TECHNOLOGIES FOR AUTOMATED SAMPLE HANDLING AND SAMPLE DISTRIBUTION ON PLANETARY LANDING MISSIONS

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ABSTRACT

Kayser-Threde has been assuming a leading role in a number of studies and projects addressing space robotics with applications ranging from vision systems, manipulation systems and active space debris removal (e.g. the On Orbit Servicing projects OLEV and DEOS) to mechanical subsystems for the ESA-Roskosmos 2018 ExoMars rover mission [1,2]. This paper describes recent results from the on-going development of the Sample Processing and Distribution Subsystem (SPDS) for the ExoMars rover as well as programmatic plans for evolutions of its design targeted to other missions, as well as development activities on regolith sampling devices.

The SPDS is being developed by Kayser-Threde under subcontract to TAS-I to supply the scientific instruments of the ExoMars rover with granular Mars rock and soil samples of a specific particle size distribution. This is achieved through a set of mechanisms making up the SPDS which crush, meter (‘dose’) and distribute the subsurface samples acquired by the ExoMars drill. The sequence of operation can be controlled from ground but pre-defined operational sequences are embedded in the control electronics and will operate the SPDS in a semi-automated way.

Throughout the ExoMars Phase B work since 2007, the emphasis has been to develop and test breadboards and engineering models of the different SPDS mechanisms, in parallel to doing the preliminary flight design. Hence, high fidelity H/W models now exist for all of the mechanisms, and functional tests of the complete SPDS have been performed at ambient laboratory conditions and in simulated Mars environment. Moreover, parabolic flight campaigns have been conducted to address the influence of reduced gravity (Mars) on the flow of the granular samples from one SPDS mechanism to the next and to support validation of a numerical simulation of the powder flow.

Systems like the SPDS are suitable not only for in-situ missions as ExoMars, but also for sample return missions which require a preliminary screening of the samples collected, as well as possibly call for mechanical pre-treatment and metering prior to transfer into the sample return canister. Candidate missions include the planned Roskosmos series of lunar landing and sample return missions Luna-Glob / Luna-Resurs / Luna Sample Return targeted to the lunar poles. Likely design modifications for a lunar polar application are associated with manipulation and handling of ice-rich samples and their protection from premature loss of their volatile contents. To this effect, recent testing performed with the SPDS on ice-containing samples provide confidence in its suitability also for this type of materials.

1. EXOMARS SPDS

1.1. Overview

Kayser-Threde, as a subcontractor to Thales-Alenia Space Italia (TAS-I), has been developing the Sample Processing and Distribution Subsystem (SPDS) for the ESA-Roscosmos 2018 ExoMars rover mission since 2007. The SPDS is a set of mechanisms designed to crush and distribute to the ‘Pasteur’ science instruments Mars subsurface samples acquired by the ExoMars drill. The different mechanisms of the SPDS are distributed among the science instruments inside the Analytical Laboratory Drawer (ALD) contained within the rover structural enclosure.

The SPDS consists of the following mechanisms, processing a sample in sequence:

- Core Sample Handling System (CSHS) (consisting of Core Sample Transfer Mechanism CSTM and Blank Sample Dispenser BSD) accepts the samples discharged from the drill and forwards them – exploiting gravity – into the ALD and to the subsequent SPDS mechanism, being the
- Crushing Station (CS), operating as a jaw crusher to comminute granular and massive samples to smaller grain sizes as required by some of the Pasteur science instruments

- Powdered Sample Dosing and Distribution System (PSDDS), being situated below the CS and receiving the sample powder resultant from the crushing; the powder can be dosed by the PSDDS dosing mechanisms and thus dispensed into sample receptacles located below the PSDDS on the
- Powdered Sample Handling System (PSHS) which essentially is a carousel wheel carrying a number of ovens for thermal and chemical processing of the powder samples by the 'Pasteur' MOMA instrument, as well as carrying a 'refillable container' (RC) to present a larger amount of sample powder to close-up observation optical science instruments.

The electronics unit controlling the SPDS – the Drill and SPDS Electronics Unit (DSEU) – is shared with the electronics controlling the ExoMars rover sample acquisition drill and is developed by Selex Electronic Systems (SES).

Fig. 1 shows the ALD / SPDS accommodation within the ExoMars rover, and Fig. 2 provides an overview of the SPDS mechanisms as part of the ALD system.

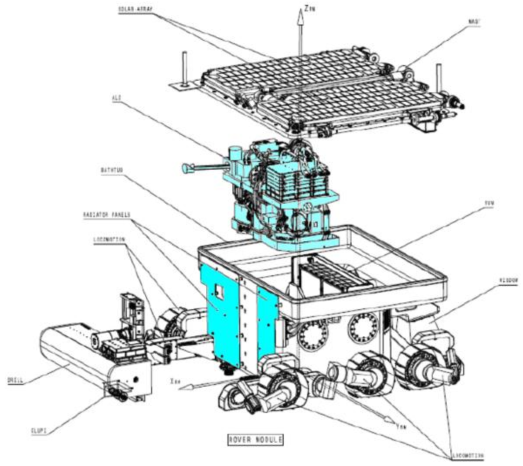

Figure 1. ExoMars rover partially exploded view, showing position of ALD with SPDS mechanisms within the rover 'bathtub' primary structure (credit: TAS-I)

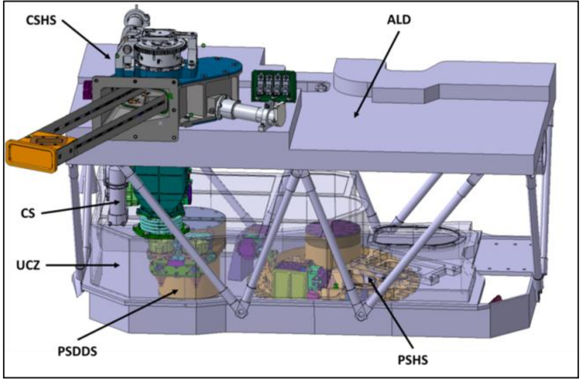

Figure 2. SPDS mechanisms (shown colourized) overall in the ALD

The whole design of the SPDS takes into consideration the ultra-clean zone (UCZ) which is part of the ALD. Those SPDS components, which are inside this zone, need to be sterilized and kept free from organic contamination until after landing on Mars. One measure for achieving this is to use a pressurized structure for the UCZ that is exposed to an internal overpressure of 0.1 bar relative to the environment. Materials used in the SPDS need to be able to withstand the temperatures necessary for sterilization. SPDS mechanisms motors and gears are positioned outside the UCZ where possible. Where this is not feasible, they are encapsulated with rotary feed-throughs equipped with dynamic seals to allow the UCZ to mainatin its overpressure.

1.2. CSHS

The CSHS as the initial mechanism for accepting the samples delivered by the ExoMars drill is a linear boom-like extension system that transfers the sample (granular or massive core) from the sample discharge port of the drill to a defined position where it is dropped into the Crushing Station. An ALD external door is attached to the CSTM mechanism for opening and closing the ALD for sample transfer and which until landing on Mars maintains the UCZ structure internal overpressure through a pre-loaded, static pressure seal.

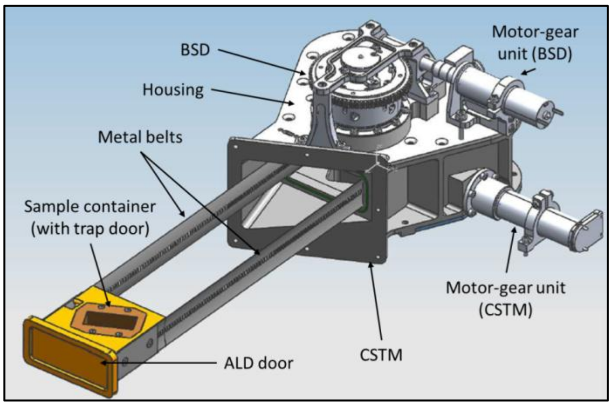

Figure 3. CSHS mechanism

A Blank Sample Dispenser (BSD) sits on top of the CSTM and holds six spherical 'blank' samples of 9 mm diameter that are organic-free. The samples must be kept under ultra-clean conditions at all times, according to the current concept. They will be encapsulated in 'blister packages' consisting of a semi-spherical blister cup and a blister foil. Six separate stamps of the BSD mechanism provide the necessary force for opening the flat breakable blister foil and perform the push-out process of each blister cup. The stamps are pushed down by a notch that is located on a turning rail driven by a worm wheel. The blank sample falls through the funnel integrated in the CSTM housing, through the open CSTM sample container, directly into the CS. A blank sample can be dispensed by the BSD and transferred into the Crushing Station, further processed by the SPDS and presented to the instruments when desired.

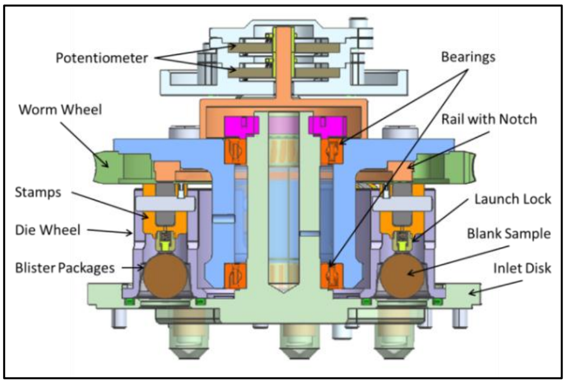

Figure 4. Cross section of BSD mechanism

Current projected mass of the CSHS flight design is 4.5 kg (including maturity margin), comprising the CSTM and the BSD.

1.3. CS

The CS is a miniaturized jaw crusher that fulfils the ExoMars requirement for comminuting drill core samples (diameter of 11 mm, length up to 35 mm) to powder fine enough to satisfy the 'Pasteur' analytical instruments' needs. A median grain size of the powder of 250 µm with 90 wt-% falling between 50 and 500 µm is required. The material is crushed between a fixed and a moving metal body (jaw), the latter actuated by an eccentric drive shaft. While milling, the samples fracture into ever smaller pieces. During the crushing, particles, once small enough, fall through a < 1 mm wide gap between the two jaws at the lower end of the crusher, to collect in the hopper of one of two redundant dosing units of the PSDDS mechanism situated below the CS. If a sample is stuck in the crushing chamber the jaws can be opened at their lower end by a de-jamming mechanism to release the uncrushed sample remains.

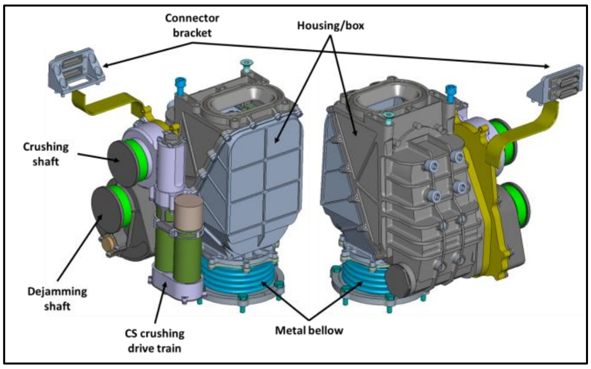

Figure 5: CS configuration

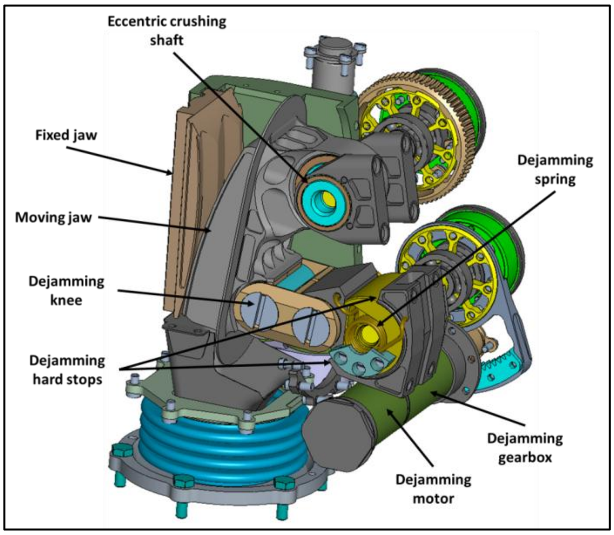

Figure 6:CS internal mechanism

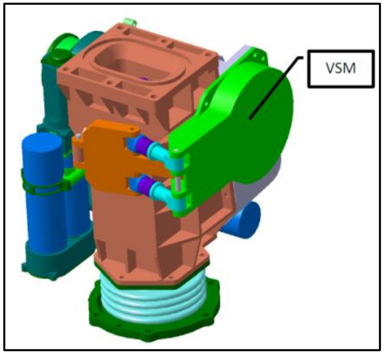

Figure 7. VSM as incorporated into CS design

To improve the performance margins of the CS, an additional Vibration & Shock Mechanism (VSM) has recently been introduced into the CS design. This follows development tests – as well as the end-to-end (E2E) test campaign with the SDPDS breadboard models (see section 1.8 below) – which suggested that hammering superimposed on the crushing action significantly improves the mass flow of sample powder through the mechanism, as well as helps to shake loose compressed powder that may cake the surfaces of the jaws and which would increase cross contamination. The VSM does not require a dedicated actuator but utilizes the CS crushing drive shaft for compressing a set of disk springs that are released to accelerate a hammer mass against the CS housing.

Current projected mass of the CS flight design is 4.7 kg, including the VSM and maturity margin.

1.4. PSDDS

In the PSDDS, two (redundant) dosing units are mounted to a rotating arm which can position the units either under the Crushing Station or at the sample discharge locations over the PSHS carousel. The dosing units include a hopper facing upwards towards the outlet of the CS crusher, in order to collect sample powder produced by the crusher. Sample powder is stored in the hoppers until dosed in amounts of 0.1 ml per dosing step. The dosing function employs a revolving wheel with hollow pockets of defined volume which are filled with the sample material. Piezo vibrators are used to ease sample discharging and cleaning.

To accommodate the rotary movement of the PSDDS rotating arm with the dosing units actuators situated within the moving structure (see Fig. 8), a flexible harness is part of the PSDDS design and allows for an up to 340° rotation at the specified qualification temperature of -60°C. This flexible harness uses a flex-rigid connection involving Kapton flexes.

Current projected mass of the PSDDS flight design is 2.3 kg (including maturity margin).

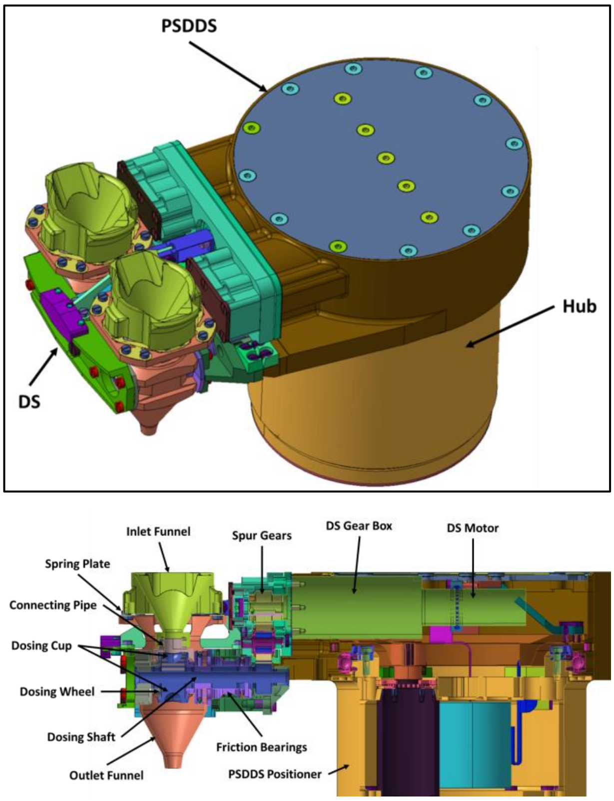

Figure 8. PSDDS external view with two dosing units (DS) (top) and cross section (bottom)

1.5. PSHS

The ExoMars 'Pasteur' analytical instruments are accommodated in the ALD around the PSHS carousel of the SPDS. The carousel holds the Refillable Sample Container tray (RC), 35 pyrolysis ovens for the MOMA mass spectrometer instrument, as well as up to 3 calibration targets. A sample surface flattening tool (a passive blade) and a cleaning tool are mounted at fixed positions. Once the RC has received a powdered sample from the PSDDS dosing unit, it is passed under the flattening blade to produce a smooth surface of the powder. The relevant requirement calls for 80 % of the optical instruments measurement points to be within +/- 0.1 mm of the nominal surface level. The carousel is then rotated to position the RC under the various instruments where the sample is analyzed. Quite stringent carousel positioning performance requirements apply, calling for 100 µm positional accuracy and 20 µm resolution. This is achieved by a backlash-free design of the drive mechanism and a rotary encoder of adequate resolution coupled to the mechanism actuator. After all analysis on a sample in the RC is completed, the RC is passed under the cleaning blade which sweeps out the sample material, readying the RC for the next sample. If a sample is deemed interesting enough by operators on Earth, part of it is also filled into one of the ovens on the carousel which is then positioned in the MOMA 'tapping station' for pyrolysis analysis to look for organics and volatile compounds. Each oven is only used once.

Current projected mass of the PSHS flight design, including the flattening and cleaning blade assemblies, is 1.9 kg (including maturity margin).

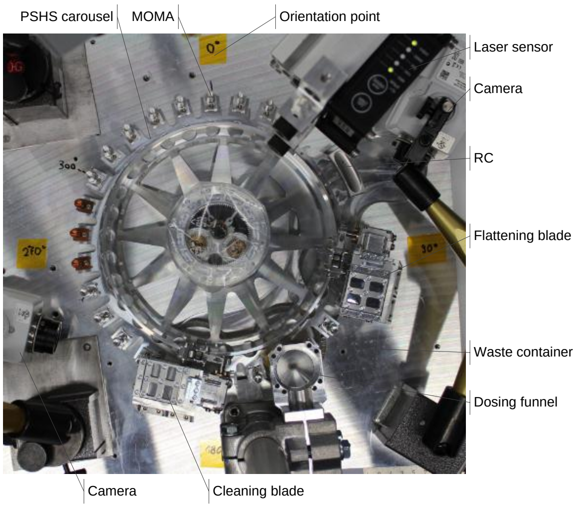

Figure 9. Overhead view of PSHS 'elegant breadboard' following integration in 2012

1.6. Effect of Mars gravity

The SPDS mechanisms rely on the action of gravity in the flow of the granular samples from one SPDS mechanism to the next. To capture and understand the effects of reduced gravity (Mars g vs. Earth g) on the performance of the SPDS, the SPDS project has been relying on a combination of testing on parabolic flights and numerical simulations. In June 2011, under contract with ESA, Kayser-Threde performed a parabolic flight campaign to test the behaviour of the PSDDS Dosing Station under Martian gravity. The aim was to verify the performance requirements of the SPDS Dosing Station at 1/3 Earth gravity (corresponding to conditions on Mars), to verify the quantity of sample dosed (throughput), to assess cross-contamination between successive samples and to assess the influence of vibration (the dosing station being equipped with piezo vibrators to assist in powder flow).

In parallel, a numerical simulation effort has been started in late 2011 together with the University of Leeds (UK) to model mechanism / sample interaction effects as a function of gravity. The modelling approach chosen was the Discrete Element Method (DEM). A subsequent parabolic flight campaign was run in December 2012 by the University of Munich (TUM / LRT), flying a series of different 2D shapes of the PSDDS Dosing Station hoppers at simulated Mars and lunar gravity, with the sample holders and powders exposed to Mars atmospheric pressure.

Simulation and testing were shown to agree in recommending a slight design change for the PSDDS dosing funnels in enlarging the outlet throat diameter to enhance mass flow at Mars gravity for cohesive materials which was subsequently implemented in the design. Further simulation work is planned which will validate the DEM model against the now existing test database at Earth gravity and at reduced gravity levels, as well as by incorporating measurements of inter-particle surface forces for the SPDS design and test reference sample materials, using AFM measurements in the lab. With the thus validated model, final predictions for powder flow performance between CSHS and CS, between CS and PSDDS and between PSDDS and PSHS will be performed for Earth and Mars gravity.

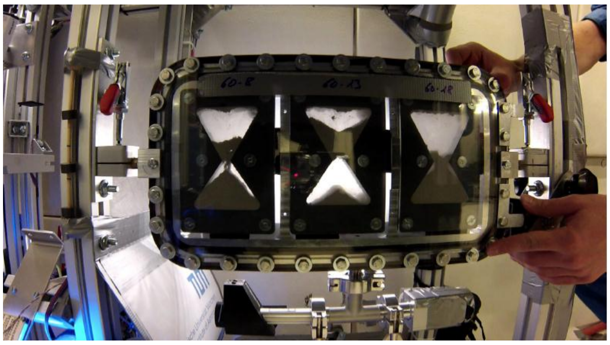

Figure 10. Still from December 2012 TUM / LRT parabolic flight experiment with 2D hoppers (set of 3 hoppers of different throat diameters is visible) (credit: P. Reiss, TUM / LRT)

1.7. Control

Control of the SPDS is by the ExoMars Drill and SPDS Electronics Unit (DSEU) which is shared with the sample acquisition drill and is developed by Selex Electronic Systems (SES).

During the Mars surface mission of the ExoMars rover, command sequences will typically be radiated from Earth to the rover once per Mars day ('Sol'). Data may be relayed up to twice per Sol from the rover to Earth, via one or more Mars orbiters passing over the landing site and offering UHF relay services to assets on the surface. The ExoMars rover, like previous and current Mars rovers by NASA, will thus extensively rely on on board autonomy to control housekeeping and communications with Earth, mobility to a designated (by operators on Earth) drive target, scientific remote sensing operations, acquisition of surface and subsurface samples by the drill, transfer of samples into the ALD and their mechanical processing by the SPDS and, finally, analysis of the resultant sample powders by the 'Pasteur' instruments in the ALD.

Some SPDS acitivities require intervention from operators on Earth before committing to a subsequent step in sample processing: currently, these are:

- Initiation of sample crushing by the CS: prior to authorizing this activity, imaging of the sample (by the rover mast-mounted cameras) residing in the CSHS sample container following its discharge from the drill head needs to be assessed in the gound control centre to verify the actual transfer of a sample and its physical appearance; at the time of image assessment, the sample will already have fallen into the CS and is therefore already protected from Mars surface UV, radiation and the surface temperature cycle; if assessment suggests not to process the sample, the CS can be commanded to move to the 'dejamming' configuration to permit the sample to exit the CS and to drop into a 'waste container'
- Initiation of dosing of sample powder following crushing in the CS: prior to authorizing this activity, engineering data from the CS crushing operation needs to be assessed in the gound control centre to verify the adequate extent of sample comminution; if deemed insufficient, a new period of crushing may be commanded (the nominal duration of crushing operation for a given sample is not to exceed 2 h)
- Initiation of a MOMA pyrolysis sequence on sample powder dosed into one of the MOMA ovens: prior to authorizing this activity, imaging of the respective oven by the µ-OMEGA science instrument in the ALD sitting on the common instrument 'working circle', following powder dosing into the oven, needs to be assessed in the ground control centre to verify presence of a sample in the oven (such as not to waste one of the single-use ovens in case of failed sample delivery).

Actual SPDS mechanisms operations, such as performing a crushing run, dosing *n* 0.1 ml aliquots of sample powder or positioning the PSHS carousel with a filled RC sample tray or a filled MOMA oven to a particular position, are then performed autonomously. To do this, the SPDS design includes a number of sensors, such as

- Rotary encoders
- Potentiometers
- Hall sensors (as proximity sensor to indicate ‘end stop’).

Crushing progress of the CS on a given sample is assessed autonomously by S/W in the DSEU currently by ‘fused’ assessment of CS motor current vs. time and strain gauge signals vs. time (strain gauges mounted on the CS housing).

As an example of the on board S/W control loops for the SPDS, the control of the PSHS sample positioning carousel, operated jointly with the RC sample powder flattening and powder sweeping blade assemblies, is briefly described. The S/W allows the PSHS to perform the following actions:

- Diagnose sensors
- Diagnose actuator
- Check the starting conditions
- Positioning zeroing
- Flatten the sample
- Move to position X
- Move Steps (Debug)
- Overboost to unblock
- Clean the RC.

The foreseen control loop consists of a position control, a velocity control and a motor control. With the position set-point (user input) and the current position of the carousel, a trapezoidal position profile is generated. The current position set-point is compared to the current absolute position (extracted from the encoder signal). The position error is transformed via a position controller to an internal velocity set-point. This set-point again is compared to the actuator velocity (also extracted from the encoder signal). The velocity error is input for a velocity controller. The output is a current set-point that enters a motor current control loop. During zeroing a constant current control is applied.

1.8. End-to-end testing results

Throughout the ExoMars SPDS Phase B work led by Kayser-Threde since 2007, the emphasis for the SPDS has been to develop and test breadboards and engineering models of the different SPDS mechanisms, in parallel to doing the preliminary flight design. Hence, high fidelity H/W models now exist for all of the mechanisms, and functional tests of the complete SPDS have been performed at ambient laboratory conditions and in simulated Mars environment.

Specifically, an end-to-end (‘E2E’) test set-up incorporating the existing breadboards and engineering models of the SPDS mechanisms has been developed during the SPDS contractual slices covered in 2012. This set-up allows for a correct relative placement of the SPDS mechanisms (as in the ALD) as well as for comprehensive electrical commanding and control through an EGSE designed for the purpose. With the E2E set-up, the overall flow of sample from one mechanism to the next can be assessed, permitting quantitative studies of sample cross contamination. Moreover, mechanisms positioning accuracy can be determined using external ranging and rotation sensors. Mars environment testing using the E2E has been performed at the Mars Simulation Laboratory of the University of Aarhus, Denmark, whereas ambient testing was conducted at Kayser-Threde’s premises. In the Mars environment tests, the E2E test set-up was subjected to a CO_2 atmosphere at 5…10 mbar in pressure, with the mechanisms being cooled down to -60 °C which is the low end of the qualification temperature. Priot to the test campaign, the mechanisms breadboards and engineering models were retrofitted with suitable low temperature actuators as well as with equivalents (or copies of) the internal position sensors foreseen in the flight design.

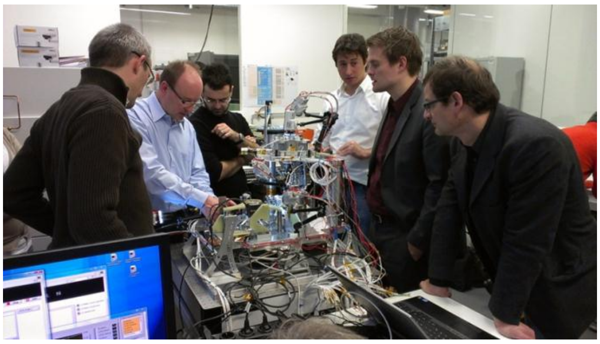

Figure 11. Scene from E2E phase 1 ambient testing in January, 2013

For the E2E testing, having taken place from January to April 2013, the reference sample materials for the ExoMars drill & SPDS were used which include cores of different rock types in the format expected from the ExoMars drill as well as several Mars regolith (soil-like materials) simulants, some of them doped with Magnesium sulfate and perchlorate salts in concentrations known to exist in the regolith of Mars. Moreover, ice-containing samples were investigated specifically during the Mars environment tests which were produced by freezing a mixture of one of the regolith simulants with 10 and 20 wt-% of water, respectively.

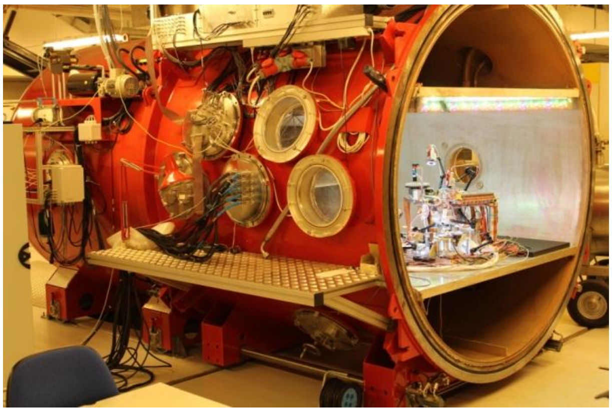

Figure 12. E2E ‚phase 2‘ testing in Mars environmental conditions: scene from March 2013 at Aarhus test facility, E2E test set-up is visible on chamber bottomplate

The E2E test programme, both at ambient and in simulated Mars envirionment, proved very successful. A comprehensive test plan was followed which included sample processing and powder delivery tests on all 8 reference materials (including the fused silica ‘blank’ sample material) plus the ‘icy’ samples described above (these only assessed in Mars environment). Earlier testing with the CS alone during 2012 had demonstrated that the grain size requirement achieved during crushing is fulfilled for the new reference materials. This observation was confirmed in the E2E testing. Dosing of the sample powder was shown to be very repeatable. Flattening of the sample powder in the RC tray, and its subsequent removal, likewise was shown to be fulfilling the requirement. Also, the PSHS carousel positioning performance was demonstrated to be in line with the requirement, both at ambient and in Mars environment.

Figure 13. Close-up of PSDDS sample inlet hopper with crushed ‘coarse sand’ having accumulated (outlet funnel of CS is visible at top)

Overall, observed caking of sample powder on the jaws of the Crushing Station (CS) was observed to be higher than expected, both at ambient and in Mars environment. This now has led to the decision to implement the VSM hammering mechanism into the CS design baseline as described in section 1.3 above. In particular in Mars environment, sample powder was observed to adhere to PSDDS dosing unit hopper internal surfaces to a larger extent than at ambient, probably due to triboelectric charging, being in line with observations on prior Mars missions with sample acquisition and handling [3]. The primary mitigation measure to ensure the required powder dosing performance in light of this behaviour is to implement a stronger powder agitation by the PSDDS piezo actuators by implementing a higher piezo supply voltage.

Figure 14. Crushing progress of gypsum sample in Mars environment; view is from the top into the CS, showing the gap between fixed and moving jaws

1.9. Programmatic status

Respecting the overall schedule of the 2018 ExoMars rover mission, the flight design of the SPDS mechanisms is currently being finalized. This follows the breadboard and engineering model programmes performed thus far, culminating in the recent E2E test programme. A combined PDR / CDR of the SPDS is planned for the summer of 2013, which will clear the way for starting manufacture of EQM’s of the SPDS mechanisms. In parallel, several component development and qualification programmes are being finalized, concerning primarily the motor-gearhead units and rotary encoders. SPDS EQM qualification testing is planned to be completed by August 2014. Finally, FM delivery by Kayser-Threde is due in September 2015, for subsequent integration into the FM ALD.

2. LUNAR APPLICATIONS

2.1. Sample handling and processing on the Moon

Several space agencies are preparing a new round of robotic landing missions to the Moon, with particular focus on the polar regions in pursuit of volatiles now confirmed by a variety of remote sensing techniques and the LCROSS impactor experiment [4,5]. In particular, Roscosmos has defined a series of lunar landing and sample return missions – Luna-Glob / Luna-Resurs / Luna Sample Return – targeted to the lunar poles and planned to commence in 2015 with a lander to a north polar site. Roscosmos has initiated talks with other space agencies, specifically ESA, to discuss possible contributions to this new programme. The upcoming lunar landing missions, also those of China, will involve regolith sample acquisition and subsequent analysis. At a polar site, lunar regolith accessible to a robotic lander may include crystalline ices as a volatile component admixed in the regolith.

If a sample handling and processing system based on the heritage of the ExoMars SPDS developed by Kayser-Threde were to be considered for such an application, likely design modifications are associated with manipulation and handling of 'icy' samples and their protection from premature loss of their volatile contents. To this effect, the recent end-to-end (E2E) testing with the SPDS breadboards (see section 1.8) did include several regolith analogs that were mixed with water and subsequently frozen to be processed by the SPDS in a simulated Mars environment. Accordingly, samples with < 20 % water ice content presented no issues to the system, with the sample being ground successfully to the desired grain sizes and dosed for observation and analysis by the science instruments.

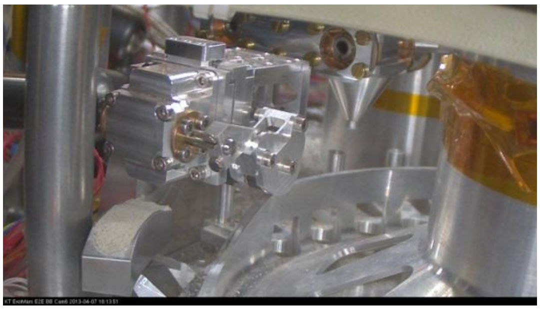

Figure 15. Regolith simulant containing 20 wt-% of water ice following crushing in the SPDS CS in simulated Mars environment (top) and resultant powder on the PSHS RC sample tray (towards the left) after flattening in simulated Mars environment (bottom)

Samples with higher water ice content were observed to stick to the CS jaws for a time (probably due to local melting under pressure and refreezing) before becoming re-engaged in the crushing process. In any case, measured temperatures within the CS did not suggest a temperature rise of the sample during crushing, favouring retention of the volatiles during mechanical processing. Therefore, there seems to be no major obstacle for utilizing the SPDS with materials containing a substantial volatile component.

Systems like the SPDS are suitable not only for in-situ missions, but also for sample returns. This is because some scenarios for robotic sample return call for a preliminary screening of the samples collected, as well as for mechanical pre-treatment and metering prior to transfer into the sample return canister. In this context, also sample fetching rovers are being studied, such as the German 'Mobile Payload Element' (MPE) [6].

2.2. Lunar regolith sample acquisition

Recently, ESA awarded the L-GRASP TRP contract to an industrial team led by SES, with Kayser-Threde as a major subcontractor. L-GRASP, 'Lunar Generic Regolith Acquisition / Sampling Paw', will trade-off concepts for a lunar regolith sampling device compatible with a lunar polar site and subsurface access down to 400 mm of depth, reflecting the requirements for ESA's 'Lunar Lander' presently being in a hiatus. The finally selected concept will be breadboarded and evaluated in simulated lunar polar regolith. During the study, Kayser-Threde – supported by consultant TC Ng from Hong Kong – will investigate several concepts for samplers, one of which is a percussive scoop equipped with a separate sample acquisition scraper, as shown in Fig. 16 below. This concept promises to be suitable for operation in dry as well as in ice-rich regolith and moreover would be effective in reaching the prescribed maximum depth of sampling. Conceptual design work will be augmented by numerical simulation and early development testing to size the design.

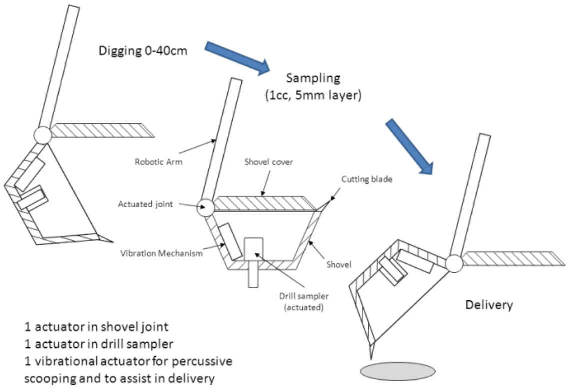

Figure 16. Percussive scoop concept planned for investigation during L-GRASP study for ESA

3. Conclusions

Space Robotics is a major line of projects at Kayser-Threde, comprising planetary exploration robotics and orbital robotics. This paper has described our on-going activities related to automated sample handling and sample distribution for planetary landing, roving and sample return mission. The major current project here is development of the Sample Processing and Distribution Subsystem (SPDS) for the ESA-Roscosmos ExoMars rover mission which recently has seen successful end-to-end test campaigns of the SPDS elegant breadboard system in both ambient environment and simulated Mars surface conditions. Also ice-containing samples relevant to lunar polar missions have been successfully subjected to testing with the SPDS. Moreover, Kayser-Threde is involved in the L-GRASP lunar polar regolith sampling device study for ESA that is just starting.

4. Acknowledgement

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