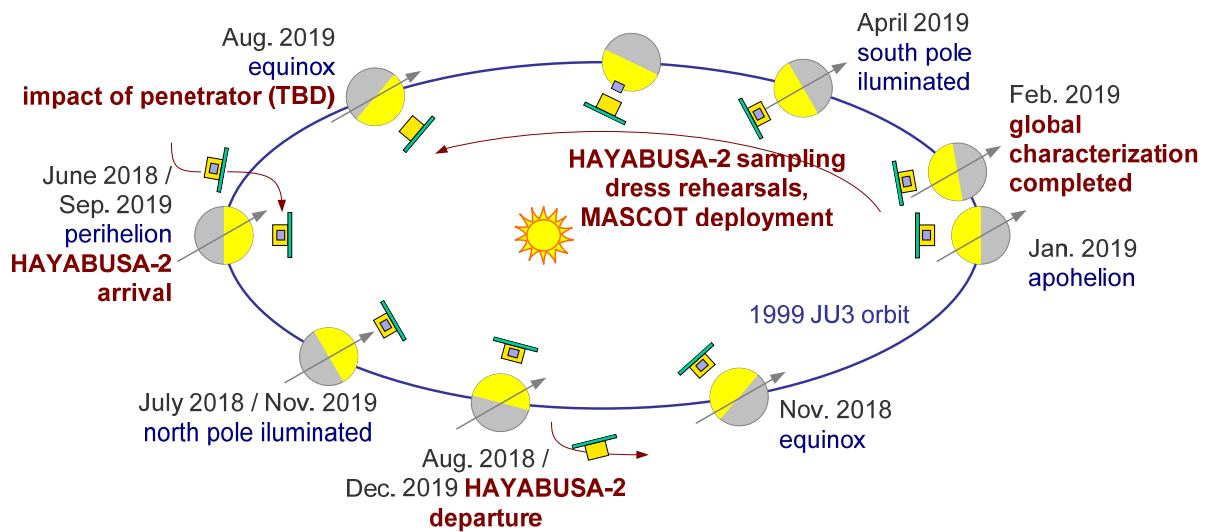


Figure 3 - HAYABUSA2 mission timeline at (162173) 1999 JU₃

After arrival at 1999JU₃, HAYABUSA2 will first perform a global mapping in order to characterise the asteroid, particularly to improve the accuracy of its main properties and for an overview of its surface geology as this is the first encounter with a small C-type asteroid and the first rendezvous with a dark non-cometary body.

parameter	Müller et al [5]
Mean volume-equivalent diameter	870 ±30 m
bulk density	1300 kg/m ³
sidereal spin period	7 ^h 37 ^m 57 ^s ±36 ^s
spin axis positive pole, ecliptic longitude	73°
spin axis positive pole, ecliptic latitude	-62°

radiometric geometric albedo p_v	0.070 \pm 0.006
obliquity	151.6° (retrograde rotation)
thermal inertia	200 ... 600 J/(m ² s ^{1/2} K) (notional: 400)
emissivity	0.9 (assumed)
surface fraction covered with craters	0.4 ... 0.9 (assumed)
absolute magnitude H_v	18.82 \pm 0.02 mag

Table 1 – Current estimates of (162173) 1999 JU₃ key parameters [5]

This phase also assists with landing sites selection, for the sample return touchdown and those of the landers. HAYABUSA2 also carries a whole set of small separable spacecraft and small landers, including three JAXA-built MINERVA landers and MASCOT. Thermal constraints are an important consideration during the landing site selection process for landers with longer periods of activity on the surface.

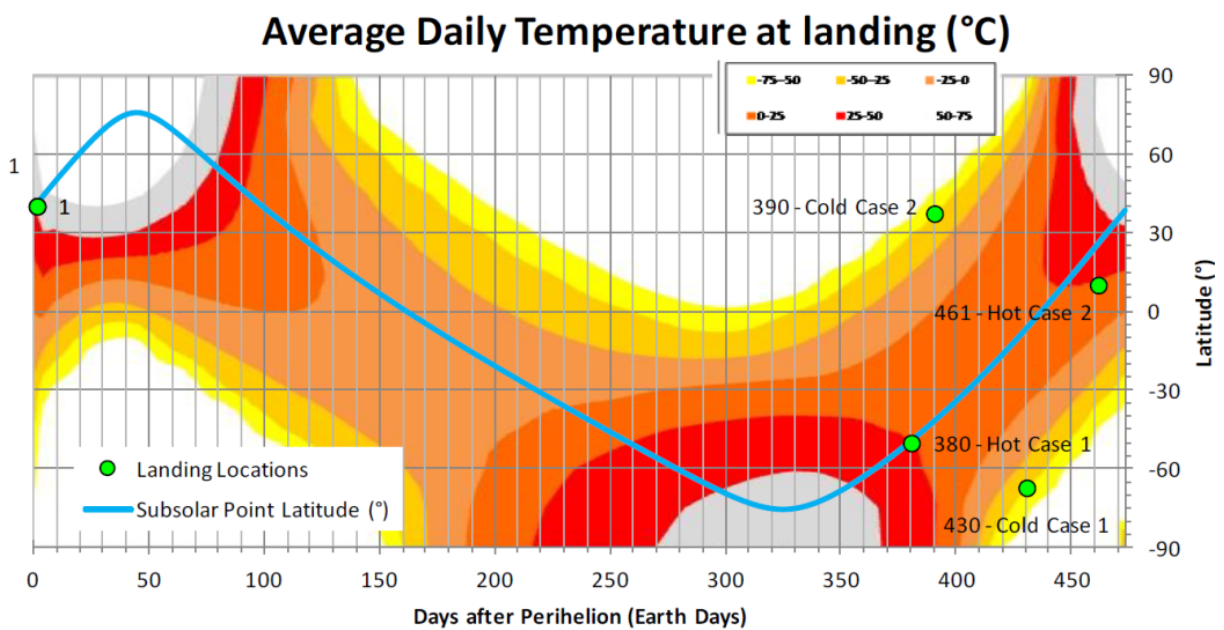


Figure 4 – Seasonal and latitudinal average temperature distribution for 1999JU₃ with design case latitude and landing date examples

With the landing site selected based on local geology and thermal constraints, MASCOT will be released to the surface, either during a dedicated descent or during one of the sampling touchdown rehearsals. The mothership will descend to the separation altitude of 100 m, at which point a Non-Explosive Actuator (NEA) will be fired and MASCOT ejected by a spring mechanism with a controlled low velocity in the order of cm/s.

Surface Science Mission Timeline

MASCOT will fall to the asteroid surface under the effects of the weak gravity field for about ½ hr, before landing in an unknown orientation. Meanwhile, HAYABUSA2 conducts search photography to locate the actual landing site of MASCOT, before retreating to its home position at up to 20 km altitude. During this phase, communications to HAYABUSA2 will be maintained throughout. While approaching the surface MASCOT will take camera images of the asteroid and measure the magnetic field in its vicinity all along the way.

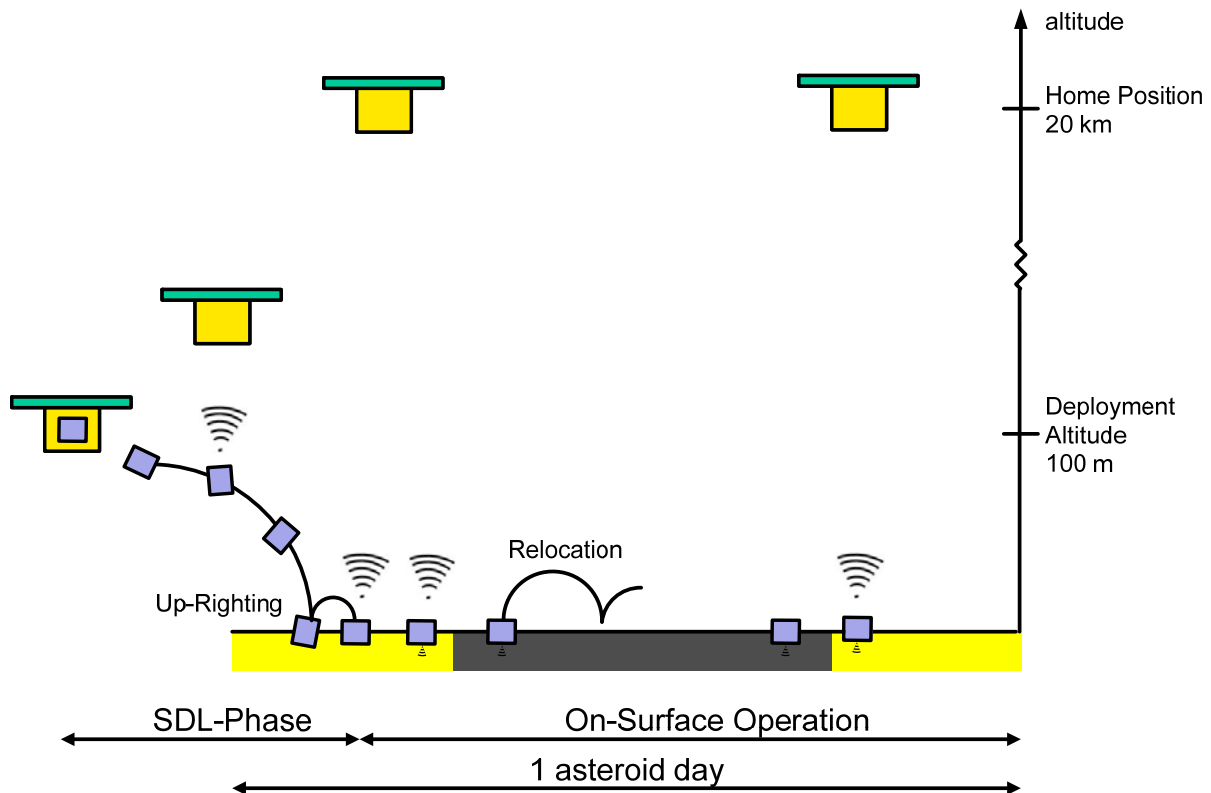


Figure 5 – MASCOT surface science operations concept

In order to conduct surface science, MASCOT must be orientated properly. Thus, after settling from eventual bounces across the surface, MASCOT will first perform an uprighting manoeuvre using the internal Mobility Mechanism.

After uprighting, MASCOT will first perform all scientific tasks which do require daylight. A landing near the subsolar meridian is expected, so nightfall can be expected after approximately 2 hours on the surface. During daylight MASCOT will be able to communicate continuously with HAYABUSA2 which nominally positions itself high above the sub-solar point on the asteroid on a line to the Sun. Telecommunications will thus be interrupted just before nightfall and resume soon after sunrise, assuming a reasonably flat terrain.

Some of MASCOT's instruments are operating also during night-time during which the collected data have to be stored in mass memory until the communications link becomes available again.

A full complement of scientific activities will be performed, involving approximately one asteroid day, before MASCOT can relocate to another site. The same internal mechanism will then be activated and send MASCOT in a semi-controlled hop across the surface; the power of the hopping impulse can be controlled though not the direction. With a sufficient margin against accidental escape from the asteroid, nominal distances up to about 220 m are expected to be covered.

Further scientific activities will take place repeating an abridged version of the first science measurements cycle at each location on the asteroid surface. Power depending, a second hop can be considered.

The expected lifetime of MASCOT is sufficient to operate during two asteroid days, mainly limited by the energy stored in the battery and to some degree dependent on the actual thermal conditions met at the landing sites.

MASCOT's communicates to ground via HAYABUSA2 as relay and vice-versa. During the on-asteroid phase, MASCOT will nominally only downlink information, due to the long turnaround times for ground intervention. About 16 minutes of transmission delay are expected for a typical landing season, plus processing and decision time on the ground. Thus, all nominal operations and a subset of failure responses need to be handled by onboard autonomy. This autonomy will be responsible for the scheduling of uplinks and determining the need for any attitude correction manoeuvres. It can also modify the scheduling of the science operations accordingly. In the event of contingencies which cannot be compensated by the onboard autonomy, ground support at the control centre at the DLR Microgravity User Support Centre (MUSC) in Cologne, Germany, will have the capability to intervene, though limited by the inevitable roundtrip delay, line-of-sight availability of MASCOT and HAYABUSA2 in the day-night-cycle, and the somewhat restricted amount of live telemetry.

THE SCIENCE INSTRUMENTS

MASCOT has the capability to add scientific value to the HAYABUSA2 mission in a threefold manner:

- It will conduct the first ever in-situ measurements on an asteroid providing ground truth information for planetary science, since rock nature (i.e. volatiles within rocks) can change during return flight.
- It will close the gap between the measurements taken from the orbiter in the scale of several meters to a few centimeters, whereas the returned samples by HAYABUSA2 will be in the micro- to millimeter scale. MASCOT's measurements in the ranges from micrometers to several centimeters scale will complete this picture and hence, provide the context of any collected samples.
- Should MASCOT be deployed before HAYABUSA2 starts to collect samples from the asteroid surface, MASCOT will also act as a scouting vehicle to provide the mother spacecraft with ground truth information for the detailed planning of near-surface operations during the critical sampling phase. [6]

MASCOT's suite of science instruments is designed for the study of the target asteroid with a focus on surface properties and the close-in space environment that it experiences during descent and landing. The design goal is to provide supporting information to the process of investigation of the asteroid surface which leads to the selection of sample recovery sites from the scientific perspective. Also, information on the characteristics of the environment to be experienced by spacecraft descending to and making contact with the surface are to be gathered for the support of engineering decisions in the mission operations of the mothership. [5]

The MASCOT Magnetometer (MAG)

Science objectives

Magnetic field observations of the primitive solar system bodies might provide us with important information about their constitution, history, and formation. The MASCOT magnetometer scientific operations will be focused on landing and hopping to get the magnetic field decay profile that tells us more about any global magnetic field or local field sources. The magnetometer shall therefore measure during the whole MASCOT operational period. In order to have measurements from more locations on the surface, relocation of MASCOT is a desired activity. Science requirements are to measure the magnetic field with the accuracy better than 10 nT, however, the MAG measurement range is suitable for measurements within Earth's magnetic field to avoid special ground operations requirements.

Instrument description

The MASCOT magnetometer instrument is a vector compensated three-axis fluxgate magnetometer. The instrument consists of a sensor head and a digital electronics board. The sensor has been developed at the Institute for Geophysics and Extraterrestrial Physics (IGeP) of the Technical University of Braunschweig (TUBS) and the electronics at Magson GmbH. Magnetometer instruments of this type have a long heritage at IGeP from previous space missions such as THEMIS (NASA) [7], VENUS EXPRESS (ESA) [8] and ROSETTA (ESA) [9].

The electronics is placed as a PCB card inside the lander's common electronics box, while the sensor itself is mounted near the bottom corner of the lander body frame. The sensor contains two ring core elements of high-permeability material for the magnetic field concentration. Around the ring cores, excitation coils are wound, that are necessary for core saturation, the prerequisite of fluxgate principle of operation. A second set of coils, the three-axial sensing coil system, picks up the induced signal. In order to keep the sensor in linear regime and avoid the need of range switching, a Helmholtz coil system provides the feedback and keeps the sensor in near zero field. Information about the ambient magnetic field is then extracted from the signal using both input and feedback values. The sensor structure is covered with a multi-layered insulation (MLI) as a passive thermal control.

Magnetometer parameters and performance	
Sensor mass [g]	89
Electronics mass [g]	180
Power consumption [W]	0.5
Sensor dimensions [mm ³]	80 x 80 x 50
Electronics dimensions [mm ³]	109 x 94 x 20
Dynamic range [nT]	+/- 12000
Sensor noise @1Hz [pT/sqrt(Hz)]	~10
Resolution [pT]	7
Sampling rate [Hz]	10

Table 2 – MAG key parameters

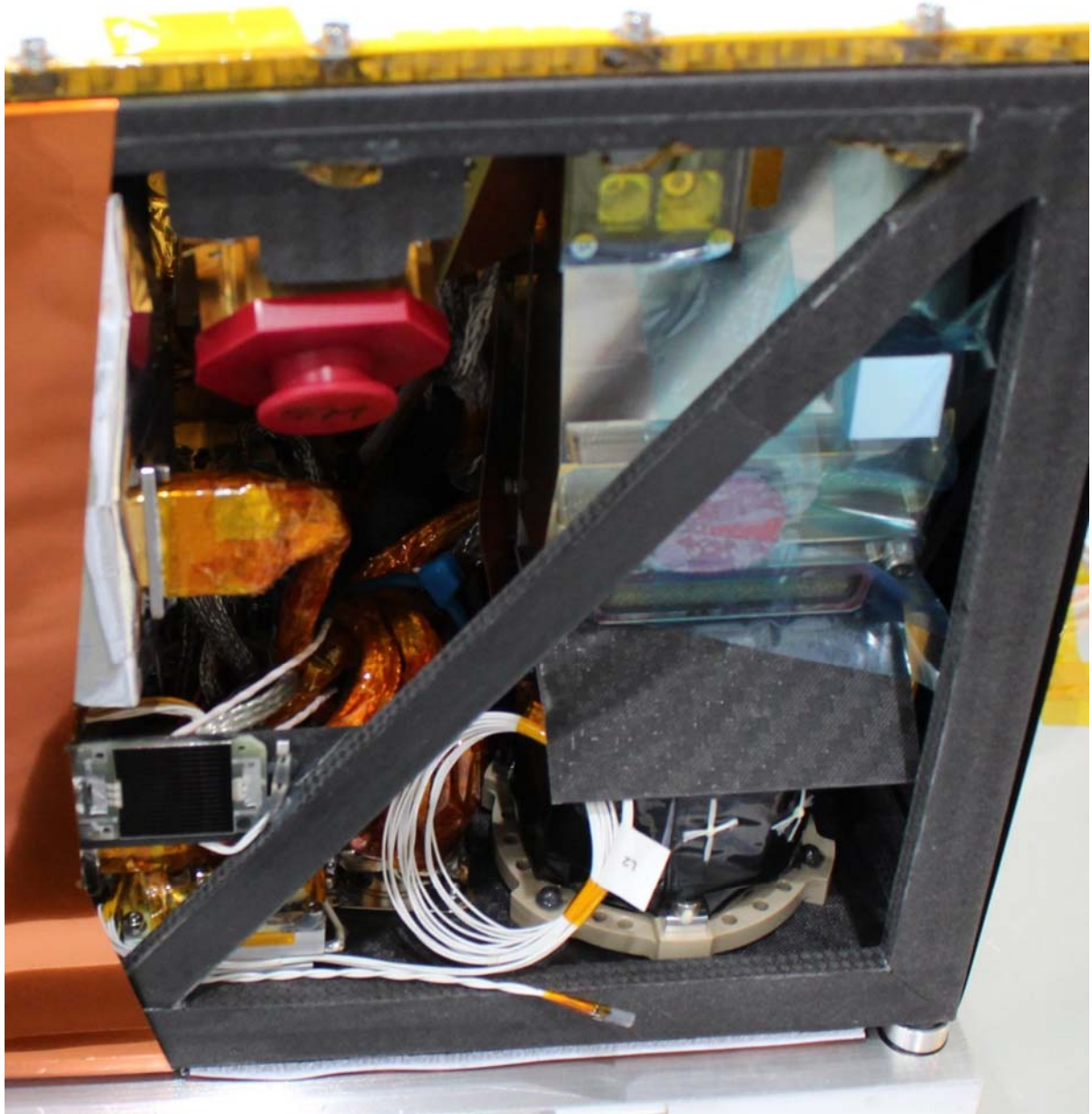


Figure 6 - Magnetometer FM integrated in the MASCOT, sensor crouching under camera in the lower right corner



Figure 7 - Magnetometer FM sensor head with a pigtail harness covered with black MLI to eliminate any reflections to MASCOT camera instrument

The sensor core is nearly identical to the ones of PHILAE, VENUSEXPRESS and THEMIS and similar to the ones flown on EQUATOR-S. The ringcores have been tested under extreme environmental conditions aboard numerous space missions as well as in applied geophysics. The sensor has been operated in a wide temperature range between -120°C on ROSETTA and $+180^{\circ}\text{C}$ for BEPICOLOMBO, therefore the sensors can be mounted outside of the temperature controlled compartment.

The processor used in MAG was originally developed for the NASA THEMIS mission and has since been continuously improved and expanded in its functionality. It is used successfully for the Themis mission as well as in reaction wheels, attitude control magnetometers, magneto-torquers and other terrestrial applications and will also be used for the MPO and MMO magnetometers of the ESA/JAXA BEPICOLOMBO mission. MAG is being developed in cooperation of Institut für Geophysik und extraterrestrische Physik of the Technische Universität zu Braunschweig (IGEP, TU-BS) and Magson GmbH. It has a mass of 0.243 kg and generates 1155 bits/measurement. It is envisaged to operate continuously throughout the mission, with some focus on the descent and hopping phases to observe the magnetic field above the surface and the interaction of the asteroid with interplanetary space.

The MASCOT Radiometer (MARA)

The MASCOT Radiometer, MARA, is a multispectral instrument which will measure the radiative flux emitted from the asteroid's surface using thermopile sensors. Six sensors with individual filters and a common field of view will be employed to measure the flux in the wavelength bands 5.5–7, 8–9.5, 9.5–11.5, 13.5–15.5, 8–14, and 5–100 μm . The primary scientific goal of the MARA instrument is the determination of the asteroid's thermal inertia, a secondary goal is the characterization of the surface mineralogy.

To determine surface thermal inertia, MARA will measure the temperature of the asteroid's surface over the period of a full rotation using the broadband and long wavelength channel from 5 to 100 μm . In addition, the emissivity of the surface can

be determined from the flux in the five narrow band-pass filters. Thermal inertia can then be determined from an investigation of the surface radiative energy balance.

The mineralogy of the surface can be characterized from an investigation of the radiative flux in the same narrow band-pass channels, as rock forming minerals like olivine and pyroxene have characteristic absorption features in the channels covered by MARA. In addition, the 8–14 μm filter is identical to the filter used by the thermal mapper on the HAYABUSA2 spacecraft, such that measurements obtained by MARA near the surface can be directly compared to the results obtained from the mothership at altitude. In this way, MARA can provide ground truth at small scales, thus providing context for the orbiting spacecraft measurements.

Due to the high-temperature environment expected on the dark surface of a C-type asteroid and spacecraft resources too limited to allow active cooling, the sensor head is constantly heated to a precisely stabilized temperature. Mounting and harness of the sensor head are optimized towards low heat leakage and a sunshield is provided, to reduce the maximum temperature to heat against. The heater elements are designed to cancel out the magnetic field created by the variable heating current.

MARA has significant heritage both from the MUPUS thermal mapper (MUPUS-TM) on ROSETTA/PHILAE as well as from the MERTIS Radiometer for BEPICOLOMBO. The MARA sensors are similar to the MUPUS-TM sensors, while the readout electronics is similar to that used in the MERTIS project. MARA is developed by the DLR Institute of Planetary Research and Magson GmbH. It has a mass of 0.32 kg and will continuously take measurements in all channels at intervals of 30 s, generating 1.9 kbit/sample.

The MASCOT Camera (CAM)

CAM is a wide-angle camera for MASCOT, using a 1024^2 pixel CMOS image sensor with 15 μm pitch. It operates in the 400 – 1000 nm wavelength and has a field of view of $60^\circ \times 60^\circ$. The instantaneous field of view is 2.1 mrad/pixel. Several pictures will be taken during the asteroid day and night. Images will also be made during descent and hopping. The sensor is not filtered and hence provides panchromatic images during the day. At night, a multispectral LED illumination unit provides blue, green, red, and near-infrared light for colour images of the surface.

CAM has heritage from the ROSETTA/PHILAE mission (ROLIS, Rosetta Lander Imaging System) and the ISS, and contributes to developments for ExoMars. The instrument is developed by DLR Institute of Planetary Research. It has a mass of 0.42 kg; each image generates 14.7 Mbit of data. Some evaluation of the images takes place on board to optimize science return within the available downlink budget.

CalTarget for Two

MARA and the visual light camera, CAM, share a common field of view, and hence, a calibration target (CalTarget) on the Mechanical Electrical Support System (MESS) carrier structure of MASCOT that remains within the -Y panel of HAYABUSA2 after separation. The CalTarget is thermally controlled by MARA to provide an in-flight calibration surface for the radiometer. For this purpose, a second heater control channel from MARA is used. The surface is coated black and structured to satisfy the requirements of both instruments for dark field exposures and high thermal

emissivity. The CalTarget is automatically disconnected with the umbilical when MASCOT is ejected from HAYABUSA2.

The hyperspectral soil microscope MicrOmega (MMEGA)

MicrOmega (MMEGA) is a near-infrared imaging spectrometer/microscope for studying mineralogy and composition, designed to characterize the composition of surface samples at their grain scale. During operations the instrument optical head needs to touch the asteroid surface. MicrOmega acquires 3D (x,y, λ) microscopic image-cubes of samples approximately (3 mm)² in size, with a spatial sampling of 25 μm^2 in 128² px images. For each pixel, the spectrum is acquired in contiguous spectral channels covering the range 0.99 to 3.55 μm . The spectral range is chosen as to include diagnostic features of most potential constituents of the surface: minerals, both pristine and altered, in particular by water; frosts and ices; organics. The spectral sampling is better than 40 cm^{-1} typically with a signal-to-noise ratio of 100, over the entire spectral range. This performance is required to retrieve features down to a few percent depth relative to the local continuum. Image-cubes are built by illuminating the samples with monochromatic light, using an AOTF-based dispersive system, so as to avoid moving parts. Images are acquired onto a 2D HgCdTe array, cooled by a dedicated cryocooler. By scanning the illumination wavelength over the spectral range with steps of 20 cm^{-1} , a complete image-cube is built in about 15 minutes during which about 101 Mbit of data are generated. Measurements are performed both during day and night, and at least one measurement will be performed during day and night for each location. MicrOmega builds on experience gained from the OMEGA spectral imager on MARS EXPRESS, and has heritage from ROSETTA/PHILAE and MicrOmega/PHOBOS GRUNT, and contributes to the development of the MicrOmega/Exomars instrument. It is being developed by the IAS, Orsay, with Steel Electronique and other industrial partners. It is the largest instrument at 2.1 kg mass.

GROUND TRUTH FOR PLANETARY SCIENCE AND PLANETARY DEFENCE

Many of the asteroid surface properties derived from the in-situ observations to be performed by MASCOT are as relevant to applications in planetary defence as they are to the selection of sampling sites for HAYABUSA2. In asteroid orbit determination, surface properties can cause small but in the long term important effects on the orbit of the asteroid that can decide between a direct hit and a wide fly-by of Earth (e.g. [10][11]), particularly if amplified by close planetary encounters. These influences mainly result from the thermo-optical properties of the surface which depend highly on the small-scale granularity and heat capacity. Here, MASCOT extends the global observations of by providing close-in reference data for its own landing sites and areas imaged close up during free-fall phases. These references help to 'tie down' models of the asteroid surface developed from remote observation to well constrained parameters at those locations. This improves accuracy for all locations that could not be observed as directly.

Improved understanding of the response of the surface and the immediate environment of the asteroid to any method of impulse transfer is key to its measured application. For kinetic deflection, the mechanical properties resulting from surface mineral composition, porosity and possible volatiles influence the factor by which

impact energy is converted to impulse. Deflection methods employing radiative ablation, whether by continuous illumination or pulse irradiation, require understanding of the surface composition, porosity, thermo-optical properties and heat capacity. Any plasma in the vicinity of the asteroid is influenced by the magnetic field resulting from the interaction of asteroid and solar wind, whether generated from gaseous ejecta ionized by solar radiation or as a product of spacecraft propulsion systems as in gravity tractors or other station-keeping missions.

Free-fall phases such as those seen by MASCOT after separation and during relocation improve the modelling of the asteroid's gravity field, providing a first glimpse at the interior structure. Bouncing phases experienced after touch-down can provide valuable information about the surface mechanical properties at several locations wherever footprints can be observed by comparing pre-separation to post-landing images.

THE MASCOT SPACECRAFT BUS

Aboard HAYABUSA2, the spacecraft consists of two elements: MASCOT, the “shoe-box sized” lander itself to be ejected from the mothership and operated on the asteroid surface and MESS, the separation cradle supporting MASCOT on the mothership. MASCOT contains all functions for the on-asteroid phase, including payload operation, communication, power storage and distribution and data processing. MESS provides the interfaces to HAYABUSA2, mechanical support and push-off mechanisms, an electrical power supply and actuator interface, and a RF connection antenna for data exchange during cruise.

MASCOT is a rectangular package measuring $0.275 \cdot 0.290 \cdot 0.195 \text{ m}^3$. The system is split into two segments: a warm bus compartment containing the majority of the electronics in a common dedicated electronics box (E-Box) machined out of aluminium which occupies most of the bus compartment and provides thermal and radiation protection to all included PCBs, the battery and the Mobility Mechanism; and a cold science compartment containing the payloads. GNC sensors are also attached to the outer walls. The top surface is used as the main radiator.

The electronics inside the E-Box are integrated as a cards-on-backplane package. The backplane carries the majority of all electrical unit-to-unit connections in MASCOT. Cable harness is mainly used to connect the sensor front-ends and provide the required interface connections as well as safe-arm connections.

The highly integrated ultra-lightweight framework structure made of CFRP-foam sandwich supports functional surfaces for thermal control and radio link. The top-plate acts as the main radiator and is split into two sub-radiators, the smaller of which is removeable for late-access activities, such as the installation of the battery and making safe-arm connections. In order to hold MASCOT during launch and cruise, a non-explosive actuator (NEA) is included on the MASCOT-sided part of the separation mechanism which is mounted to the internal wall and provides a clamping force of 2.5 kN, thus ensuring a firm connection at the four connection corners from MASCOT to MESS.

The non-functional surfaces of MASCOT are covered by strong foils of Single-Layer Insulation (SLI) for thermal control purposes and mechanical protection against the asteroid environment.

Lander Module Structure

To meet the strict mass requirement an ultra-lightweight CFRP-foam sandwich frame structure is used in MASCOT. The highly integrated lander structure, developed by the DLR Institute of Composite Structures and Adaptive Systems in Braunschweig, consists of four external side walls; one internal vertical/middle wall, the base plate and a top plate. The middle wall is used as the main load bearing path, with the separation mechanism introducing the loads into the overall structural framework. The top-plate frame supports MASCOT's radiator. To allow late-access activities, such as the installation of the battery, the radiator has been divided into a fixed main radiator and a hatch-like removable sub-radiator. The electronics box (E-Box) is made of aluminium and provides thermal and radiation protection to all included PCBs. Integrated in the warm compartment it serves also as the structural interface for the Mobility Mechanism, the Communication Transceivers (CCOM) and the Battery Package. Thermal insulation from the main structure is realised by the use of PEEK washers.

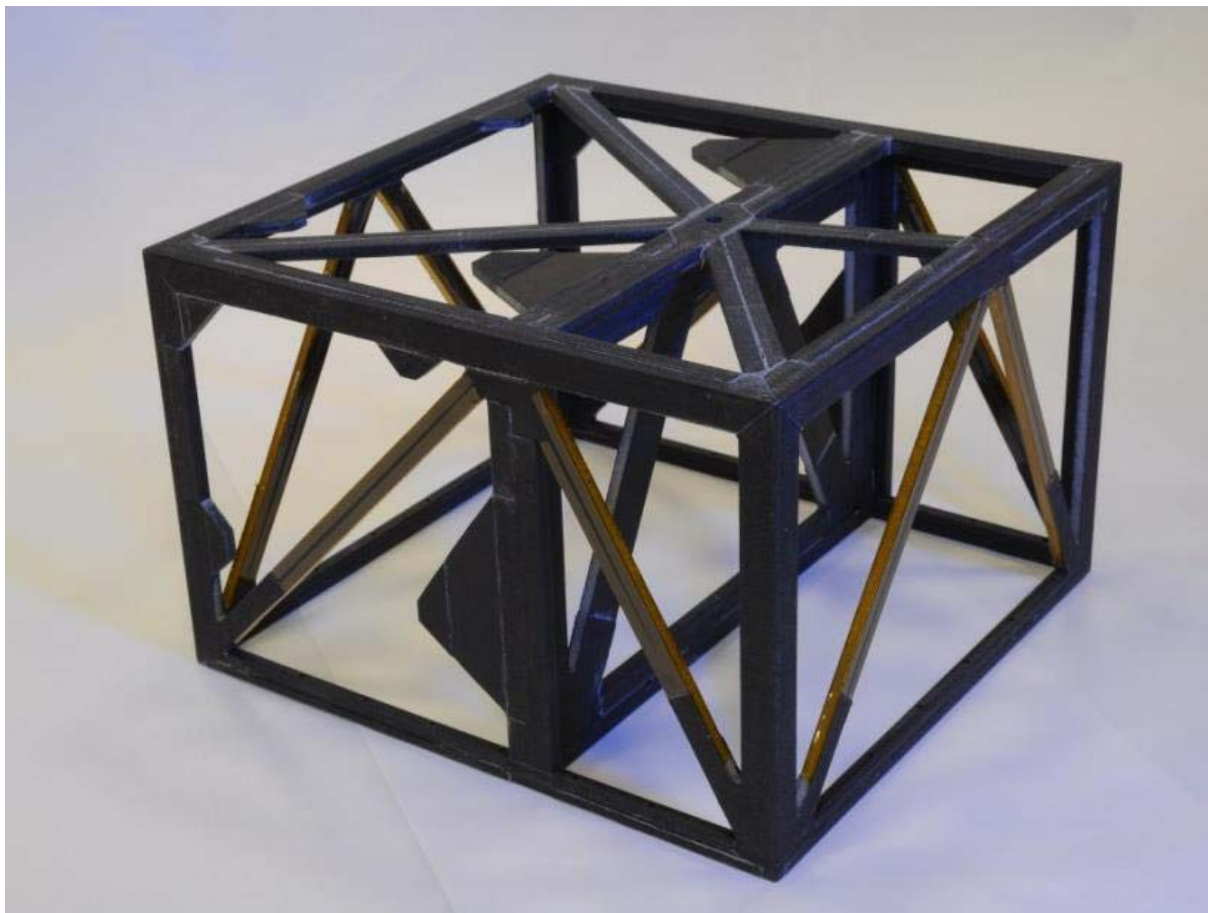


Figure 8 – MASCOT Landing Module structure STM 2.2, bottom up

Mechanical Electrical Support System Structure

The Mechanical Electrical Support System (MESS) was designed to provide the required interface functionalities to HAYABUSA2: mechanical support, push-off mechanisms, a power interface and a RF connection for data transmission during

cruise. Its main parts are: a mechanical frame which holds MASCOT in place during launch and cruise, a push-off mechanism to deploy MASCOT at the asteroid, an electrical connection to HAYABUSA2 for providing to MASCOT thermal control during cruise and electrical power during checkout activities, support for the the calibration target for MARA and CAM, and the MESS antenna to allow RF communication between HAYABUSA2 and MASCOT during cruise activities. The MESS remains attached to HAYABUSA2 during the entire mission and carries no other payload. The MESS structure is made of the same material as the MASCOT lander. CFRP struts are used again to cope with the launch loads. In order to decouple HAYABUSA2 thermally from MASCOT during cruise and to provide thermal insulation after MASCOT's deployment, the entire volume created by the struts and filled during cruise by MASCOT is surrounded by Multilayer Insulation (MLI).

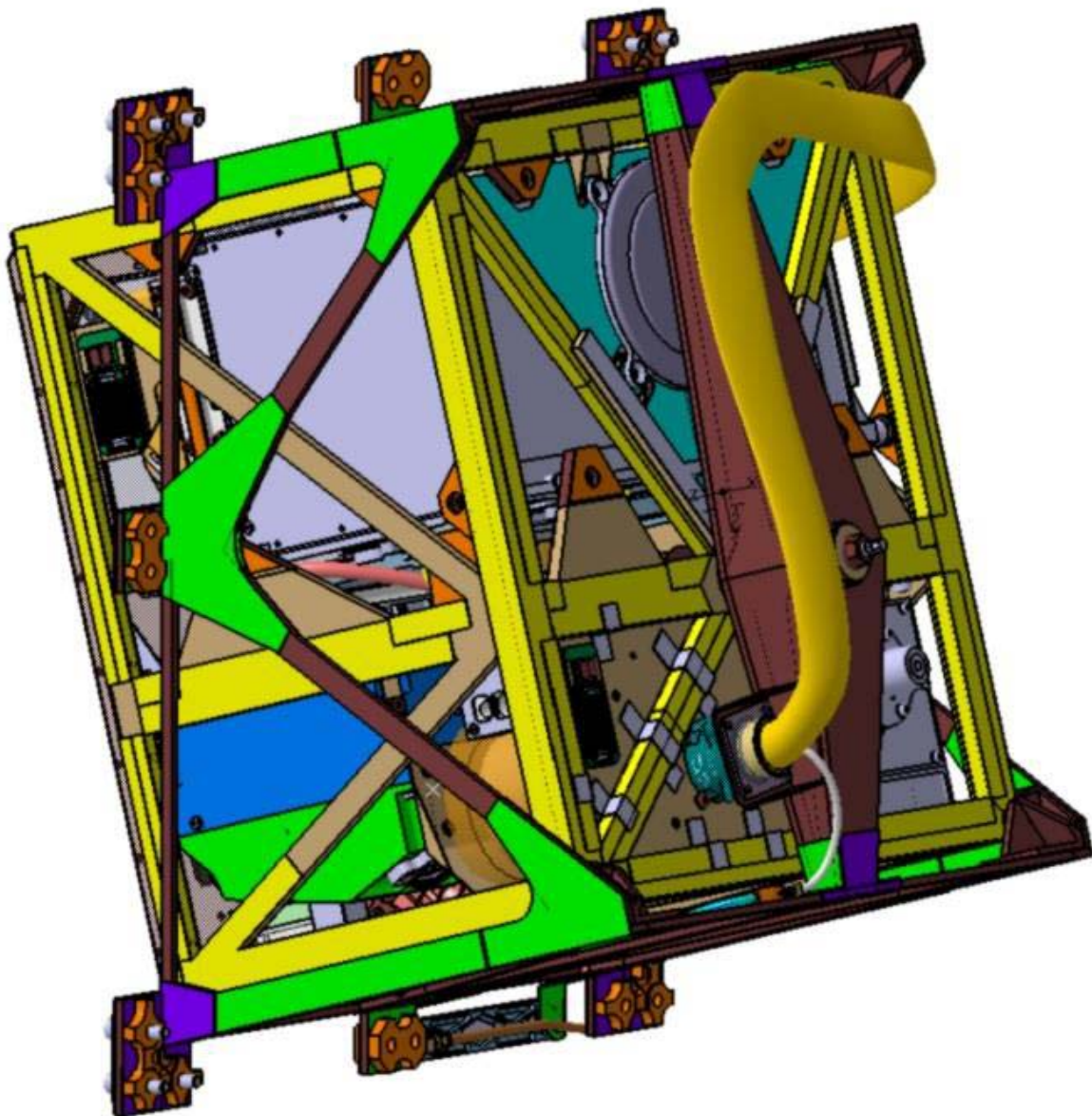


Figure 9 – MASCOT inside MESS, MLI foils omitted for clarity

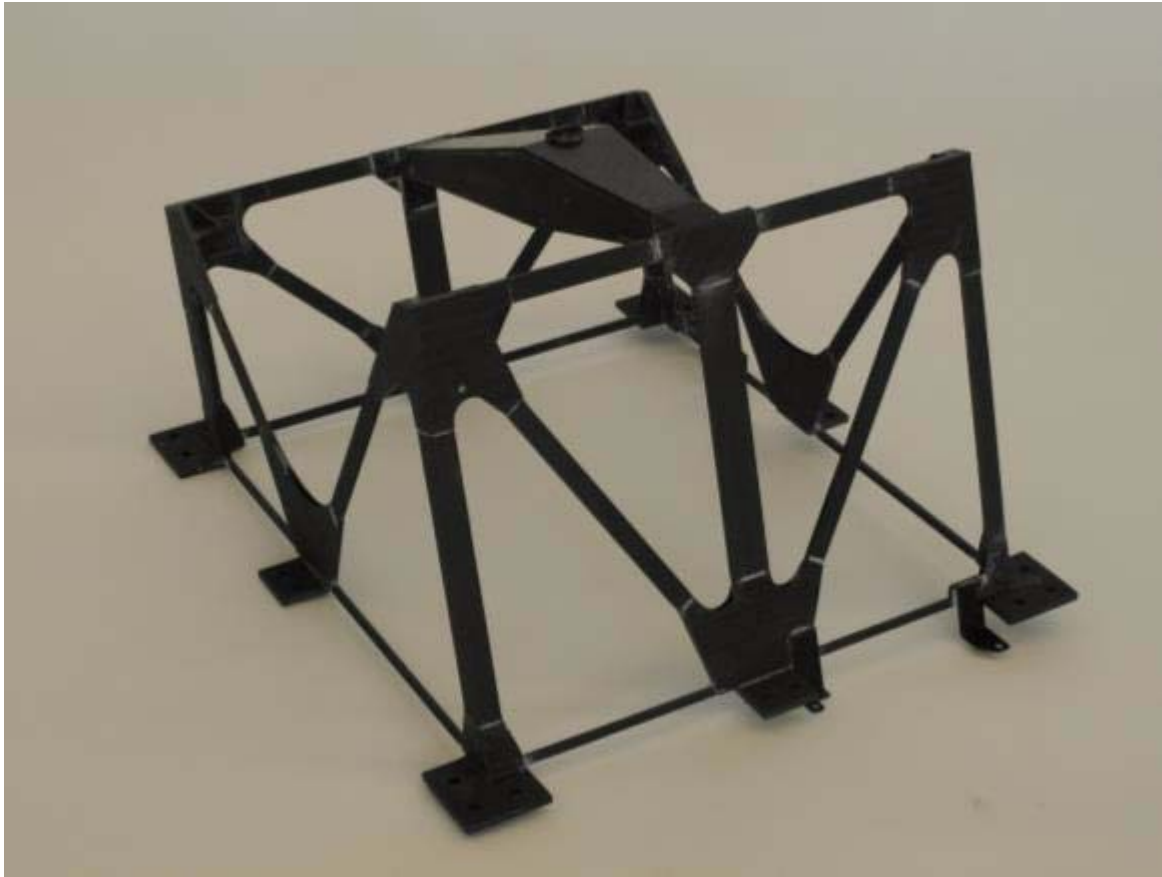


Figure 10 – MESS structure STM 2.2

Separation Mechanism

MASCOT's separation mechanism consists of a preload relief mechanism (PRM), a NEA and the push-off mechanism. The push-off mechanism uses a compressed spring and a V-shaped push-off plate to eject MASCOT from the MESS at a velocity of 0.05 m/s. The NEA, as well as the PRM, is a part of MASCOT, but controlled by HAYABUSA2. During launch and cruise MASCOT is held by a NEA. The mechanism is mounted to the internal wall and provides a clamping force of 2.5 kN, ensuring a firm connection between MASCOT and MESS at the four corner support pedestals of the MESS. After launch, the high mechanical preload force is no longer required can be reduced by about one order of magnitude by a preload relief mechanism.

Both the push-off and preload release mechanisms are designed according to ESA standards for the minimization of misalignment errors and cold welding risk. The functionality of the separation mechanism was proven in dedicated drop tower campaigns at nearby ZARM, Bremen.

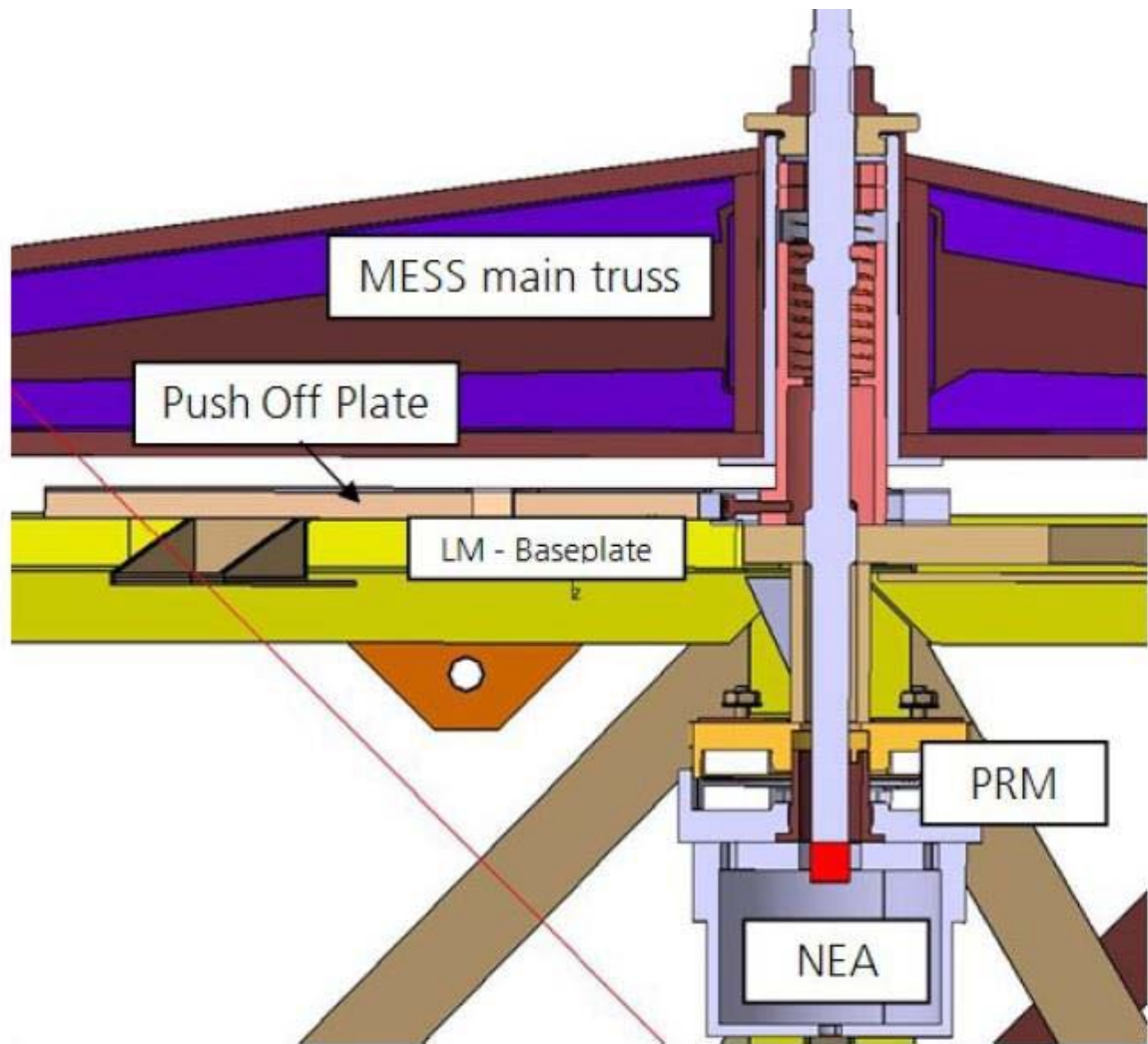


Figure 11 – MASCOT separation mechanism with Preload Relief Mechanism and Push-Off Mechanism

Preload Relief Mechanism

The PRM is used to reduce the high stored preload of 2.5 kN to less than 200 N. During launch the high preload will assure that MASCOT stays in place and does not tilt or bounce within the MESS due to launch loads and vibrations. But during MASCOT's deployment the high preload could lead to a too high ejection velocity which could cause MASCOT to bounce off the asteroid and drift off into space. The PRM is composed of two thermoplastic disks which deform when heated to relax the spring tension. The preload relief activation will be part of the first upcoming activities after launch. It is powered and controlled by MASCOT while it is active and supplied by HAYABUSA2 during cruise check-out activities.

As the PRM is a new development and has no heritage it has undergone an extensive qualification program comprising environmental and functional unit level tests.

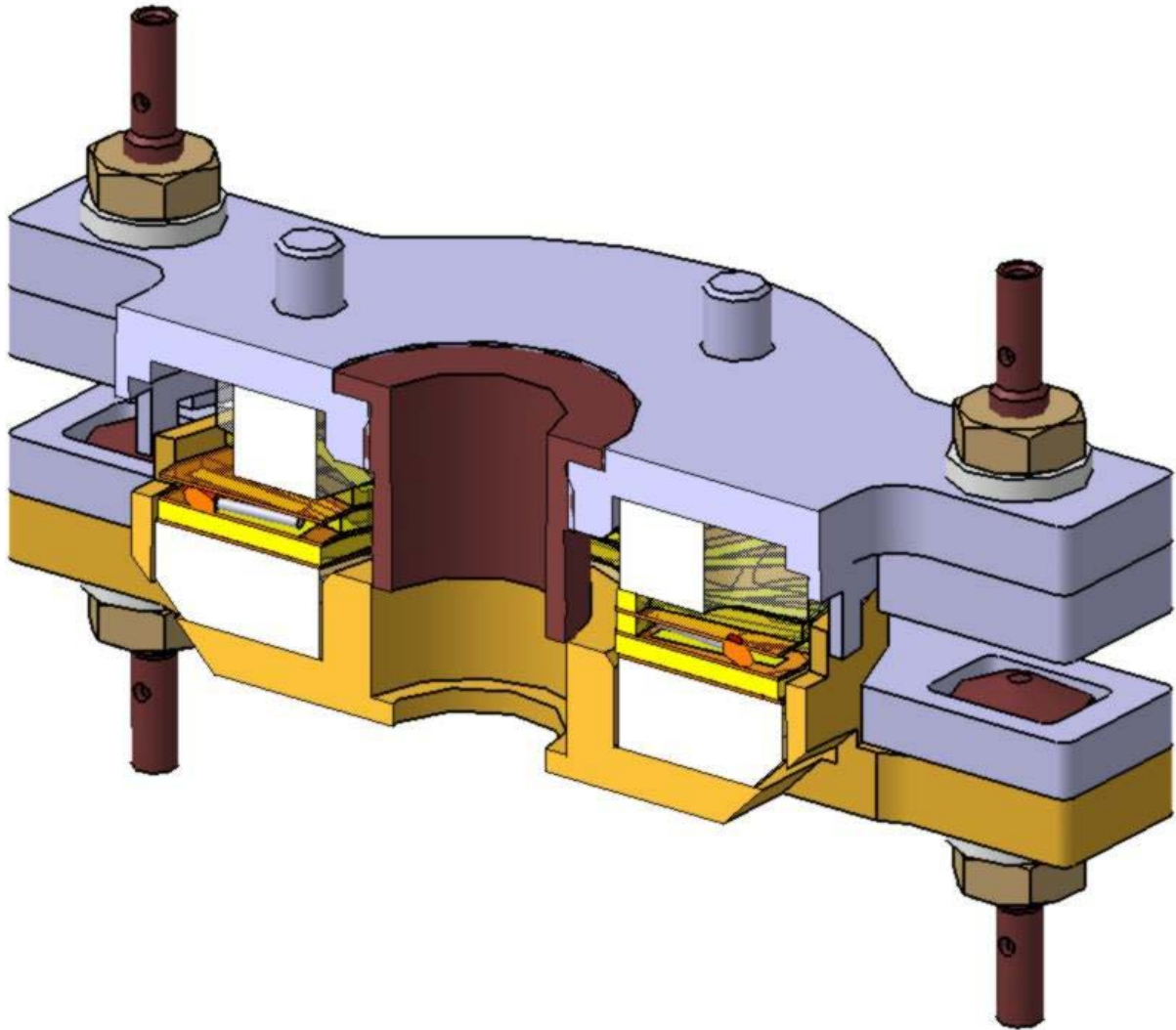


Figure 12 – Preload Relief Mechanism

Electrical Umbilical Connection

MASCOT is electrically connected with HAYABUSA2 via an umbilical that runs from HAYABUSA2 through the MESS to MASCOT. The umbilical connector which connects MESS and MASCOT across the separation plane is based on a MIL standard Matrix KJ connector with gold-plated spring-loaded pins and concave platinum counter faces on the opposing sides. Even though the design has heritage from Rosetta Philae the umbilical connector has undergone an extensive qualification program including environmental and functional unit level tests to assure proper functionality of this mission critical component.

Mobility

MASCOT needs the capability to upright itself when it lands on any side other than the baseplate since it has no attitude control in free-fall. To explore the asteroid's surface properties with confidence it also needs to change the location on the asteroid surface via hopping.

MASCOT Mobility Concept

Several scientific instruments onboard of MASCOT need nominal orientation and additionally there is the need for relocation on asteroid surface. Therefore a small and lightweight mobility unit was designed by DLR Robotics and Mechatronics Center. By means of applying a momentum pulse to the MASCOT structure the system is able to hop and set upright in unknown terrain. Other mobility principles suffer from low contact forces resulting from the low gravity and unknown environmental conditions. The momentum pulse is generated by a small brushless DC motor that drives an eccentric arm with 120 g eccentric mass. To achieve highest reliability, redundant concepts were realized as much as possible. The Mobility electronics is set up completely cold redundant with the OBC switching the redundancy paths on and off via the power supply. Details on this topology can be seen in **Fehler! Verweisquelle konnte nicht gefunden werden..** Due to mass and space limitations the actuator hardware cannot be realized redundant. The following figure shows the PCB with the motor unit.

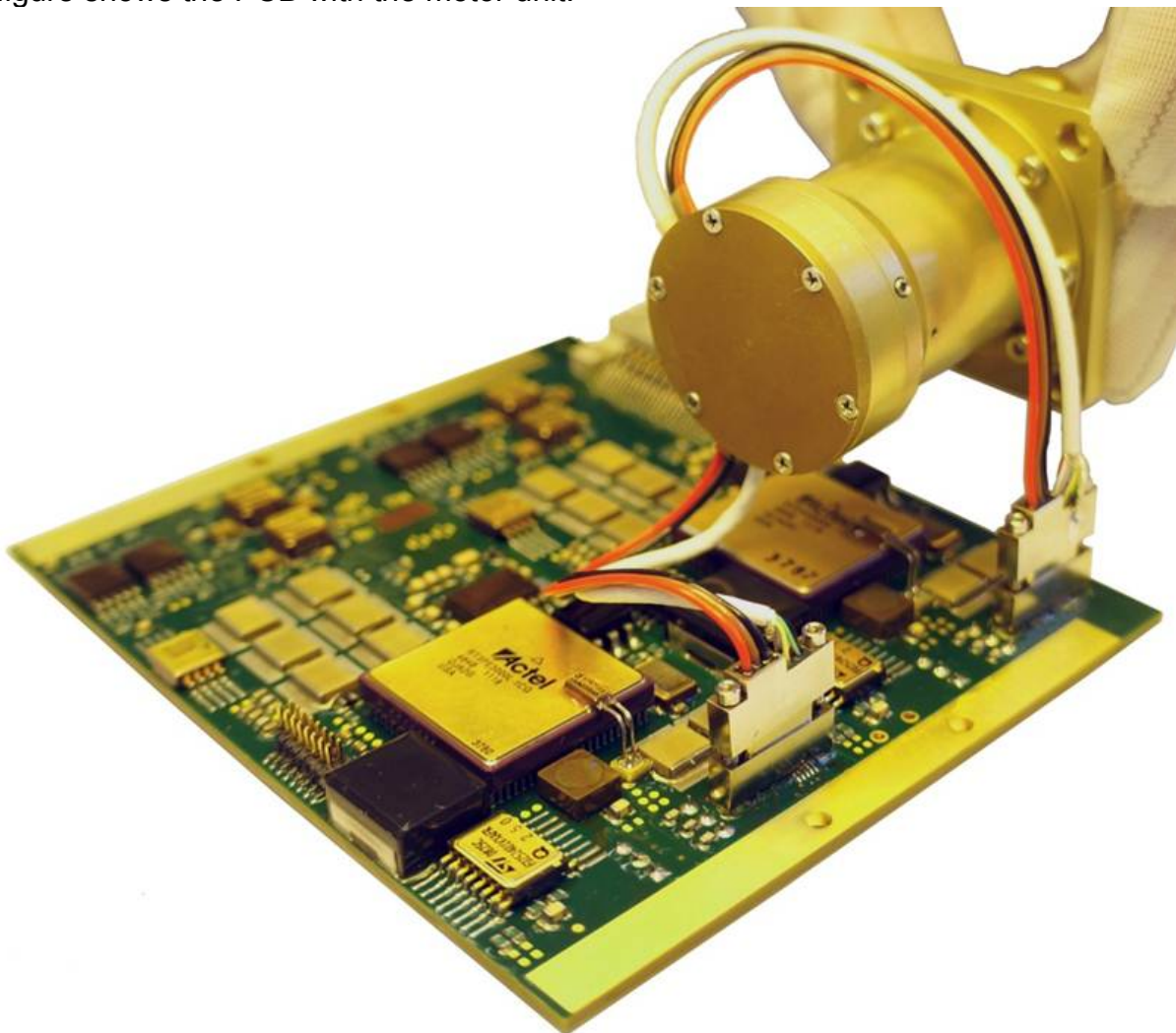


Figure 13: Mobility Unit (MobUnit) with controller PCB (MobCon).

Mobility Mechanics

A harmonic drive gearbox is integrated into the motor housing. This solution is very compact and allows high gear ratios with only few mechanical parts. This results in high reliability and high power density combined with low weight and compact design. The figure below shows some details of the mobility unit in CAD images. The fully non-redundant unit is mounted with its flange to the MASCOT E-Box with four screws. The eccentric arm is outside of the E-Box and the motor with hall sensor PCB is inside close to the motion controller PCB.

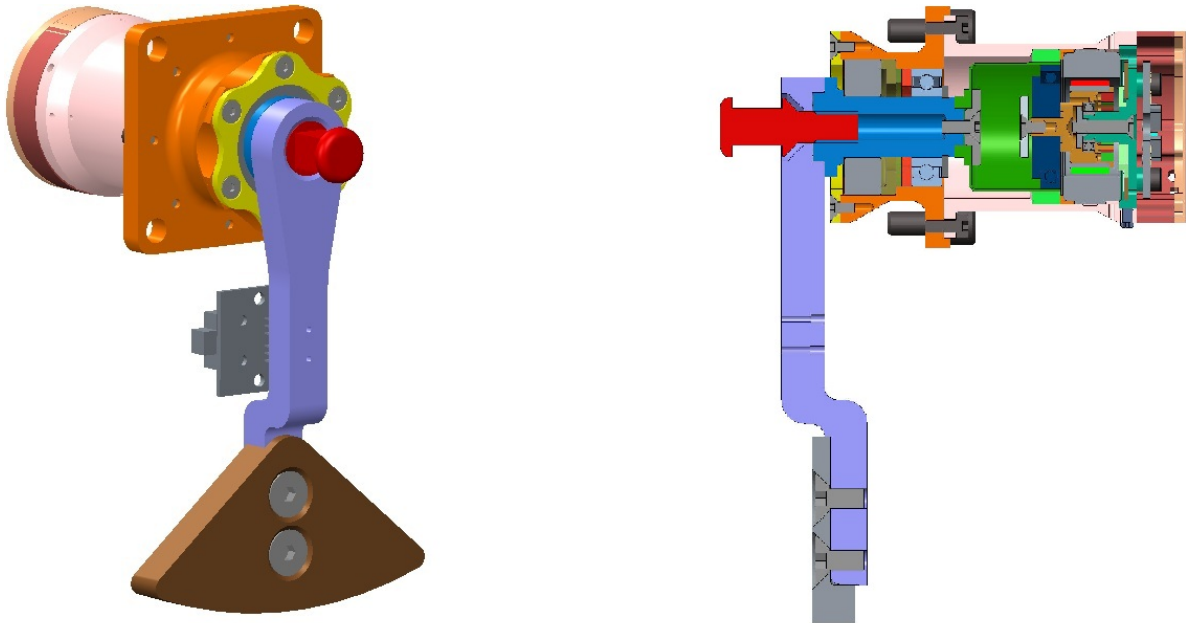


Figure 14: CAD images of the MobUnit consisting of motor, gearing, PCB with hall sensors and bearing with eccentric arm.

To cope with the rough environmental conditions and to prevent cold welding effects, the harmonic drive gear teeth and the ball bearings are coated with MoS_2 . In the harmonic drive wave-generator bearings Dicronite coating was applied. The MobUnit bearings are hybrid ball-bearings with a combination of stainless-steel rings, PEEK bearing cages and ceramic balls. The mechanical design was optimized regarding reliability, weight and space limitations, eigenfrequency of the unit and thermal aspects. The shape of the eccentric arm needed to be adapted to save space for other MASCOT instruments. The figure below shows a photo of the final FM assembly.

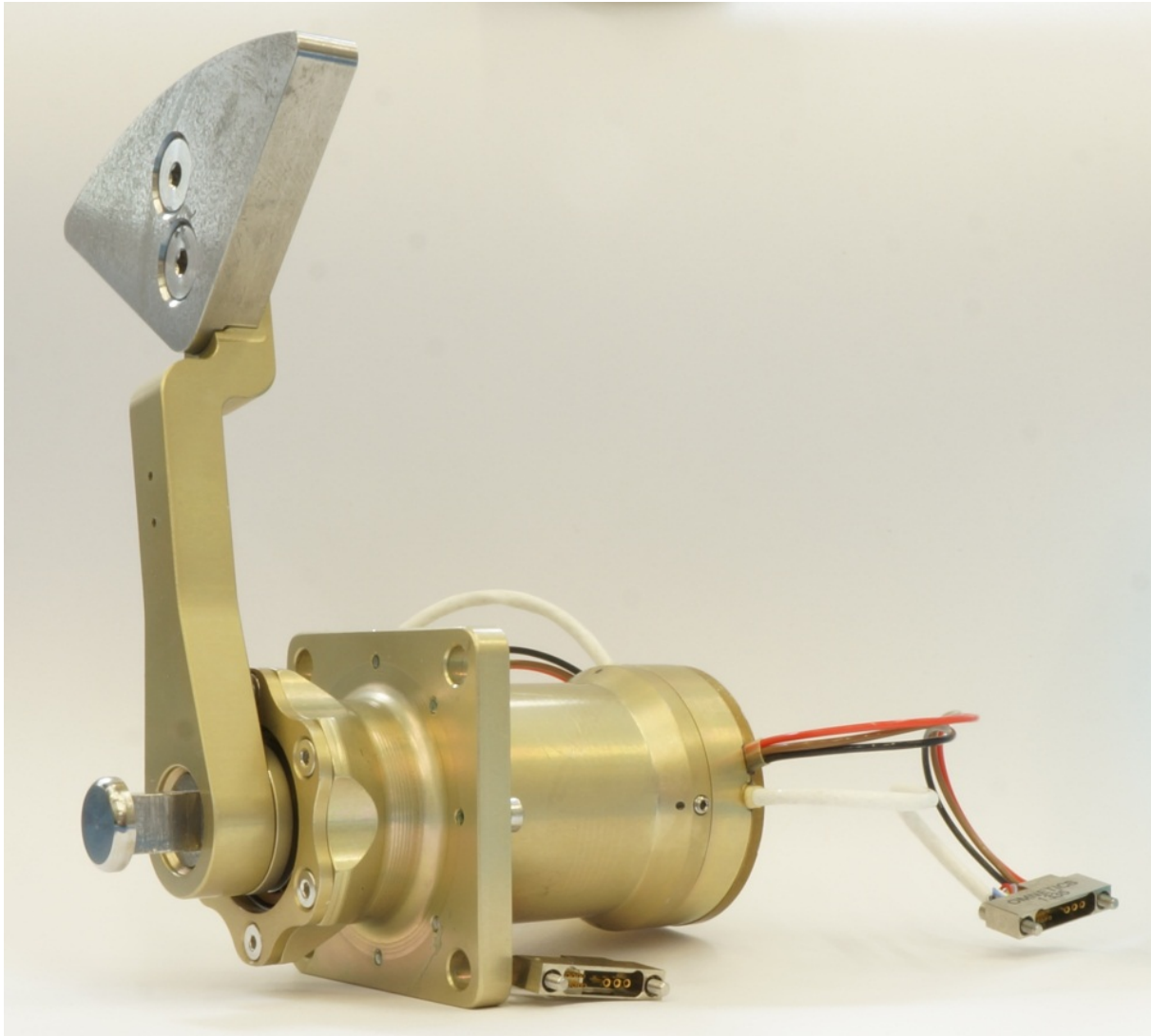


Figure 15: Photo of MobUnit FM.

Mobility Electronics

Like the mechanics also the electronics were designed to withstand the expected rough environment, therefore this component was designed with two redundant signal paths. Since there is only one motor a coupling network was developed to overcome malfunctions and prevent the working path from being influenced by the damaged path. The figure below shows the MobCon motion controller PCB which contains a six-step motion controller. On the FPGA there is a control algorithm implemented that ensures the movement of the eccentric arm with given parameters to generate a defined momentum pulse. Depending on the MASCOT orientation and the desired movement, parameters are taken from a lookup table. The FPGA calculates the absolute position of the eccentric arm by means of the motor hall signals and an additional reference hall sensor that detects reference magnets inserted in the eccentric arm. Also data collection for housekeeping and safety features as well as OBC communication via RS422 is coordinated by FPGA.

The movement parameters are optimized offline by use of a Simpack multibody simulation model. The Robotics and Mechatronics Department designed the hardware while the simulation was done by Department for System Dynamics and Control. The OBC gets the complete GNC information and sends the appropriate

movement parameters to the MobCon. The motion controller PCB ensures the desired behavior and gives feedback to the OBC. The movement is recorded by MobCon and can be sent to ground for further analysis offline.

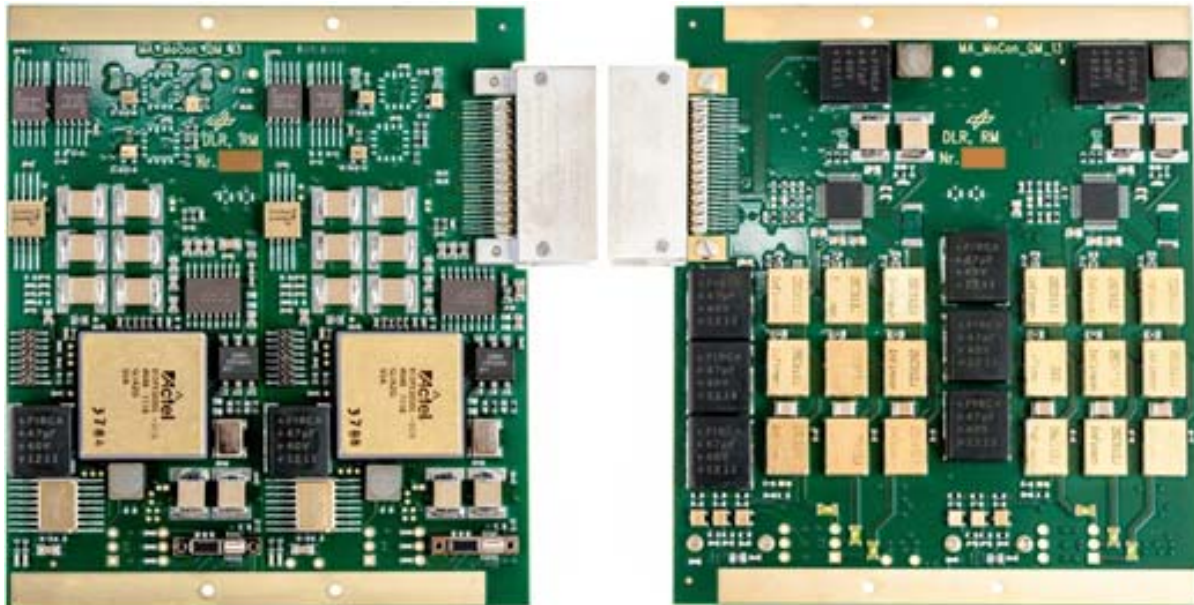


Figure 16: FM of MobCon motion controller PCB (left: top side, right: bottom side).

The electronics was designed to withstand a total ionizing dose TID of 10 kRad while the expected TID inside of MASCOT E-Box is 4.2 kRad. To increase reliability radiation hard components were used as much as possible. The FPGA is a flash based Microsemi FPGA from the RT3 series in ceramic column grid array CCGA package. The power MOSFETs (BUY25CSJ) were developed by Infineon based on DLR/ESA contracts (50PS0301, 50PS0409, 50PS0601, 50PS0903) within the European Component Initiative (ECI). The MOSFETs are located in Figure on the bottom side. For each redundancy path six MOSFETs were used to drive the three motor phases and three to ensure the coupling of the two redundancy levels.

Due to the small PCB envelope size of 95 mm x 105 mm and weight of 200 g it was not possible to use radiation hardened components only. Therefore a Spin-In of a BLDC motor controller and MOSFET driver for automotive application was used. Radiation, proton and ion tests were conducted beforehand to assure sufficient behavior in rough environment.

Summary of Mobility concept

The developed mechatronics consists of a tightly packed motion controller PCB and a motor unit that was developed to work in rough environment. The drive unit can apply 3 Nm output torque at a cylindrical size of 31 mm diameter with 64 mm length and a weight of 166 g. The PCB power output is 12 V and 4 A nominal. The mobility unit was extensively tested during the various checkouts also while attached to HAYABUSA2. The eccentric arm was able to move with a desired trajectory showing nominal sensor values in the recorded data.

Mobility Operational Concept

The acceleration and deceleration as well as the start and stop positions of the excenter arm are controlled parameters which are used to execute short flips for the uprighting with a low force implied and long distance hops to change the location with a strong force implied. The parameters of the excenter rotation impulse applied determine the departure velocity, hence the flight duration and thus the distance obtained. An off-axis alignment and imperfections in the underlying soil will ensure that 6-degree rotation is possible for uprighting. However, successful uprighting is likely to require several attempts as the result approximates a random walk of the orientation vector. The mobility mechanism design minimizes risk by relying on only a single point of actuation and avoiding the abrasive dust contamination problems and potential jamming by pebbles facing external mechanisms. It is also relatively tolerant regarding a wide spectrum of possible soil characteristics. By commanding appropriate actuation parameters, the radial components of any uprighting or hopping move are restricted to less than half the escape velocity of the asteroid to ensure safe operation. Uprighting should be performed in less than 30 minutes, while hopping at distances of up to 220 m should be possible within 60 minutes.

Even though no lander before has used such a mobility mechanism to perform surface operations this innovative design does offer some clear advantages. As the gravitational conditions on the asteroid can be hardly simulated on Earth, the principal functionality of the mobility mechanism was verified through a zero-g flight test campaign for the uprighting and through numerical simulations for the hopping.

Thermal Control and the Asteroid Environment

A combined semi-passive/passive thermal control concept is used in MASCOT. During cruise, MLI and a redundant heater powered by HAYABUSA2 keeps the battery in its nominal non-operational low-temperature long-term cold storage range. Heat from conducted out from the battery heater will also be used to keep the electronics at a safe temperature. Two additional heater sets are connected open-loop in parallel to the battery heater further improve and adjust this heat transfer to the E-Box and one instrument, MicrOmega. The heater power is configured such that the nominal cruise duty cycle is low, thus allowing the use of a single heater in the event of failure. During cruise checkouts or before deployment, the temperature setpoint of the battery heater will be raised and hence duty cycle will be increased to warm the components to a suitable switch-on temperature.

The main radiative means of heat removal is via the MASCOT top-plate, which is split into two parts: the larger being the electronics radiator, and the smaller, the (removable) battery radiator. The electronics radiator is connected to the electronics via redundant heat pipes. The smaller radiator is connected to the battery by four fixed metal rods. The thermo-optical properties of the other surfaces have been selected mainly for thermal control reasons.

For the on-asteroid phase, the focus shifts to the removal of heat from the hot components. To reduce risk in development and operations on the surface, the system is now passive, i.e. no active or actively controlled heating or cooling is used on system level. Since the selected landing site for the first landing can not be reached precisely due to the ballistic descent, a wide range of surface temperatures has to be anticipated. Depending on the seasons of the asteroid which rotates about a highly inclined axis on an eccentric orbit, the *average* daily temperature on the

surface can easily exceed spacecraft operational limits. Even along the equator it varies between -55 and +50 °C [5]. The superimposed diurnal cycle which also depends on surface thermal inertia limits the accessible area for the first landing. Since relocation hops can not be targeted at all except for some control of the momentum imparted, it is possible that the mission ends due to thermal rather than other factors.

Even though such a semi-passive/passive thermal control system offers many advantages in reliability and complexity we experienced that developing such a system to the point at which it works under a wide range of thermal conditions is quite challenging as careful adjustment of many parameters is required and the choice of those which can be adjusted can be quite limited in some cases. Thus, the development turned out to be more time consuming than expected and some dedicated characterization testing of MASCOT's thermal control system continued after launch on the flight spare model (FS) and selected subsystems.

The thermal design of the lander represented one of the main challenges of the whole project because of multiple constraints, depending on the mission phase, mass, power and free space available, for example: low heat exchange between the lander and the exterior (including the main spacecraft) in cruise (maximum insulation), necessity to remove all the heat dissipated by the internal payloads and electronic boards during operations on asteroid surface.

MASCOT, notwithstanding its small size, is equipped with heat-pipe system, MLI blankets and heaters. After the trade-off analysis and selecting variable conductance heat pipes as baseline, a development phase was undertaken by the partners for manufacturing, testing, thermal characterization and analytical modelling in order to match the thermal requirements.

Heaters are used to assure the survival of the most delicate parts of the lander during cold cruise phases: the battery cells (primary battery on-board), the electronic boards and the main payload.

MLI blankets are used where space is available: to partially insulate the Ebox from the rest of the lander creating a warm compartment, and between the lander and the main spacecraft to reduce the heat exchange with it during cruise to satisfy the requirements.

The whole system sustained multiple thermal vacuum campaigns, followed by thermal model correlation activities.

Communication

Communication is established via relay by the mothership. HAYABUSA2 will hover at 20 km attitude during most of the MASCOT mission, and will stay always on the sunlit side of the asteroid and facing Earth. As such, no communications are possible with MASCOT during night time, meaning that the communications and science operations need to be sized for daylight transmission only. Patch antennae on the top and bottom surfaces provide quasi-omnidirectional coverage in order to communicate with HAYABUSA2 in any tumbling and landed orientation.

Communications during cruise is enabled through an additional antenna on the MESS which is connected to HAYABUSA2. All three antennas as well as the corresponding RF-cables and couplers are provided by CNES.

Due to the short surface lifetime, live data exchange with Earth is extremely limited, requiring almost complete autonomy of the lander. The communication architecture

is based on a redundant Child-Communication transceiver (CCOM) transceiver provided by JAXA which exchanges data with the Parent-Communication transceiver (PCOM) on HAYABUSA2. This system will be shared with the three MINERVA landers based on a half-duplex communication scheme using Time division multiple access (TDMA) methods. All communications with HAYABUSA2 uses UHF frequencies at an uplink rate of 40kbps. This allows for a considerable amount of housekeeping and science data to be sent, but still can constitute a bottleneck for science return from the mission depending on the line of sight situation between landers and mothership. Hence, payload data are prioritised in the uplink to ensure that the maximum amount of science data is received on Earth.

Autonomy

Since all telemetry and commands will be relayed to and from ground via HAYABUSA2 during the on-asteroid phase and the minimum turnaround time for ground intervention is determined by the 16 minute delay per transmission, all nominal operations and a limited set of failure responses, need to be handled by onboard autonomy. This onboard autonomy needs to be highly robust and well-tested, as it is one of the most critical aspects on the on-asteroid operation. To save time in the event of failure, MASCOT must be able to perform limited Failure Detection and Recovery (FDIR) measures. Ground control is only expected to have to interfere in the case of serious malfunction. In all other cases, a large degree of autonomy is required to ensure the best use of the limited lifetime for surface science.

As the surface operating conditions remain hardly predictable and Ground Segment intervention is limited, MASCOT needs to perform its tasks highly autonomously to react and adjust its operations sequence. This task is done by the MASCOT Autonomy Manager, running as an application on the Onboard Computer (OBC). Its main functions are to provide a timer and sequencer for coordinating the timeline of events, to prioritize stored data, initiate site changes and to enact attitude corrections. The MAM algorithm has been tested in a simulation framework before it was implemented into the OBC Flight SW for extensive end-to-end tests.

OBC

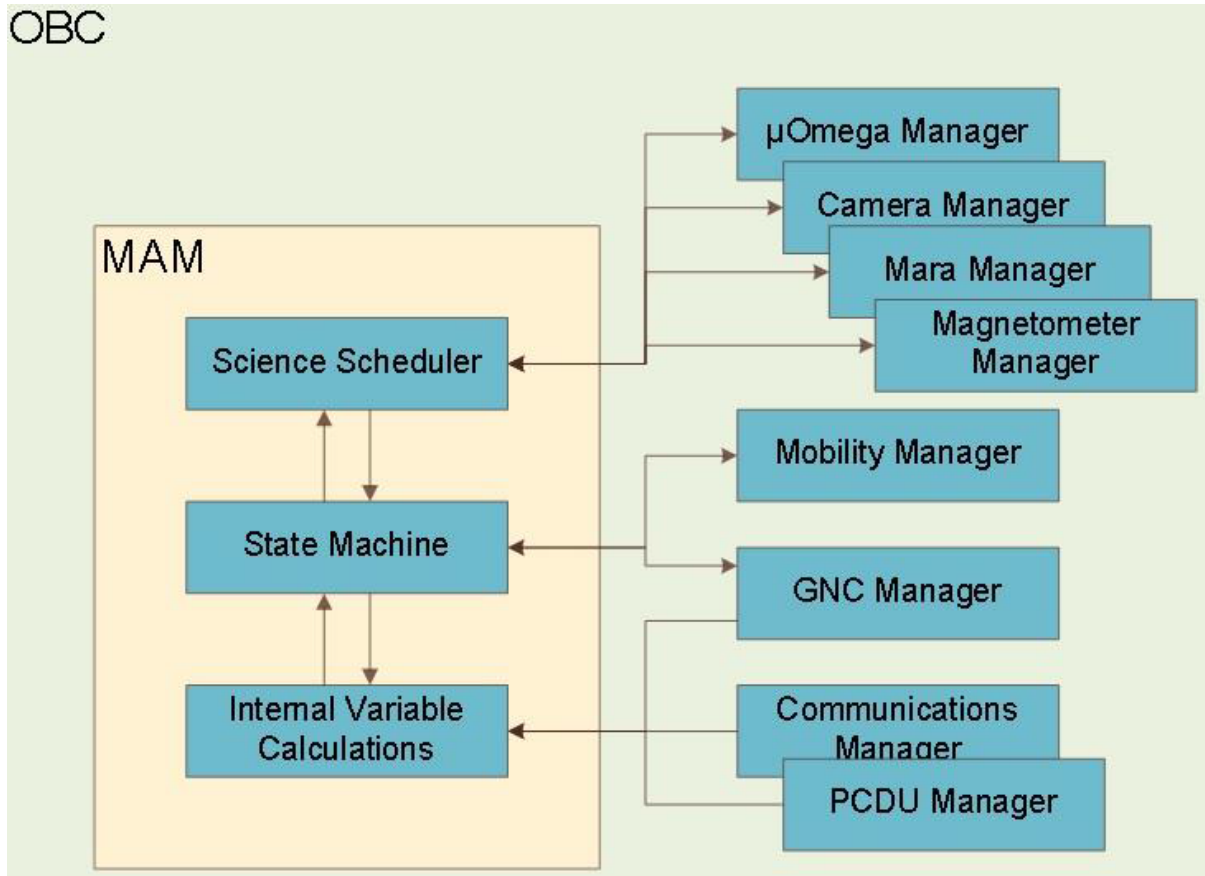


Figure 17 – Implementation of the MASCOT Autonomy Manager in the OBC software

Onboard Data Handling

The high level of required onboard autonomy and failure tolerance has led to an onboard computer (OBC) design which is dual redundant and capable to deal with health checking and providing FDIR processes in the event of failure. Beyond that it is responsible for gathering, compressing and storing the scientific data. MASCOT's OBC consists of four boards in total which are located in the electronics-box. The two CPU-boards (main and redundant) are equipped with the Aeroflex Dual Core LEON3FT GR712RC processor. The two I/O-boards (main and redundant) provide interfaces to all of MASCOT's subsystems and payloads, and are cross-trapped with the CPU boards. Furthermore, they are equipped with NAND FLASH mass memory to store over 2 Gbit of science data.

The cold redundant CPU as well as the hot redundant I/O-boards will be operated in a worker-monitor redundancy, whereby the functionality of the "worker" board is constantly supervised by the "monitor". The switch-over logic runs on an FPGA on the hot redundant I/O-boards.

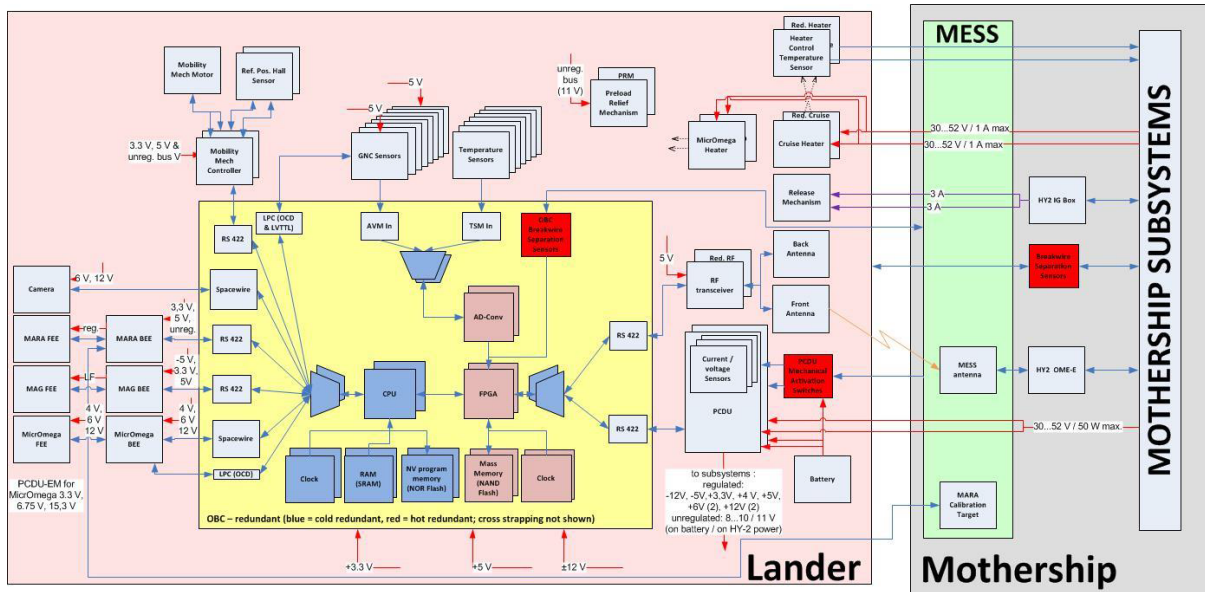


Figure 18 – Functional Block Diagram of MASCOT and MESS

Orientation Determination, Navigation and Control (GNC)

In order to determine MASCOT's motion state and orientation on the asteroid surface different kinds of sensors have been investigated. At first, the use of active optical distance sensors which would cover all directions was preferred but this solution could not be accommodated within the tight constraints given for the system design. Therefore alternative solutions were investigated including thermal orientation sensors, simpler active optical proximity sensors (OPS), and photoelectric cells (PEC) based on Triple Junction photovoltaic power generation cells from AZUR Space. In the end a design was chosen which comprises of 5 OPS and 6 PCB-mounted PECs to provide reference information from the local surface topology and solar direction respectively. This information is then passed through a filter to determine which side of MASCOT is pointing to the surface. The thermal orientation sensors have not been selected as a prime orientation sensor mainly due to technical maturity considerations, however two have been integrated as a technology experiment and small conventional thermal sensors were mounted for reference near the PECs on the respective surfaces. Even though it was possible to find two alternative compact sensor types, it was quite difficult to accommodate the five OPS as the assigned envelope has also been changed which is a good example for the risks in a constraint engineering environment.

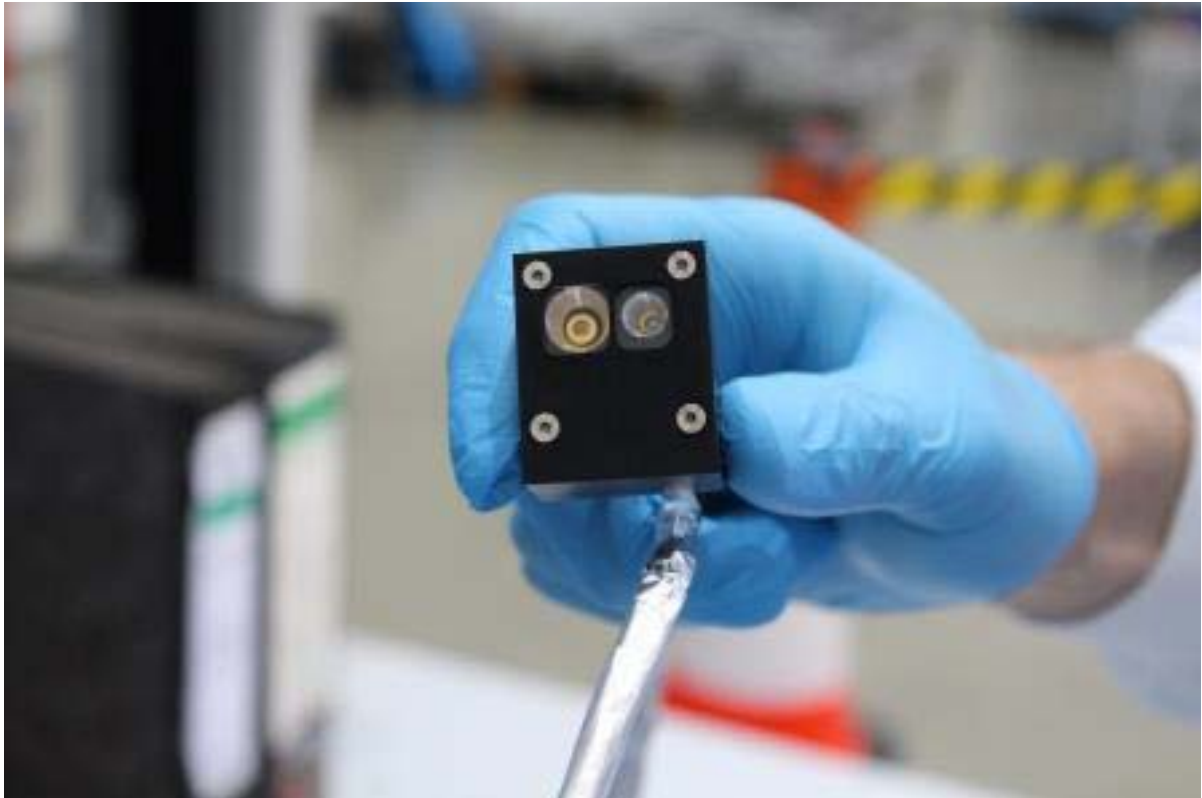


Figure 19 – Optical Proximity Sensor (EQM)

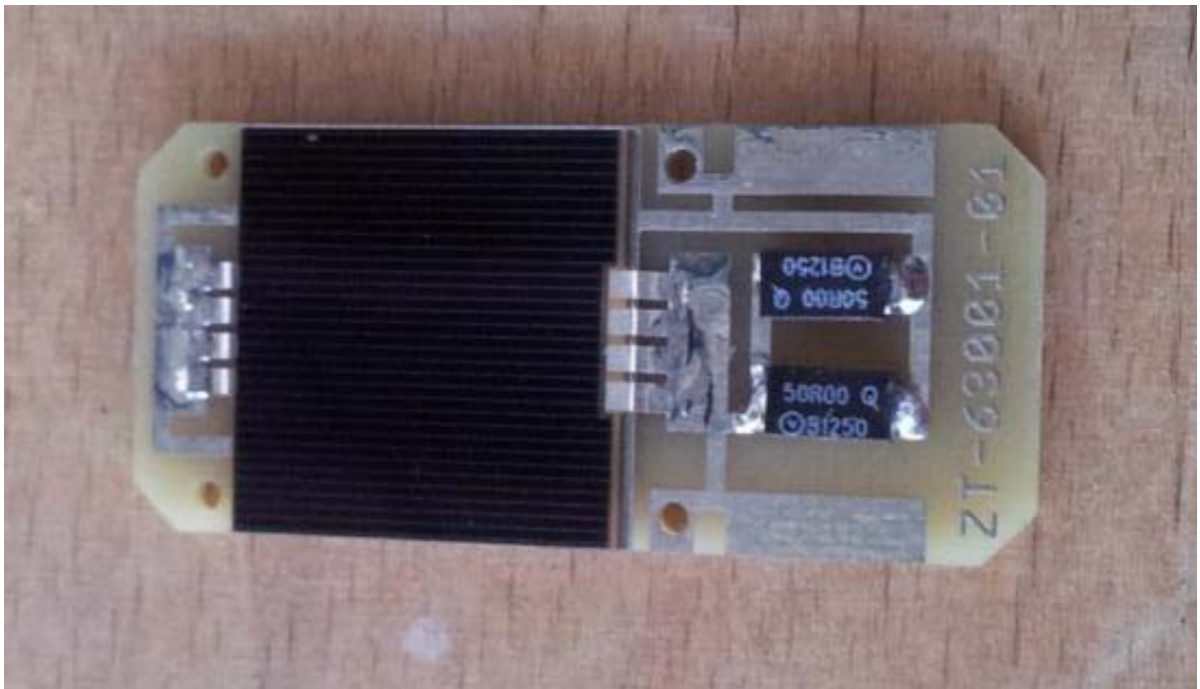


Figure 20 – Photo Electric Cell illumination sensor

Orientation Temperature Sensors (OTS) Experiment

One sensor that was considered for the GNC system of MASCOT are the Orientation Temperature Sensors (OTS), shown in the figure below. They were intended to provide orientation information by measuring the temperature on multiple sides of the lander, based on external influences, present on the surface of 1999 JU₃. After the selection of optical sensors for the operational GNC, two OTS were retained on the bottom side of MASCOT as a technology experiment.

These sensors use a resistance temperature device (RTD) The design of the OTS hereby provides sufficient isolation from internal influences, originating from MASCOT itself.



Figure 21: Flight model (FM) of the black (right) and soil (left) type OTS

To provide accurate temperature readings the RTD is attached to a sensor-plate (SP) which has well defined optical properties (absorptance α , emittance ϵ), and ensures a uniform temperature distribution over its entire surface area. The SP is isolated from MASCOT by a MLI which minimizes heat transfer to the SP from the back of the OTS. Attachment of the OTS to MASCOT is provided by a face-sheet (FS). The FS also provides lateral thermal isolation between the SP and the attachment points.

Low conductance wiring is used to minimize heat transfer to the RTD through the sensor's electrical wiring. The figure below shows a schematic of the OTS.

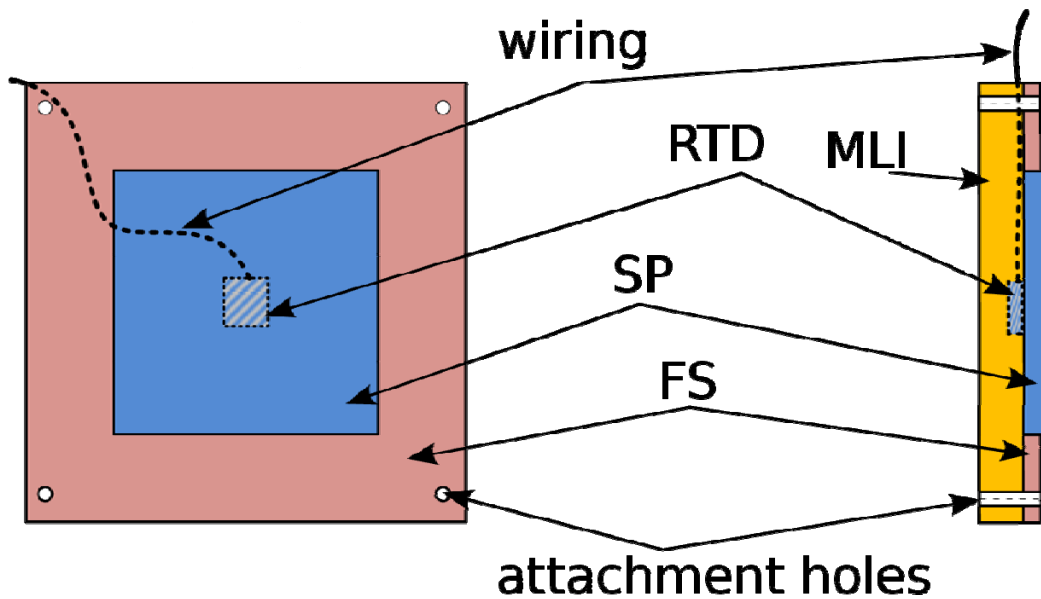


Figure 22: Schematic, showing the top and side view of the OTS and its components.

Different optical coatings for the SP have been investigated, each with distinctive optical properties. Investigations have been made to evaluate each sensor type based on its performance to provide temperature readings that can be used to determine the attitude of MASCOT on the asteroid surface.

Extensive thermal-vacuum testing and simulation of the OTS has been undertaken and attitude determination determination concepts based on the use of one or two OTS on each side of MASCOT were evaluated for their performance. A more detailed overview is provided by [13], with a detailed description of the OTS development and testing available in [14].

One observed limitation of the sensors is the slower reaction time, compared with optical sensors such as the PECs which can lead to a required stabilization time of up to 20 min under worst case conditions. While such a long time is unlikely to occur during an actual mission scenario, the unknown orientation of MASCOT during its fall to the asteroid surface, and the limited lifetime of MASCOT, together with the availability of faster sensor alternatives has led to the OTS not being included in the final GNC concept of MASCOT.

However, one set of sensors, consisting of one black and one soil type OTS has been included in the final FM design of MASCOT, as shown in the next figure.

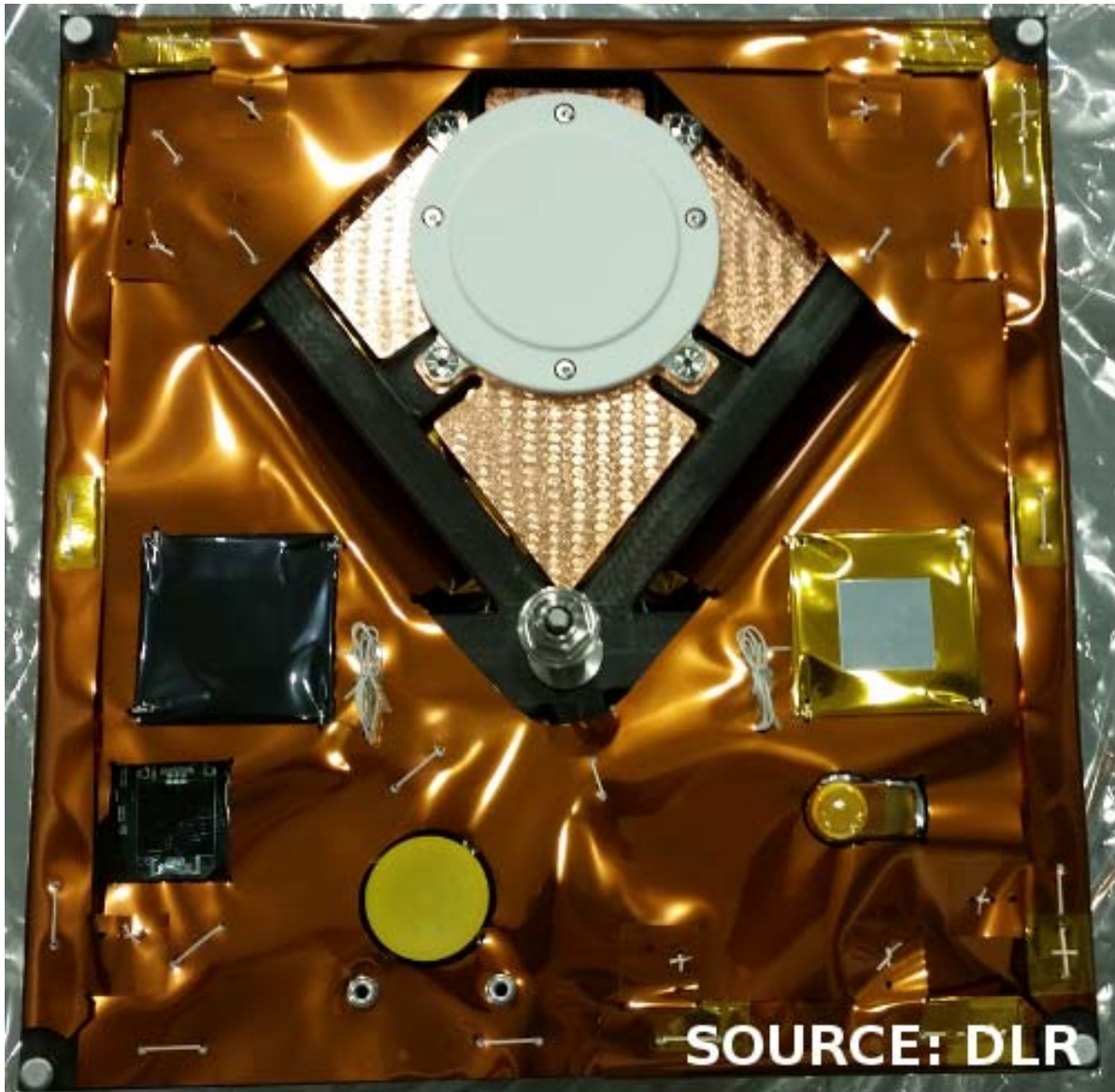


Figure 23: FM of the black (left) and soil (right) type OTS, attached to the MASCOT FM.

This provides an opportunity to evaluate the developed attitude determination concepts and sensor performance during an actual mission, for use in future missions, as an a lightweight, robots and low-cost alternative of other sensors. A direct comparison with the MASCOT GNC sensors – especially the photoelectric cell sensors (PEC) – is hereby possible.

Moreover, the OTS can also be used to gather additional science data about the thermal environment on the surface of 1999 JU₃. Based on the location of the OTS on the –Z side of MASCOT, thermal properties and subsurface temperatures of the asteroid soil can be investigated as well. In this aspect, they are supported by an array of conventional Pt1000 chip type temperature sensors which are co-located with the PEC sensors on each side of MASCOT, mostly in pairs.

SYSTEM ENGINEERING & AIV – CONCURRENT & CONSTRAINTS-DRIVEN

Strict mission requirements, a harsh environment at the landing site and short development time have led to a constraint driven system engineering and concurrent AIV approach in order to realize the mission.

In order to be accommodated aboard HAYABUSA2, MASCOT had to fit into a volume of $\sim 0.3 \times 0.3 \times 0.2 \text{ m}^3$ and a mass limit is set strictly at $\sim 11 \text{ kg}$. These constraints excluded the use of more sophisticated landing/mobility mechanisms as e.g. on PHILAE. [15] which would have resulted in a lander in the 40 kg range. [1]

In order to meet JAXA's requirements and still maintain sufficient resources for an effective suite of scientific payloads a simple and robust lander design with an unguided descent was selected. This necessitates an omni-directional communications system to assure communication during to the uncontrolled descent.

As HAYABUSA2 will normally not orbit but station-keep with 1999JU₃ high over its sunlit side, communications with MASCOT on the surface are not possible during the asteroid night. This means that the communications and science operations need to be sized for daylight transmission only.

Due to the long turnaround time and a short mission lifetime during the on-asteroid phase, realtime commanding access to MASCOT is so limited that its use has to be restricted to emergency cases. Thus, a large degree of autonomy is required and this onboard autonomy needs to be highly robust and well-tested, as it directly affects science operations and potentially the quality of the results obtained.

MASCOT will be exposed to a wide temperature range, with sometimes diametrically opposed requirements on the conditions during cruise and on the surface; e.g. the battery needs to be in cold storage during cruise but needs to be rather warm to deliver sufficient power after separation when active heating by HAYABUSA2 is no longer available.

In a conventional approach, spacecraft design evolves in a mostly linear fashion from mission requirements by well-defined procedures through a series of reviewed baseline designs. Development follows stakeholder requirements typically agreed on by a wider scientific community. The mission defines a suite of instruments, whose needs then shape the spacecraft bus, and it is finally mated to a dedicated launch vehicle. Later, it is operated under a custom-tailored optimized operational concept. In systems engineering, the "Vee"-model best describes this process of iterative refinement on different levels of complexity. In MASCOT, this has been handled in a similar manner, but with quite a bit of tailoring and introduced short-cuts.

With HAYABUSA2, as a successor and improved development of an already flown spacecraft, [4] being already in Phase B when MASCOT was at the end of Phase A, interface issues became a new dimension. While this offset in design phases was not technically constrained, interfaces to the main spacecraft had to be fixed before the interior of the lander system had reached the same maturity level.

Within the given envelope, the capacity and lifetime of the battery has essentially been determined by the available mass and volume, thus the overall design process was reversed from system to subsystem level.

Behind all the activities, there was and sometimes still is a very tight schedule, before launch due to the fixed launch date, and since by the occasional need for characterization tests of the system that were not a required part of pre-launch qualification. As MASCOT's maturity level was in the beginning behind that of the main spacecraft in its own schedule, and due to the early delivery date of the FM as an instrument to the mothership, MASCOT was required to constantly race and catch up with the mothership timeline to finally overtake it.

As MASCOT development set out with what was available off the shelf at the project partners' in very heterogeneous maturity levels, the system could in the early stages not be tested as a co-evolved entity that was in all parts developed to a common pre-defined state of maturity. Hence, the rather time consuming methods of classical approaches in system engineering, integration and testing through a progression of cyclical model developments could not be applied. On the other hand, the faster protoflight approach did also seem to be not ideal, since there were – and still are – too many unknowns in the development of a spacecraft intended to go where no other has ventured before.

Hence, the development philosophy of MASCOT applied a mixture of conventional and tailored interface definition and model strategies. Design consolidation and hardware integration followed a construction set philosophy in which subsystems often followed varied approaches according to their own preferences and customs. This allows the skipping of some models, testing similar models in parallel, and also qualification on system level. However, to make system level tests valid, simulation units need to be included. [6]

In the course of designing, building and testing MASCOT, the concurrent engineering approach which is commonly only used for very early studies in Phases 0 and A was considerably expanded. Building on previous local experience in the use of the DLR Bremen Concurrent Engineering Facility (CEF) up into Phase B of the AsteroidFinder project [16][17][18] the approach was successfully extended to and used in all project phases of MASCOT so far, though sometimes without the need for the CEF as a location. (cf. [19]) In particular, a new approach of Concurrent AIV [23] was developed which is described in another paper for this conference. [24] Presently, this development is continued for MASCOT into the operations planning for the flight phase, as a welcome necessity of an organically integrated design which demands and thereby promotes a high level of system understanding with all participating partners, leading to a closely knit, robust and reliable team.

This set of experience and methods is also carried over to other projects centred at DLR Bremen such as the GOSSAMER large lightweight deployables project for large-scale photovoltaics and solar sail, [19][20] and in the form of a wider approach with Model-Based System Engineering [21][22] tools to be applied for future and follow-on studies of small landers [19][25][26] and in the CEF.

During Phase C/D in concurrent AIV, MASCOT saw on average in four major test campaigns per month in all kinds of tests, including separation testing in the ZARM drop tower just across the road from DLR's Bremen facility, shaker tests, thermal-vacuum campaigns, EMC measurements, and many functional tests. This meant that subsystem units needed to be transferred between test setups in facilities that in turn need to be booked a relatively long time in advance in MASCOT terms. As test results and lessons learned sometimes only became known briefly before the next test, and preliminary results often need further evaluation, their full application sometimes had to skip a model or testing increment and could only be fully applied to the next one after.

CONCLUSION

Despite tough technical and schedule constraints, MASCOT is now on the way aboard HAYABUSA2 towards their target asteroid where it will provide in-situ science at different locations of the asteroid surface and throughout the asteroid day of

1999JU₃, helping to characterise it as part of the mission. It is also capable of supporting key events in HAYABUSA2 very own part of mission.

Developing a lander within two years turned out to be possible by following concurrent design, development and AIT/AIV approaches, leveraging off-the-shelf and heritage knowledge, experience, designs and parts; and by restricting new developments to only a handful of mission critical components, which could not be available otherwise.

But realising MASCOT also taught us also about the inherent risks and limitations of such a fast paced approach. The compressed development schedule left little time for design iterations and little response time after failures which can always come up during testing.

In the end we managed to develop and deliver an organically integrated and within the set constraints optimized lander. The constant focus on the minimisation of mass, volume and power often guided the design and helped stringent decisionmaking by restricting the choice of options and viciously removing nice-to-haves from the discussion. MASCOT can act as a design and development methods pathfinder for projects with similar requirements in many fields.

In light of the 2015 PDC exercise scenario provided for this conference, we again see a demanding timeline coupled to the same very dynamic field of science that we hope to have contributed to for the successful exploration of 1999JU₃ by HAYABUSA2. We also hope that the methods developed for and practised in the building of MASCOT could become useful to address many other highly pressing technical challenges, beyond space.

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