EXOMARS ROVER SAMPLE HANDLING SYSTEM QM/FM DESIGN AND TESTING

*Robert Paul[1], Daniel Redlich[1], Tim Tattusch[1], Quirin Mühlbauer[1], Christiane Bergemann[1], Markus Thiel[1], Fabio Musso[2], Stephen Durrant[3]

[1]*OHB System AG, Manfred-Fuchs-Str. 1, D-82234 Weßling, Germany, E-mail: robert.paul@ohb.de*

[2]*Thales Alenia Space, Strada Antica di Collegno, 253, I-10146 Torino, Italy, E-mail: fabio.musso@thalesaleniaspace.com*

[3]*European Space research and TEchnology Centre (ESTEC), Keplerlaan 1, PO Box 299, 2200 AG Noordwijk, The Netherlands, E-mail: stephen.durrant@esa.int*

ABSTRACT

This paper presents the design and the results of the QM/FM test campaign of the four subunits of the Sample Preparation and Distribution System (SPDS) along with the lessons learned focusing on operational procedures and constraints to optimize the system and solve occurring problems.

The SPDS is developed and tested by OHB System AG as part of the rover of the European Space Agency's ExoMars Mission under subcontract to the mission prime Thales Alenia Space. The ExoMars Rover and Surface Platform planned for launch in 2020 is a large international cooperation between the European Space Agency and Roscosmos with a contribution from NASA.

The task of the SPDS is to convey drilled samples into an ultra-clean environment where these are milled, dosed and prepared in a way that allows subsequent investigation of selected grains by different optical instruments thus providing combined science.

1 INTRODUCTION

Exploring whether life ever existed, or is still present on Mars today, is one of the most exciting scientific questions of our time. Therefore, ESA, together with Roscosmos, decided to conduct the ExoMars program, which is divided into two missions: an orbiter that was successfully launched in 2016, and a lander with a rover in 2020. The rover is equipped with a drill to take sub-soil samples from a depth down to 2 m, which will be analyzed in-situ by several instruments on the rover, the so-called Pasteur payload (PPL). These are located in the Analytical Laboratory Drawer (ALD) inside the rover, namely:

- MicrOmega, a visible and IR imaging spectrometer
- Raman Laser Spectrometer (RLS)
- Mars Organic Molecule Analyzer (MOMA) consisting of a Laser Desorption Mass Spectrometer (LDMS) and a Gas Chromatography Mass Spectrometer (GC-MS), including a mechanism to interface with pyrolysis and derivatization ovens

In order for these instruments to perform their analyses accurately, the rover is equipped with the Sample Preparation and Distribution System (SPDS), which is also part of the ALD and represents one of the key components of the 2020 mission [1]. It is developed by OHB System AG as subcontractor to the mission prime Thales Alenia Space. To ensure the required cleanliness for the highly sensitive instruments, the ALD and the SPDS form an enclosed volume, the so-called Ultra-Clean Zone (UCZ), which is pressurized until the first opening on Mars to avoid contamination.

The SPDS (see Fig. 1) consists of four separate sub-systems that interact with each other to transport the sample within the UCZ. The Core Sample Handling System (CSHS, [2]) receives the sample from the rover-mounted drill and transfers it to the Crushing Station (CS), where it is crushed to a defined grain size range. The Powdered Sample Dosing and Distribution System (PSDDS, [4]) receives the powder and doses it in defined quantities to different sample receptacles, which are brought to the instruments for analysis by the Powdered Sample Handling System (PSHS, [3]).

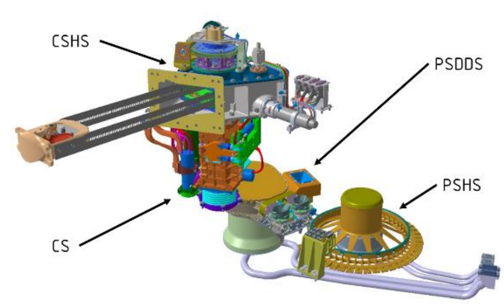

Figure 1: SPDS FM CAD model.

The remainder of this paper is structured as follows:

- The design drivers are described in chapter 2.

- Chapters 3 – 6 provide design descriptions of each SPDS subunit along with the major outcomes of the corresponding QM/FM testing.
- Chapter 7 contains a short summary and outlook on the upcoming project activities.

2 DESIGN DRIVER

The design drivers for the SPDS can be divided into four main groups:

- Design drivers originating from sample properties and sample handling
- Design drivers imposed by the instruments
- Design drivers derived from the planetary protection, cleanliness and contamination control requirements of the mission and the sensitive instruments
- Design drivers imposed by the planetary environment on Mars

The first group of design drivers all require a certain robustness of the mechanisms against existing sample and dust. As the samples received from the drill can vary from solid cores over broken pieces to regolith, the SPDS needs to be able to process a large variety of samples independent of their state and constitution. In addition, the sample types can range from soft, rather sticky materials such as clays to very hard stones. After milling, all samples are in powdered form with grain sizes up to maximum 500 µm. This powder is subjected to triboelectric charging, as the rover is not grounded in the traditional sense, but only by interaction with the atmosphere [5]. This can lead to layer formation or clogging which shall be minimized to avoid loss of functionality and cross contamination between subsequent samples. Possible fractions of water inside the sample together with hygroscopic samples can lead to cementation effects, which shall also be avoided. As this might not always be possible and short interim storage of milled samples is essential for scientific research, the system is required to provide measures to loosen up cemented material.

The second group of design drivers are imposed by the instruments and their needs for sample preparation and presentation. Besides the required grain size range, a certain flatness of the presented sample and a defined sample quantity, one of the major requirements is the positioning performance for correct sample presentation. If an optical instrument discovers an interesting grain within its field of view on the refillable container of the PSHS, the aim is to subject this one grain to a subsequent series of investigations by different instruments. To achieve this, the sample receptacle has to be positioned with an accuracy of 100 µm on its diameter of 240 mm, which is equivalent to an angular accuracy of 0.05 degrees. To perform a complete analysis of the sample, the instruments need to scan the sample in very small steps, thus requiring a command resolution of 20 µm on the circumference (= 0.01 degrees).

The third group of major design drivers is imposed by the sterility, cleanliness and contamination control demands raised by the mission itself, and the sensitivity of the instruments. It shall by all means be avoided that any kind of contamination originating from earth leads to false measurements by the instruments. As that could invalidate all potential findings on Mars a maximum contamination of 0.03 spores per square meter and maximum 50 ng contamination level per gram of Martian sample delivered to ALD Scientific Instruments are imposed on the hardware. For this reason, an UCZ was implemented in which the SPDS shall operate.

To keep contamination out, this UCZ needs to be pressurized from the moment of its closure during integration in a highly clean environment (ISO3 AMC-9 (or) glove box, developed by and located at Thales Alenia Space, Torino premises), until first opening on Mars. Since actuators as well as sensors and other electrical components are a high source of contamination, SPDS electronics are not allowed inside the UCZ. This calls for the need of dynamic feed-throughs that on the one hand need to be gas-tight and, on the other hand, need to avoid high parasitic torques to allow smooth motion and a low system mass. These two challenging requirements drive the need for an optimized compromise to be able to meet the required performance within the available resources. Furthermore, structural parts of the mechanisms that enclose the UCZ need gas-tight seals on their interfaces requiring a stiff structure with a minimum number of internal interfaces.

Other origins of contamination are different types of materials or coatings. Basically, the only material group accepted inside the UCZ is metals. When unavoidable a very limited use of specific polymers and low temperature grease is allowed. Also the choice of coating is limited by several factors, such as the chemical compatibility to the instrument requirements, as well as the demanded robustness and surface roughness (Ra = 0.1 - 0.2 µm maximum for all surfaces in contact with sample), to be compliant to the ultra-cleaning procedure, which includes bake-outs, ultra-sonic baths with different solvents and CO_2 snow-cleaning and a sterilization process.

Last but not least, the environmental conditions on Mars impose several restrictions on the design, such as the operative temperature range of -60°C to +40°C, and the dry low-pressure CO_2 atmosphere. Contrary to the sterile vacuum in which most space mechanisms operate, the sample processing produces a very dusty environment, imposing many challenges for the mechanisms' tribological elements. The dry atmosphere causes additional triboelectric charging of the particles which can cause them to adhere to all surfaces they come in contact with. The UCZ is thus converted into an extremely dirty (but uncontaminated) environment during sample handling.

3 CORE SAMPLE HANDLING SYSTEM (CSHS)

3.1 CSHS Functionality and Design

The CSHS, see Fig. 2, is the first SPDS sub-unit and was developed by Hoch Technologie Systeme GmbH (HTS) and OHB System AG. The main functions are, a) receiving the samples from the Drill and entering them into the UCZ and, b) providing six blank samples for instrument calibration. It is composed of the following mechanisms:

- Core Sample Transportation Mechanism (CSTM) providing a linear motion that moves a passively actuated sample carrier between the Drill I/F and the UCZ
- Blank Sample Dispenser (BSD) for dispensing six blank samples for subsequent processing
- An HDRM (Frangibolt) as launch-lock for the sample carrier which also serves as ALD door to seal the UCZ until first operation on Mars

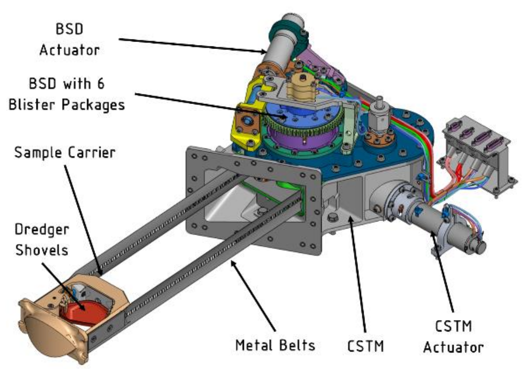

Figure 2: CSHS QM/FM CAD model

The CSTM design is based on the tape measure principle where the sample carrier is connected to two curved metal belts which wind up internally on drums. The rotational actuator motion is equally distributed on both sides and transformed into the transversal belt motion via spur gears that mesh the belt perforations. To minimize loads on the belts and to avoid buckling, the belts are guided on rollers and the belt wind-up is supported with torsion springs and a motion of the drums that is coupled to the belt motion.

The sample carrier consists of two dredger shovels and a passive actuation mechanism that is locked in closed configuration during Sample Carrier motion. During retraction it opens at the sample delivery point to the CS by a pin that opens the lock. During extension it is closed via a coulisse attached to the housing. Besides the Sample transport and delivery functions, it also serves as only access point to the internal volume of the ALD where the sample handling takes place. As this volume is required to remain pressurized until first operations on Mars it is closed until then with high force via a Frangibolt actuator.

The BSD stores six individually sealed blank samples in so-called Blister packages, which work like pill packages but are made of steel to ensure their cleanability, which, in this case, means to sustain a 500°C bake-out. They are delivered one by one, on demand, to calibrate the instruments and to confirm the cleanliness of the sample path from earth-born contamination. They are pushed out via stamps which move translationally due to a rotating coulisse driven by an actuator and a worm gear.

3.2 CSHS QM Test Results

The main performance requirements for the CSHS are the positioning accuracy of the sample carrier, the sample handling and the Blank sample release of the BSD.

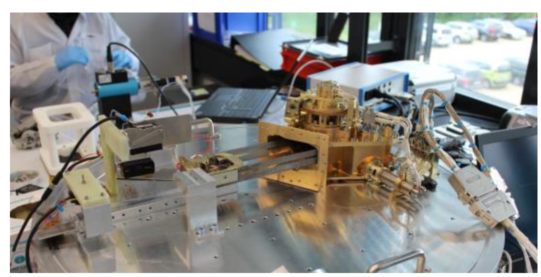

Figure 3: CSHS-QM during CSTM positioning performance test

CSTM motion has a very high accuracy (+/- 0.12 mm) and repeatability (+- 0.02 mm). The backlash of 0.6 mm, on the other hand, is rather large as it is introduced by the play of the gear teeth engaged in the belt slots and the play in the drive-train. Therefore, to reach the desired performance the target position always has to be approached from the same direction.

The most critical parts regarding failure cases are the belts, which can either have the relatively thin bars between the slots broken off or buckle to the side. The first is avoided by reducing the loads on the belts during actuation. This is achieved by avoiding sliding contacts, using rolling contacts instead, to minimize friction. The latter is tested in worst case tilted conditions where the container is extended to the maximum range (320 mm) and excited additionally by a lateral force. The elasticities of the belts over the high mechanism range, especially under maximum worst case tilt, has to be accounted for early on in the kinematic envelope. Another critical action is the reaching the end-stop at full retraction. The incremental sensor on the motor shaft requires the determination of an absolute zero. This is done by driving against the mechanical hard stop that limits the motion. As this is a retraction motion, the backlash also has to be accounted for.

Sample handling was first tested on a 3D-printed representative breadboard of the sample carrier (see Fig. 4 and [6]). Additional to the nominal testing of simply putting samples in the container and delivering it via retraction, failures were provoked to explore the failure modes and failure tolerance of the mechanism. This way, several improvements have been discovered and implemented into the final QM design.

Figure 4: SC breadboard testing [6]

On the QM the sample delivery to the mechanism was not flight like and just done via a simple drop of the entire sample at once. This is considered worst case as the drill is supposed to perform a more controlled delivery. However, the mechanism could successfully receive and deliver all sample types independent of their state (full core, broken core, granular) even when some particles dropped outside the shovels due to the simplified delivery (see Fig. 5, red arrow), proving the robustness of the final design. Still the failure tolerance is limited and the concept can only work reliably if the sample is delivered within the specified sample delivery envelope.

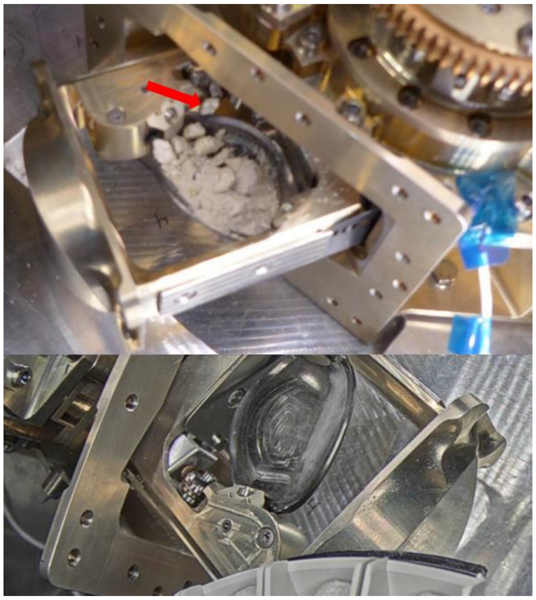

Figure 5: SC before and after sample delivery

4 CRUSHING STATION (CS)

4.1 CS Functionality and Design

The CS cracks and mills the uncrushed sample delivered from the CSHS in order to provide a fine powder for further analysis by the PPL instruments. To increase the amount of processed sample and to reduce the risk of cross contamination between subsequent samples, a hammering device induces single shocks locally in the CS. Furthermore, the subunit provides the possibility to eject undesired sample.

The CS consists of three mechanisms that work together:

- CS crushing mechanism providing the cyclic motion to crack and mill Martian samples in order to produce the fine powder needed for analysis by the PPL instruments.
- CS Dejamming Mechanism that opens the crushing jaws to eject a complete unwanted sample (even complete cores) and to restore crushing function in case of a jam.
- Vibration and Shock Mechanism (VSM) that induces on demand a single shock into the passive jaw to loosen sample from it

The general concept is the one of a jaw crusher with one actuated jaw and a passive jaw (see Fig. 6), both made of hardened steel. The passive jaw is mounted on a hinge and preloaded via stacks of disc springs to provide the counterforce for the crushing. Thus the jaw performs small oscillations around its top hinge. At the back of the passive jaw the VSM can introduce single shock events to remove adhering sample. To minimize the shock propagation outside the jaw, metal damping pads are used.

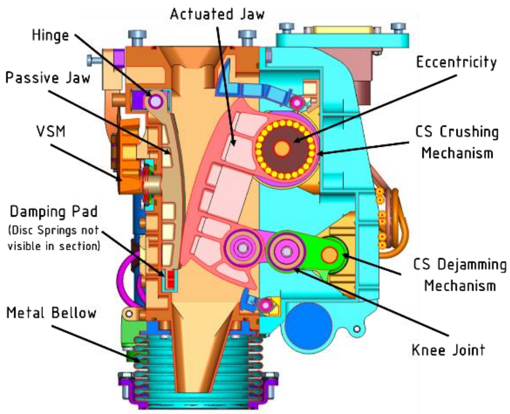

Figure 6: CS QM CAD model cross-section

The crushing motion of the moving jaw is realized by an actuated shaft that contains an eccentricity, which is embedded by needle bearings. The lower side of the jaw is connected to the Dejamming Mechanism, which allows a retraction of the jaw until passage of full samples is possible. This is done via a knee joint.

4.2 CS QM/FM Test Results

The main performance requirement for the CS is the sample crushing which has to be performed within two hours. As the mechanism has to be compatible to a wide range of sample materials with largely different properties, an operational strategy had to be devised that ensured proper crushing, independent of material composition. During extensive breadboard testing, a procedure was determined that uses alternation of the crushing direction (upwards or downwards motion of the crushing jaw at the smallest crushing gap). Originally it was planned to monitor the crushing progress either via strain gauges or via the required current that is necessary to keep the crushing speed constant for the velocity control loop. This concept had to be abandoned, as some materials are so brittle that they do not show an unambiguous current peak, and the danger of losing material is too high. Therefore, crushing is always over the full two hours. However, most samples are completely processed during the first 30 minutes (see Fig. 7).

Another important factor is the grain size distribution of the crushed material, which has to be in a certain range to be compliant to the subsequent sample preparation and the analysis by the instruments. 90% of the sample needs to have a grain size between 50 and 500 µm. Even without having a dedicated sieving mechanism, the CS has been able to demonstrate compliance to this requirement for all relevant sample materials with only minor (and acceptable) deviations (see Fig. 8).

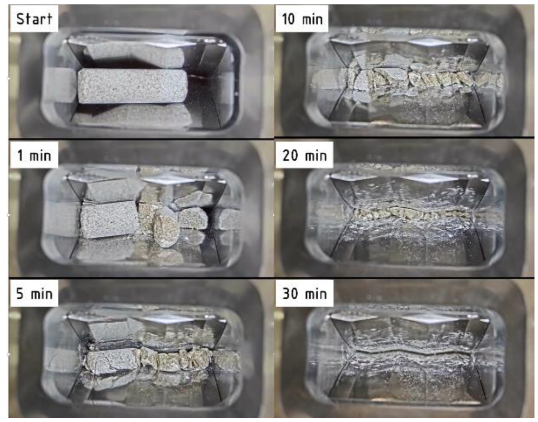

Figure 7: CS QM crushing progress

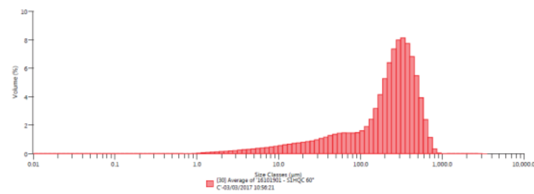

Figure 8: Exemplary grain size distribution for Sandstone HQC (High Quartz Content) after crushing under Mars-like conditions

Finally, it also has to be ensured that the CS is empty after crushing to minimize the cross contamination between subsequent samples which was a major concern after breadboard testing, where at times larger sample agglomerates of sticky materials tended to adhere to one of the jaws. To loosen them the VSM was introduced. During QM testing it was found that other design updates such as the elasticities and bearing introduced into the fixed jaw suffice to avoid this from happening even under Mars-like conditions where the dry atmosphere promotes adhesion of particles to surfaces due to triboelectric charging of the sample particles (see [5]). Nevertheless, the VSM will remain and actuated as an additional precaution, as no visual confirmation on the CS cleanliness is possible on Mars.

As the crushing tests are time consuming, an extra life test model was manufactured which was successfully tested with 132 different samples. A post inspection confirmed that besides the high repetitive loads during the crushing process, no signs of critical wear were observed in the drive-train parts. Only the surface of the steel jaws was roughened, which was expected.

5 POWDERED SAMPLE DOSING AND DISTRIBUTION SYSTEM (PSDDS)

5.1 PSDDS Functionality and Design

The function of the PSDDS is to receive powdered samples from the CS and to distribute them in defined quantities to the PSHS under ultra-clean conditions.

The PSDDS consists of the following mechanisms:

- Positioner providing the placing of both Dosing Stations (DS), the Alternative Transport Container (ATC) and the Cleaning Device with the required accuracy.
- Two identical DS units, each collecting into their inlet funnels the complete amount of a crushed sample and providing a stepwise output of a constant volume of this powder.
- One passive ATC to collect a complete sample processed by the CS and to distribute the entire sample at once to the RC of the PSHS (in case the DS are clogged with material).
- Passive Cleaning Device to empty the Refillable Container (RC) of the PSHS

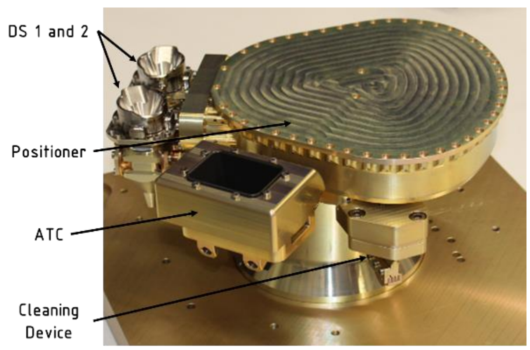

Figure 9: PSDDS QM

The Positioner mechanism is actuated by a brushed DC motor with integrated gear-box with a pre-torque device mounted on its output shaft. This device divides the torque to two spur gears that are pre-torqued to minimize the mechanism backlash. The counterparts of each spur gear are located on the input shafts of two identical planetary gear-boxes in a parallel arrangement. Each output is summed up via a last gear stage on an internal ring gear, providing the absolute torque for the Positioner motion. The rotary degree of freedom of the hub is provided by a wire race bearing and incorporates the dynamic feed-through, which guarantees the sealing and encapsulation of the UCZ with the entire drive-train remaining outside of it.

The two DS are mounted on the Positioner output. The central elements for each DS are the dosing shaft providing two dosing chambers shifted by 180° and the inlet and outlet funnels. Filling and emptying of these chambers is done by a motor-driven shaft rotation and supported by a Piezo vibrator that is coupled to a membrane, which guides the vibration to the DS funnels.

The ATC consists of two hatches that are opened simultaneously by a passive coulisse. The motion is again provided by the Positioner. The same applies for the Cleaning Device, which is a set of polymeric brushes whose shape mirror the RC located on the PSHS.

All the above require interaction between the PSDDS and the PSHS, which is very critical, as the dynamic envelopes of both subunits require overlapping to fulfill all the required tasks. This implies the danger of clashes, which have to be avoided by operations at all means, even in the event of system failures (e.g. uncontrolled motion of a mechanism).

5.2 PSDDS QM/FM Test Results

The two key requirements to be verified are the positioning and the sample delivery performance.

The positioning performance has been successfully tested on a representative profile containing all relevant target positions for the mechanism. Manufacturing tolerances on the last gear stage could be compensated by a correction curve which corrects the set values for the target positions. The backlash could be reduced via the pre-torquing device from 0.53 deg to 0.006 deg. Full removal of the backlash is not possible due to remaining elasticities of the drive-train components. However, even the remaining backlash can be compensated by always approaching the target positions from the same direction. To overcome the remaining backlash, an overdriving of 1 deg is sufficient so the impact on operational duration and lifetime is marginal. With these measures, an absolute accuracy of +/- 0.05 deg could be achieved on a mechanism operating in a dusty environment through a helium-tight dynamic seal, only being driven by a simple brushed motor with an 8 quadcound encoder on the motor shaft. This allows for simple and therefore robust driving electronics, as all precision originates from the mechanical part.

As the encoder is incremental the mechanism requires zeroing via a hard stop. To maximize the driving range for the mechanism, the hard-stop had to be made as compact as possible still providing sufficient stiffness to ensure repeatable zeroing. A final motion range reduction of 10 deg was possible in combination with a zeroing method that minimizes the inaccuracy of the zero position. This is achieved by driving with constant speed against the hard-stop, then limiting the motor current to a defined threshold and stopping the motor after a defined time that the current demand reached the defined threshold.

The zeroing however still remains the major contributor to the accuracy budget. Without zeroing in between, the repeatability of the mechanism for single positions reaches +/- 0.001 deg. Including zeroings the repeatability for single positions increases to +/- 0.038 deg.

Combined tests between the PSDDS as sample providing system and the PSHS as sample receiver are necessary to judge sample delivery performance and confirm the operation principle.

Figure 10: Sampling with ATC on RC (left) and with DS in MOMA oven dummy (right)

Sample delivery was tested with dummy ovens that have a representative filling volume and aperture. Two dosings always provide sufficient sample to fill the oven without sample overflow. Also the sample spill outside the oven was minimized to acceptable values even under maximum tilt, to still allow correct oven closure and to minimize loss of valuable sample material.

Also the sample delivery to the RC was tested successfully. More details are in chapter 6.2, as the sampling success is highly dependent on the flattening performance provided by the PSHS.

Another critical factor for the PSDDS DS is to avoid sample cementation especially for samples that might contain fractions of ice. This has been tested on a representative breadboard in dedicated tests by the University of Graz [7]. The main challenge was to produce representative samples that contain ice under Mars-like conditions, since simply adding water content (or ice) to the sample is not enough, as it sublimates during evacuation of the test chamber. This was solved by introducing water vapor to the test chamber to provoke realistic cementation effects that might occur on Mars. The occurring cementing has always been successfully resolved by the DS and its Piezo induced vibration.

6 POWDERED SAMPLE HANDLING SYSTEM (PSHS)

6.1 PSHS Functionality and Design

The PSDDS DS doses the powdered sample material in defined quantities into the sample receptacles that are located on the circumference of a carousel-like mechanism, the PSHS. The function of the PSHS is to position these receptacles to the different instruments with high accuracy and under ultra clean conditions.

The PSHS consists of the following mechanisms

- A rotating Carousel to position the different sample receptacles (namely the RC and 31 different pyrolytic ovens) and 4 calibration targets to the different instruments with the required accuracy (both the targets and the ovens are contributed by the MOMA instrument).
- A passive Flattening Device to flatten a sample on the RC

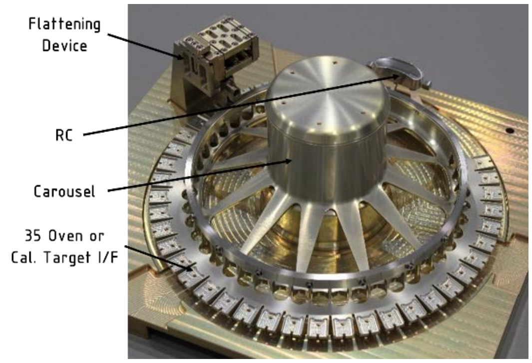

Figure 11: PSHS QM

The mechanism principle of the PSHS Carousel is the same as for the PSDDS Positioner (see chapter 5.1).

Over a diameter of 240 mm the PSHS has a refillable container and 35 interfaces that can either be used for one-time use ovens for the gas chromatographer or for a calibration target for one of the three optical instruments. To prepare the sample on the refillable container for the instruments, the PSHS is equipped with an additional flattening device located on the circumference of the carousel. The flattening blade has an optimized geometry to flatten all kinds of milled samples to a flatness of +/- 100 µm with respect to a defined sample investigation plane. The vertical DOF of the blade is provided by a solid state hinge that is realized by a thin metal sheet to avoid sliding interfaces. The blade is passively pushed down by springs and lifted by the carousel rotation via a sliding shoe that runs on the coulisse of the carousel.

6.2 PSHS QM/FM Test Results

The two key requirements to be verified for the PSHS are the positioning and the flattening performance. The positioning performance proved the same high accuracy and repeatability as for the PSDDS. As the PSHS has to perform scanning motions underneath the optical instruments to analyze the entire sample surface, it also needs to have a high relative accuracy for small steps of 0.01 deg. The high repeatability and the absence of vibrations during motion allow for combined science in any desired order. The mechanism is capable of showing to each of the optical instruments single grains on the RC on demand.

Besides the preloading of the drive-train this performance is enhanced by approaching the position from the same direction. As the mechanism is constrained by a hard-stop for zeroing, it has to overrun the position and drive back to fulfill this. Testing proved that 1 deg override already suffices to compensate the drive-train backlash.

For the flattening procedure the PSHS needs to handle samples that are rather sticky (cohesive and adhesive) and samples that are rather loose. Besides the material type, flattening is highly impacted by the geometry of the flattening blade (which has been optimized, see [1]), the test conditions (especially the humidity wrt. Hygroscopic samples can lead to over-testing) and by the flattening procedure.

Regarding the flattening procedure, several parameters have been optimized to achieve the desired performance under all conditions for all sample types:

- Position on the RC where the sample is initially delivered
- Flattening speed
- Flattening repetitions with sample adding in between.

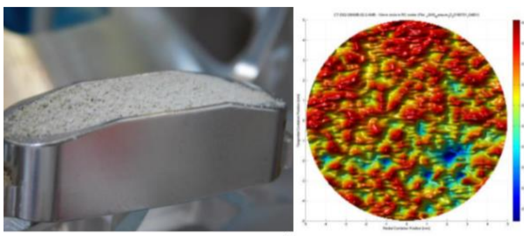

Figure 12: RC after flattening (left) and 3D measurement of flatness.

The final procedure could be established in a compact test run using a subset of samples that represent extreme behavior within the key properties, e.g. a sample that is very loose against one that is extremely sticky. Single tests show the impact of each process parameter (e.g. speed). Both are then combined to the complete procedure that then can be optimized where necessary. Validation has then later been performed with the entity of all reference materials during the QM sample testing.

7 CONCLUSION AND OUTLOOK

Extensive testing with elaborated breadboards during early project phases has provided a lot of data and valuable information to optimize the SPDS system regarding sample flow and performance. All four subsystems proved during their qualification campaign their compliance to the sample handling requirements for a broad range of different representative sample materials under realistic Mars-like conditions and critical factors, as the cross contamination could indeed be minimized to acceptable values. Furthermore, the systems successfully performed environmental testing.

At the writing of this paper, the CS, PSDDS and PSHS flight models already completed successfully the acceptance testing and FM integration has begun on the CSHS. It is foreseen to complete these activities in the course of 2018. In parallel, the system level activities performed by the mission prime Thales Alenia Space are ongoing using the SPDS QMs and the already available FMs.

Acknowledgement

The OHB SPDS activities are performed in the frame of ESA contracts as subcontractor to the mission prime Thales Alenia Space that we gratefully acknowledge.

References

[1] Paul, R., et. al. (2017) Sample Flow and Implications on Design and Testing for the SPDS Mechanism Chain on the ExoMars 2020 Rover. *ASTRA 2017*, Leiden, The Netherlands.

[2] Paul, R., Tattusch, T., et. al. (2017) „Backlash-free“ Gas-Tight High-Precision Sample Handling Mechanisms – Lessons Learned from Qualification Testing & Design and Lessons Learned of the Core Sample Handling Mechanism (CSHS) on the ExoMars 2020 Rover. ESMATS 2017, Hatfield, United Kingdom.

[3] Redlich, D., et. al. (2016) Development and Testing of a “Backlash-Free” Gas-Tight High-Precision Sample Dosing Mechanism for the ExoMars 2018 Rover. AMS 2016, Santa Clara, USA.

[4] Paul, R., et. al. (2015) Development and Testing of a „Backlash-Free“ Gas-Tight High Precision Sample Handling Mechanism for Combined Science on the ExoMars 2018 Rover. ESMATS 2015, Bilbao, Spain.

[5] Anderson, R., et. al. (2009). Particle transport and distribution on the Mars Science Laboratory mission: Effects of triboelectric charging, Icarus 204, p.545-557

[6] Melzer, Ch. et. al. (2015). Mechanical Testing on the Core Sample Transportation Mechanism of the ExoMars 2018 Mission, ESMATS 2015, Bilbao, Spain

[7] Kömle, N., et. al. (2018) Sampling of Mars analogue materials in a laboratory environment. Acta Geotechnica.

[8] Lopez-Reyes, G. (2015). Development of Algorithms and Methodological Analyses for the Definition of the Operation Mode of the Raman Laser Spectrometer Instrument, Universidad de Valladolid, Valladolid, Spain