Development and Testing of a "Backlash-Free" Gas-Tight High-Precision Sample Dosing Mechanism for the ExoMars 2018 Rover

Daniel Redlich*, Robert Paul*, Sebastian Ott*, Lutz Richter*, Quirin Mühlbauer*, Markus Thiel*, Tim Tattusch*, Harald Weisz**, Fabio Musso*** and Stephen Durrant****

Abstract

This paper presents the development and testing by OHB System AG of the Powdered Sample Dosing and Distribution System (PSDDS) with specific focus on the bearing and sealing design. The PSDDS is a sample handling mechanism on the Rover of the European Space Agency 2018 ExoMars Mission, a cooperative mission with Roscosmos including a scientific instrument contribution from NASA. It is entirely developed by OHB as a subcontractor to Thales Alenia Space Italia who is the prime contractor for the whole ExoMars program. The PSDDS is the third part of a chain consisting of four individual mechanisms that compose the Sample Preparation and Distribution System (SPDS).

The main task of the PSDDS is to receive powdered samples from a stone mill (Crushing Station) and distribute the samples in defined quantities to two different kinds of receptacles, a refillable container and several one-time use Ovens, which are mounted on a carousel (4th mechanism). The sample distribution is performed by a redundant Dosing Station (DS). As these powdered samples are quite sensitive to cementation, two counter-measures have been implemented. A Piezo to vibrate the Dosing Station and to loosen the sample material as well as a device to bypass the two Dosing Stations which is able to distribute the sample in a more robust way but without the capability to control the amount (Alternative Transport Container (ATC)). Another task of the PSDDS is to clean the refillable container to allow its reuse without cross contaminating the samples (Cleaning Device).

These components and procedures need to be compatible with the Martian environment. This includes sample handling and challenging demands for cleanliness and contamination control resulting in stronger constraints for the mechanism's design and ultimately requiring the development of unique design solutions.

The PSDDS design as well as the results of the qualification test campaign under Mars-like conditions are described in this paper.

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: the first mission consists of an Orbiter plus an Entry, Descent and Landing Demonstrator Module to be launched in 2016 whereas the second mission consists of a Lander with a Rover to be launched in 2018. The Rover is equipped with a Drill to take sub-soil samples down to a depth of 2 m, which will then be analyzed in-situ by several instruments dedicated to exobiology and geochemistry research, the so-called Pasteur payload. These instruments are located in the Analytical Laboratory Drawer (ALD) inside of the Rover. These instruments are:

* OHB System AG, Oberfpfaffenhofen, Germany
** Weisz, Munich, Germany
*** Thales Alenia Space Italia S.p.A., Torino, Italy
**** ESA-ESTEC, Noordwijk, The Netherlands

Proceedings of the 43rd Aerospace Mechanisms Symposium, NASA Ames Research Center, May 4-6, 2016

- MicrOmega, a visible and infrared imaging spectrometer
- Raman Laser Spectrometer
- Mars Organic Molecule Analyzer consisting of a Laser Desorption Mass Spectrometer and a Gas Chromatography Mass Spectrometer, including a mechanism to seal Ovens (the so-called Tapping Station)

In order to supply samples to the instruments in a condition allowing an accurate analysis, 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 2018 mission [1]. It is developed by OHB System AG as subcontractor to the mission prime contractor Thales Alenia Space Italia. 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 remains pressurized until first opening on Mars.

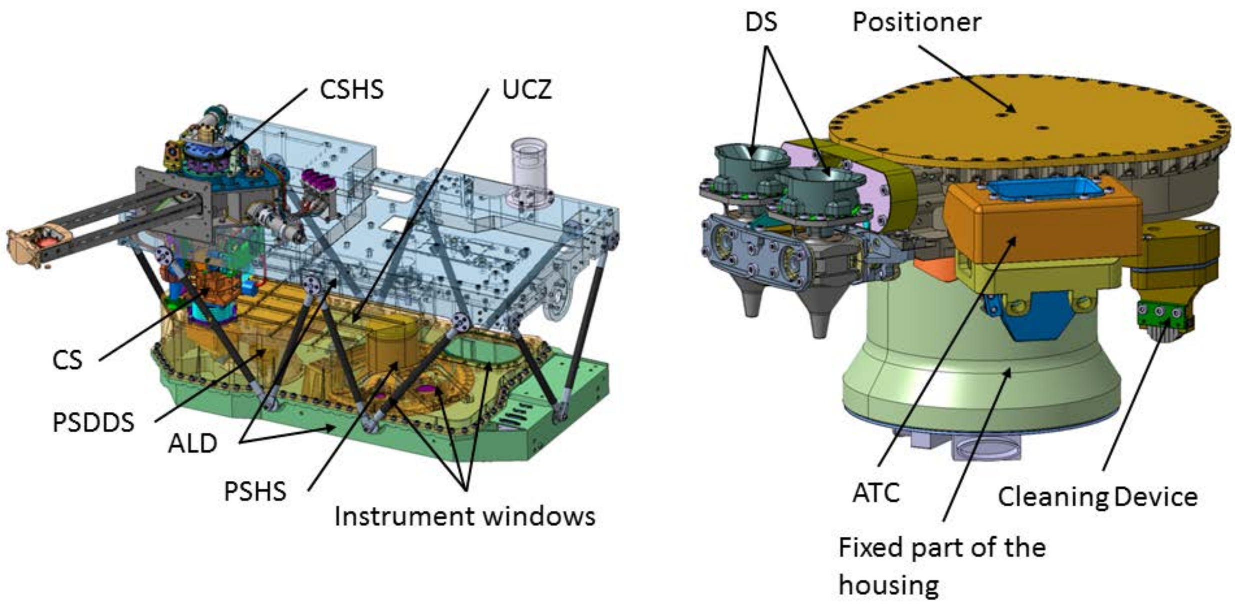

Figure 1. SPDS (left) and PSDDS (right) Qualification CAD models.

The SPDS (see Figure 1, left side, integrated into the ALD) consists of four separate mechanisms that interact with each other to transport the sample within the UCZ. The Core Sample Handling System (CSHS) transfers the sample to the Crushing Station (CS) where it is crushed to a certain grain size (50 µm-500 µm). The PSDDS (see Figure 1, right side) receives the powdered sample and doses it in defined quantities to different sample receptacles, which are subsequently brought to the instruments for analysis by the Powdered Sample Handling System (PSHS) [2].

This sample handling mechanism has three unique design solutions originated by the mission specific challenges:

- Prevent cementation of powdered sample during storage time on Mars
- It is designed to be virtually “backlash-free” to achieve compliance to the positioning requirements originated by sample handover demands of the instruments
- The design is gas-tight to preserve the UCZ pressurized until operation on Mars and to ensure sealing barriers to the Rover’s internal non ultra-cleaned volume, to preventing false measurements of the instruments due to sample contamination originated from the Rover itself.

The paper is structured as follows: In the first section, the main design drivers of the PSDDS are described. This is followed by a detailed description of the PSDDS design. In three sub-sections, special attention is given to the three main design topics: pre-torque device, bearing concept and dynamic feed-through. In the subsequent section, the test results and lessons learned of the described design topics are presented. The paper concludes with a short summary including an outlook to future activities.

Design Drivers

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

- Design drivers derived from the positioning demands for the hand-over of the sample;
- Design drivers originated from Planetary Protection, Cleanliness and Contamination Control requirements preserve Mars and analyzed Martian Samples from Earth contamination;
- Design drivers imposed by the planetary environment on Mars;
- Design drivers created by the behavior of the powdered sample.

The first group of design drivers requires a high radial and angular PSDDS positioning performance in order to be able to dose the powdered sample into the small receptacles accommodated on the ensuing mechanism (PSHS). These receptacles are 32 single-use pyrolysis Ovens plus one multiple use Refillable Container. The pyrolysis Ovens are the most critical receptacles in terms of sample dosing requirements. They have an inlet diameter of few mm and shall be accurately filled with about 0.2 ml of powdered sample. The dosing performance is therefore also dependent upon the relative positioning of the Dosing Station output funnel and Ovens inlet. To ensure that the sample is correctly delivered to the Ovens, the PSDDS shall comply with an absolute position accuracy of approx. ±0.055°. This requirement has been derived from an absolute position accuracy of ±0.1 mm of the dosing funnel with respect to the nominal position of the Ovens at the hand-over port, this considering that the dosing funnels are at a distance of 105 mm from the PSDDS rotational axis.

The second group of major design drivers is imposed by Planetary Protection, Cleanliness and Contamination Control requirements. Any kind of contamination originated from Earth could lead to false positives and false negatives findings of the ALD Analytical Instruments while searching for traces of extraterrestrial life on Mars. For this reason, an Ultra Clean Zone (UCZ) has been designed and implemented within which the PSDDS as well as the other SPDS mechanisms operate. A priority requirement is therefore to control and minimize the organic contamination (molecular, particulate and biological) to an extremely small extent, which allows in the end to arrive at a total organic contamination of the whole UCZ of very few tens of nano-grams (ng). Moreover, for Planetary Protection reasons and to preserve UCZ sensitive items from microbial contamination, all UCZ parts are also treated with a rigorous bioburden reduction process (Dry Heat Microbial Reduction) which will bring the UCZ Hardware bioburden to a level of 0.03 spores per square meter maximum. To achieve these very challenging Planetary Protection, Cleanliness and Contamination Control requirements, all UCZ constituent parts are integrated in an ultra-clean environment (ISO3 AMC-9 [or] glove boxes train) and to avoid risk of recontamination the UCZ will be over-pressurized from the moment of its sealing after integration in the ultra-clean environment until the first opening on Mars. Since actuators as well as sensors and other electrical components are a high source of contamination, SPDS electro-mechanics components are not allowed inside the UCZ. This calls for the need of dynamic feed-through that, on the one hand needs to be gas-tight and, on the other hand, need to avoid high parasitic torques to allow smooth motion and a low system weight. These are two contradictory requirements that require the adoption of carefully balanced compromises. Furthermore, all structural parts of the mechanism 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 that is acceptable 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 its compatibility with the ultra-cleaning processes applied to the parts before entering in the ultra-clean integration environment (which includes bake-outs, ultra-sonic baths with different solvents, bioburden reduction and CO_2 snow-cleaning), chemical compatibility with instruments analysis, and the demanded small surface roughness (Ra = 0.1 / 0.2 µm) for all surfaces in contact with the sample to improve cleaning efficiency and reduce sample contamination by contact transfer.

The third group of design drivers are a result of the environmental conditions on Mars and represents one of the main drivers. The environmental conditions impose several restriction 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 mechanism's tribological elements. The dry atmosphere causes additional triboelectric charging of the particles, which can cause them to stick to all surfaces they come into contact with. The UCZ is thus exposed to an extremely dirty (but uncontaminated) environment during sample handling [2].

Another group of design drivers is concerned with the properties of the powdered sample material. For instance, the cementation of the sample could lead to a blocking and therefore to a loss of a major part of the scientific ExoMars mission. The main reasons for cementation are long storage time and contact of the sample with humidity. Sample cementation can lead to the creation of large agglomerates of sample, which could cause a clogging of the system.

Design Description of the PSDDS

The PSDDS has the following main functions:

- Collection and delivery of sample material to three different points along a circumference
- Delivery of sample into two different receptacle types or waste containers
- Delivery of the sample in defined amounts
- Provide the possibility to store one sample and process a second sample in parallel
- Active prevention of sample cementation
- If the main delivery system has a defect or clogged, the sample delivery system must remain operative albeit possibly with degraded performance
- Provide a system that can remove an entire sample on a specified surface on the next mechanism
- Sealing of the Ultra Clean Zone

The mechanism (see Figure 2, left) is actuated by a brushed DC motor that is modified and qualified by the manufacturer Maxon to work in the environmental conditions on Mars [3]. It is coupled to a gear-box on whose output shaft a pre-torque device is mounted, which 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 and also developed and adapted by Maxon. The outputs of these two gear-boxes are connected via a gear mechanism to an internal ring gear, which transfers the torque into carousel motion. To allow integration of the drive-train after UCZ closure the entire drive-train and harness are integrated onto their own frame. This allows its introduction as an entire unit into the integrated hub. The motors, potentiometer and piezo, which are placed in the movable part of the mechanism, has to be connected to the harness of the PSDDS. Therefore, the frame also includes a flexible harness (Printed Circuit Board). The rotary degree of freedom (DOF) 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 [2].

The Dosing Station is mounted on the outside of the rotating hub of the PSDDS structure. The central elements for each single Dosing Station (see Figure 2, right) are the dosing wheel and the inlet and outlet funnels. The dosing wheel is part of the dosing shaft, providing two dosing chambers shifted by 180°. The inlet funnel collects the sample from the Crushing Station and guides it into one of dosing chambers. When the dosing wheel is turned the sample falls out of the dosing chamber and the outlet funnel guides the defined sample powder doses to the receptacles on the PSHS. This dosing wheel is driven by a

Motor, which is inside of the housing. The sealing is guaranteed through a dynamic seal to ensure that the UCZ maintains its cleanliness level. To make sure that the dosing works correctly and to avoid cementation of the sample in the inlet funnel, a Piezo vibrator, which is placed inside the PSDDS hub, shakes the complete Dosing Station. To transmit the vibration to the inlet funnels within the UCZ, the Piezo is coupled to a membrane, which guides the vibration to the Dosing Station funnels.

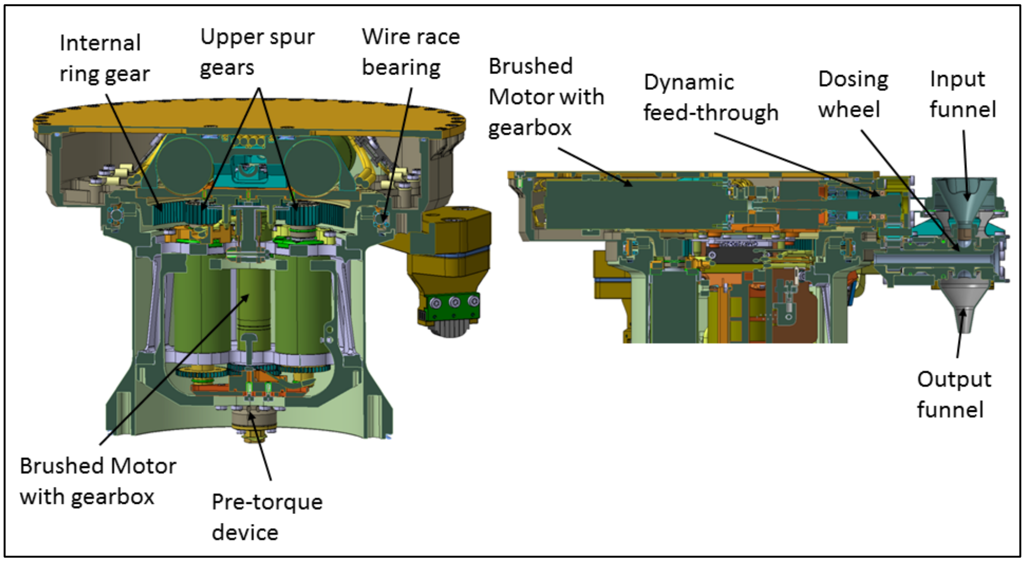

Figure 2. Cross Section of the PSDDS (left) and Dosing Station (right).

The Alternative Transport Container (ATC) is a passive mechanism to by-pass the Dosing Station in case both of them have lost their functionalities due to cementation effects. It can only deliver the entire sample at once to the receptacles of the PSHS. Specifically defined dosing quantities as required by the Ovens are not possible. The design of the ATC can be seen in Figure 3. The ATC consists of two hatches that are opened simultaneously by a passive coulisse when the ATC is driven to the PSHS ATC port. The coulisse is located on the PSDDS housing, The ATC is fixed on the moving hub of the PSDDS-Positioner. The position of the ATC was chosen in such a way that an undesired actuation is avoided during nominal PSDDS operation to eliminate this potential single point failure. The ATC is only actuated when commanded to that position and not during other operations. The ATC input is large enough to collect the entire sample that exits the Crushing Station. The outer hatch is pressed against the inner hatch via springs when the ATC is closed during sample acquisition and transport. When the ATC is moved to its interface port with the PSHS, the ball bearing wheel that is connected to the outer hatch is pushed down by the coulisse, so that the hatch rotates around its hinge against the spring pressure. They are coupled via a spur gear pair to ensure both hatches open simultaneously. To protect the mechanism from dust, a dust shield is screwed onto the top of the outer hatch.

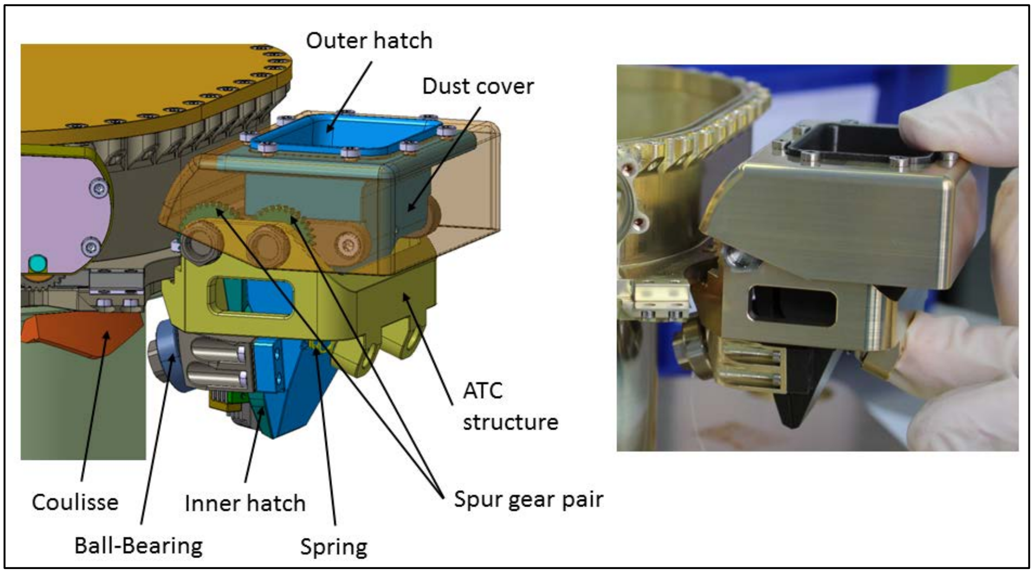

Figure 3. ATC CAD Modell (left) and ATC integrated (right).

The last functionality of the PSDDS provides the Cleaning Device, which is placed on the PSDDS hub. Its design and position can be seen in Figure 1. The Cleaning Device consists of a series of four cleaning blades with spacers in between that are all cut into stripes providing enough flexibility to have the effect of a brush. The cuts are shifted from blade to blade to enable the complete cleaning of the entire powdered sample on the Refillable Container of the PSHS and leaving it visibly clean for the next sample. The blades are made of Gylon (a PTFE-based plastic) which provides enough stiffness for the cleaning function without being too stiff to have powder flicked off the Refillable Container through the ALD. Gylon is one of the few plastics that fulfills the requirements for planetary protection and thus avoids contamination risks.

In the next three subsections three particularly noteworthy design solutions are be described.

<u>Pre-torque Device</u>
Due to the required high accuracy of the mechanism and the limitation with regards to space, mass and ultra-cleaning, a high-resolution encoder could not be implemented on the last gear stage, as it is usually done if such high accuracy is needed. Instead, a low-resolution encoder (8 quad-counts) has been placed on the rear side of the motor, which provides the advantage of a simpler electronic unit and greater robustness. To achieve the required resolution on the end-shaft, a gear with a high resolution (27228:1) has been installed in between the motor and the end-effector shaft. With this, it is possible to measure a high resolution at the end of the drive train but the resulting problem is the high play in the system. The minimization of this play has been achieved through preloading the gears. This means that the actuator is equipped with two spur gears on its output shaft that are counter-preloaded via a leg spring with a constant torque to minimize the backlash in the following gear stages. The torque is divided by these spur gears into two identical gear-boxes and combined again in the internal ring gear on the positioner end shaft. On each gearbox output shaft, a spur gear is mounted that interfaces with this wheel. Due to the preload, both wheels are in contact with the opposite flanks of the internal ring gear teeth, leading to a large reduction of backlash. When torque is introduced by the actuator, the torque at one spur gear increases in the same way the other reduces to provide the resulting torque to perform the motion. However, the torque is never reduced below zero on any one of the spur gears to maintain the preload to always ensure a reduced backlash.

The moving hub is connected to the fixed positioner by a preloaded wire race bearing.

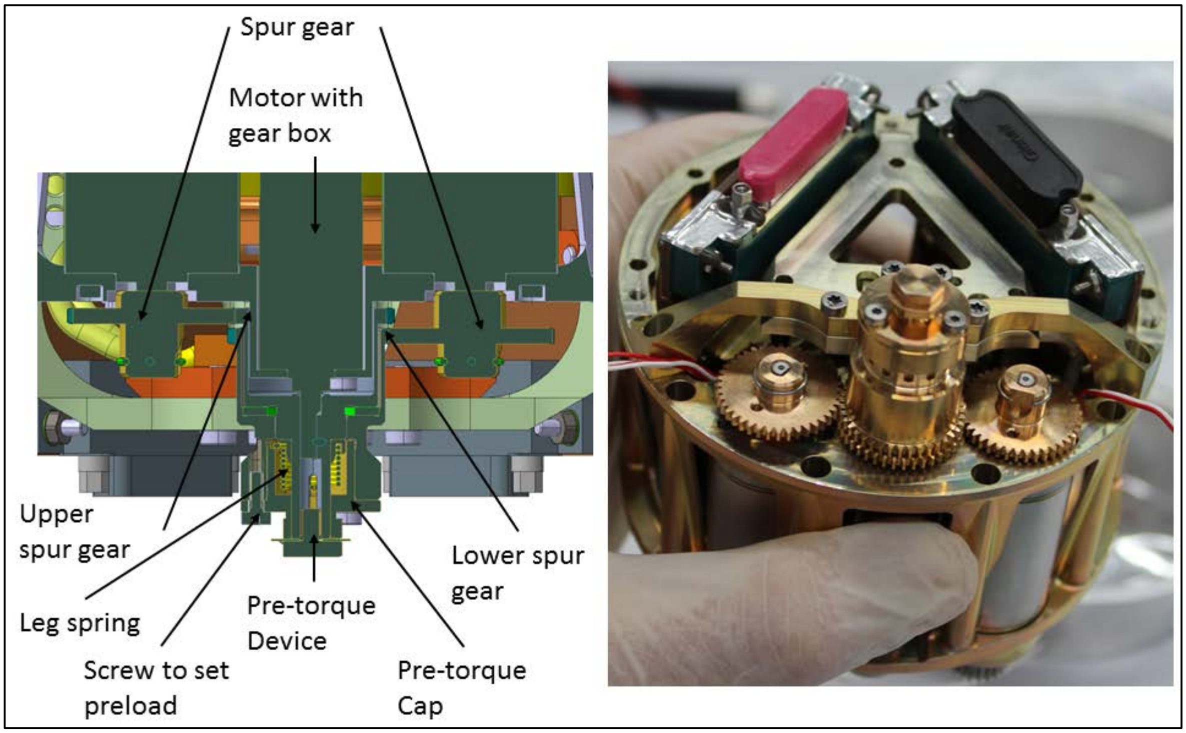

Figure 4. Pre-torque Device CAD model (left) and hardware (right).

<u>Bearing Concept</u>

The only bearing on the positioner to take the axial and radial loads as well as to provide the rotational DOF is a wire race bearing (see Figure 5). This bearing connects the movable part with the fixed structure of the PSDDS. The balls are guided in a PTFE cage and run on four wire races. The bearing is preloaded to sustain the launch loads and to provide the demanded accuracy. It is dry lubricated via the PTFE cage. The balls and the wire races are made of steel.

It is preloaded via the preload frame that is mounted with screws on the structure. The bearing and the outer two wire races are integrated into the bearing housing and the lower inner wire race in the fixed part of the housing. When the bearing housing is placed onto the fixed part of the housing, the last wire race is installed and pushed down by the preload frame, which is shimmed to adjust the preload. This force eliminates the play in the bearing and induces a preload.

The accuracy of the bearing strongly depends on the surrounding structure that has been optimized according to the recommendations provided by the bearing supplier (Franke).

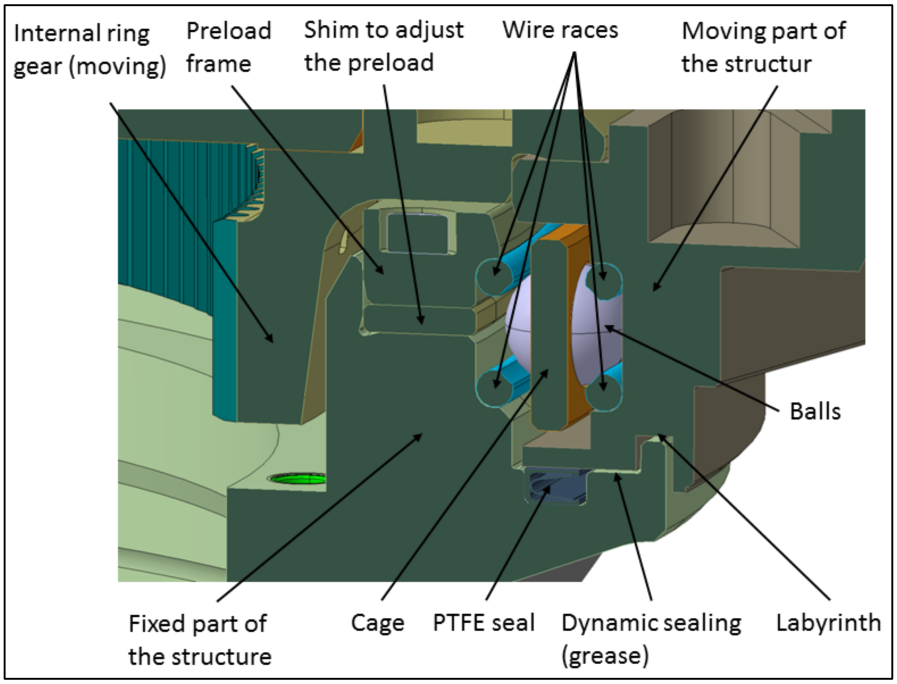

Figure 5. Wire race bearing and dynamic feed-through of the PSDDS.

<u>Dynamic Feed-through</u>
At the beginning of the ExoMars project, a test campaign has been performed in which different possible rotating shaft sealing technologies have been investigated under a representative environment.

The sealing types examined first were O-rings or other polymeric seals supported by springs. These kind of seals were assessed to be not appropriate because of the inherent strong parasitic torque that is created during shaft rotation and the strict material requirements of the mission. The second sealing type that was subjected to these tests was breakable seals. However, this option had to be discarded because, after the unavoidable breakage of the seal, the volume where the instrument measurements take place would have been exposed to the contamination generated by other components of the Rover. Also, the possibility of using magnetic feed-throughs has been investigated but they failed the qualitative assessment because the envelope and mass that was required to transfer the torque would have exceeded the allowed limits.

These preliminary tests showed that dynamic seals, consisting of a grease barrier which is kept in place by polymeric seals or a so-called grease labyrinth provide a leakage rate (even after motion) of 6E-7 mbar*l(He)/s by a seal length of 170 mm and a friction torque not exceeding 950 mNm over a temperature range between room temperature (20°C) and -60°C, which is the worst case operational temperature.

These preliminary tests determined that the dynamic sealing is the option that is to be implemented into the SPDS and practically evaluated in detail. The realization of this concept for the PSDDS can be seen in Figure 5. The sealing function is realized by Braycote 601EF grease that is placed in a labyrinth between the moving and the fixed part of the housing. It is kept in position by one flexible C-shaped sealing ring (which is preloaded by an internal spring) to avoid having the grease pushed out of the sealing over time when the differential pressure of 0.1 bar is applied for a long period or 0.25 bar for a short period (proof pressure). The sealing has a very low stiffness to minimize its frictional torque. This is possible because it does not need to fulfill any sealing function itself.

Testing and Lessons learned

Due to the challenging manufacturing tolerances and constraints, the integration of PSDDS mechanism had to be shortly postponed, this leading to not being able to complete the full testing program in time for the submission of this paper. However, the three major sub-systems of the PSDDS previously discussed in this paper are also present in the PSHS which has already successfully completed the qualification campaign. Test results and lessons learned of the PSHS are fully valid also for PSDDS and are presented in this paper, together with test results already provided by the ongoing PSDDS qualification campaign. The full PSDDS test results will be presented in the oral presentation at the AMS 2016.

<u>Pre-torque Device</u>
PSDDS and PSHS are using the same pre-torque device. They are identical.

During this test, the positioning performance of the PSHS has been determined with an external absolute encoder, which can measure the correct position of the PSHS movable part at any time with reference to the fixed part of the housing. This measurement has been performed under ambient condition (20°C and 1bar absolute air pressure) and Mars-like conditions (-60°C and 7 mbar absolute CO_2 atmosphere). For the evaluation of the positioning performance, the following parameters are important:

- Hard-Stop accuracy:
  - Describes the positioning uncertainty introduced by the Hard-Stop parts when they become in contact.
  - Depends strongly on how the Hard-Stop is achieved and on the switch-off criteria of the motor current when the Hard-Stop is reached.
- Mechanism Play:
  - Is the distance the motor has to run until the end-shaft moves again after a direction change?
- Repeatability:
  - Is the spread of the reached positions when the mechanism is operated multiple times in the same conditions?
- Relative accuracy:
  - Is the accuracy that can be achieved when the mechanism is moved from one point to another?
- Absolute accuracy:
  - Is the distance between the actual position and the position measured by the mechanism's sensor?

During the first positioning accuracy tests, a relatively high deviation from the required absolute accuracy was found. After several measurement series, it became obvious that the measured deviation was completely static and thus reproducible. In consequence, it was easy to compensate this deviation with a compensation curve that has been implemented into the control electronics. The fact that the position tolerances of the teeth in the internal ring gear has the same value as the distance between max and min value of the compensation curve suggests that the observed inaccuracy is solely a result of the manufacturing tolerances of this (last) gear stage.

The results show that all accuracy requirements (resolution 20 µm, absolute accuracy 100 µm) are fulfilled under an ambient as well as a Mars-like environment.

<u>Bearing Concept:</u>
PSHS and PSDDS are using the same kind of wire race bearing. The only difference is that the bearing in the PDDS has a diameter of 110 mm and the PSHS has a diameter of 70 mm. Since the distance between the balls is the same in both systems, the amount of balls in the PSDDS is higher.

The integration procedure for the wire race bearing in PSHS and PSDDS is identical and is performed in the following order:

1. The two bottom rings and the upper outer ring are placed on its dedicated positions
2. The structure is put in position on spacers
3. The cage is inserted
4. All balls are inserted into the pockets of the cage
5. The upper inner ring is inserted
6. The shim and load is inserted
7. The screws are inserted
8. The spacer is removed
9. The screws are tightened

Table 1. Results of the Positioning and Performance Tests

	Ambient	**Mars-like**
Mechanism play		
Min play [µm]	33.3	77.6
Mean play [µm]	63.6	108.7
Max play [µm]	98.5	137.4
Peak-to-Peak value [µm]	65.2	59.8
Hard Stop accuracy		
Hard-Stop accuracy ± [µm]	8.8	5.9
Max [µm]	-0.3	27.6
Mean [µm]	-8.7	20.4
Min [µm]	-17.9	15.8
Repeatability		
Repeatability CW ± [µm]	4.3	3
Repeatability CCW ± [µm]	1.1	1.9
Relative accuracy		
Relative accuracy 1deg step ± [µm]	24	15.3
Relative accuracy 0.1deg step ± [µm]	8.4	6
Relative accuracy 0.01deg step ± [µm]	7.6	8.6
Absolute accuracy		
Max value [µm]	127.6	103.6
Mean [µm]	43	-5.3
Min [µm]	-25.5	-60.6
Peak-to-Peak [µm]	153.1	164.2
Absolute accuracy only CW		
Max [µm]	84.2	0.1
Mean [µm]	39.3	-25.5
Min [µm]	-25.5	-60.6
Peak-to-Peak [µm]	109.7	60.7

The bearing is not self-holding until all the steps are completed. After the integration of the bearing, the rotational torque of bearing preload has to be measured.

The measurement of the bearing torque has to be measured without any other additional torque contribution to achieve a direct conclusion on the torque. The force that is needed to turn the bearing has been measured along a circumference (see Figure 6).

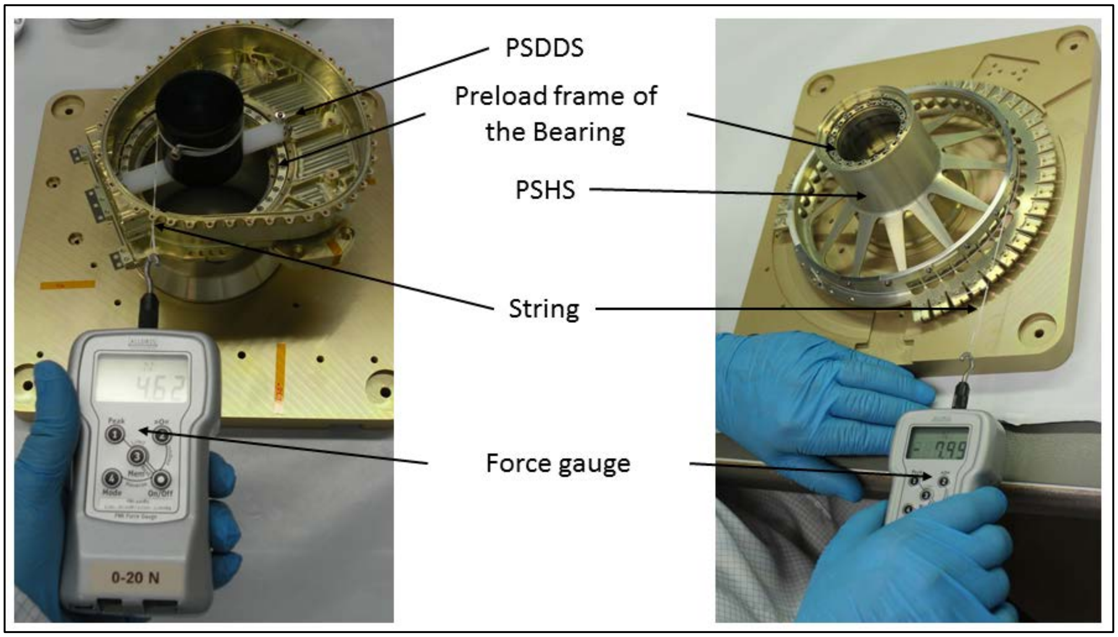

Figure 6. Test setup to measure the preload torque

The nominal values have been determined considering the following requirements:

- The preload is required to be high enough to ensure that the bearing balls do not start moving during launch vibration that would result in a gap between balls and bearing wires. This can cause damages on the bearing race wires, reducing accuracy and lifetime of the bearing.
- The torque resulting from the preload is required to be as small as possible to ensure the movement of the bearing. This needs to be guaranteed over the whole operational temperature range.

In a next step, the shim under the preload frame has to be selected, such that the given preload value is met. During the integration, it was observed that the recommended step width between the different shims of 20 µm was too high to meet the required torque. To achieve the defined torque values the shim step width was reduced to 10 µm. A second observation during the integration was that the tightening torque of the screws has a big impact on the preload. This means that the full preload has to be applied to the screws for every test in order to achieve representative results.

An important positioning requirement for both PSDDS and PSHS is the relative radial position of the dosing output funnel (PSDDS) with respect to the Pyrolysis Oven (installed on the PSHS) and radial position of the Pyrolysis Oven (PSHS) with respect to the Oven Tapping Stations (which is an Instrument mechanism that when operated closes the Oven to facilitate analysis with a Gas Chromatographer. It contains the Gas Chromatographer inlet head and a separable connector to the side of the Oven to supply power to the Oven heaters and read the achieved temperature to control the pyrolysis process.

To verify the Oven position performance during the PSHS test campaign, that due to PSDDS-PSHS mechanisms similarity is directly linked to the Dosing Station positioning performance, the PSHS roundness and evenness have been measured. Their deviations are caused only by the manufacturing tolerances of the structure parts and the precision of the wire race bearing. It has to be mentioned that since the bearing only runs on thin and therefore flexible wires, the structure can be considered as part of the bearing and has also an influence on the performance of the bearing. PSHS roundness and evenness were measured via distance laser sensors. The test parameters under which the test has been conducted are the following:

- 4x ambient, no tilt, velocity 2 deg/s
- 6x Mars-like(-60°C, 6 mbar CO_2), no tilt, velocity 2 deg/s
- 4x ambient, tilt, velocity 2 deg/s
- 4x Mars-like(-60°C, 6 mbar CO_2), tilt, velocity 2 deg/s

The tilt measurements (see Figure 7) has been performed under an inclination of 10° to the horizontal position, which is the maximal incline under which the measurements will be performed on Mars.

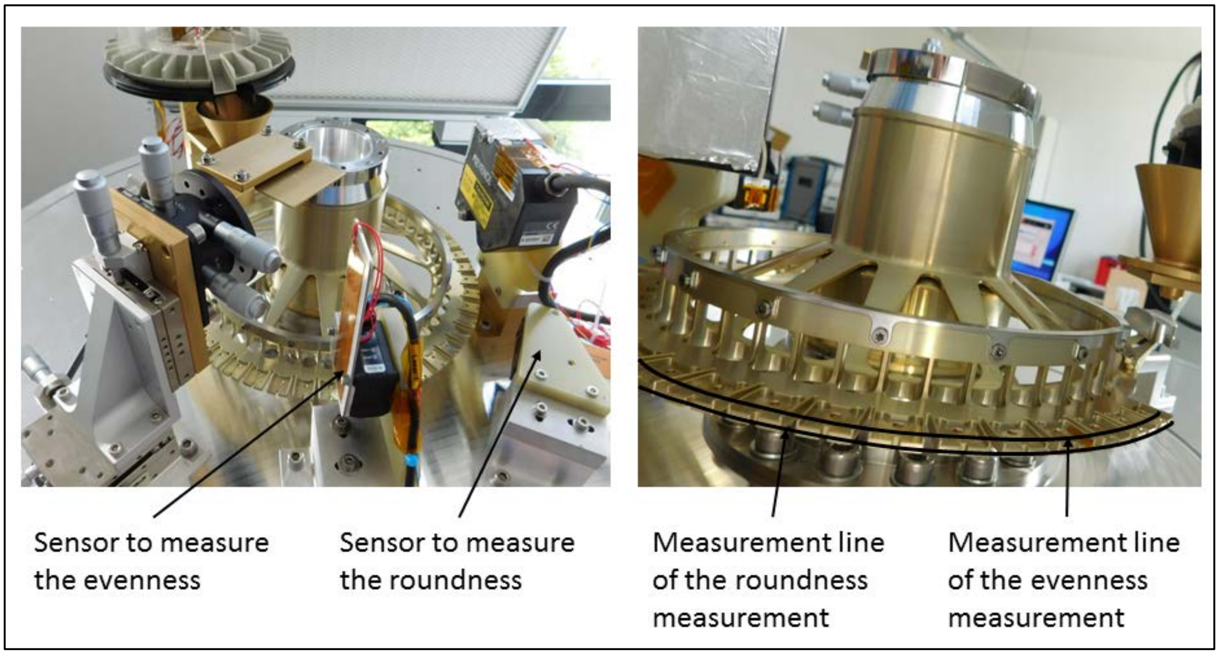

Figure 7. Test setup for roughness and evenness (left), measurement lines for roughness and evenness (right)

Table 2. Results of the Roundness and Evenness Measurements

Repetition	1	2	3	4	5	6	Maximum
Roundness [µm]							
ambient, no tilt	0.152	0.099	0.133	0.094			**0.152**
Mars-like, no tilt	0.143	0.089	0.106	0.147	0.122	0.110	**0.147**
ambient, tilt	0.098	0.120	0.118	0.102			**0.120**
Mars-like, no tilt	0.107	0.185	0.107	0.164			**0.185**
Evenness [µm]							
ambient, no tilt	0.083	0.112	0.079	0.117			**0.117**
Mars-like, no tilt	0.124	0.144	0.122	0.144	0.115	0.154	**0.154**
ambient, tilt	0.156	0.158	0.158	0.166			**0.166**
Mars-like, no tilt	0.130	0.118	0.118	0.126			**0.130**

The results are showing that the maximum radial difference of all measured points along a circle is 0.185 mm (requirement, peak-to-peak 150 µm) and the maximum difference of all measured points along a circle in plane is 0.166 mm (requirement, peak-to-peak 200 µm). The same performances are expected on the PSDDS, this allows precise positioning of Dosing Stations output funnels on the Ovens receptacles for an optimal dosing performance.

Dynamic Feed-through (grease seal)
PSDDS and PSHS both have the same type of dynamic feed-through sealing but they are implemented in different ways. While the PSDDS has on one side an axial plastic seal and a labyrinth on the other side to keep the grease in place (see Figure 5), the PSHS has two radial plastic sealings with grease in between (see Figure 8 [2]).

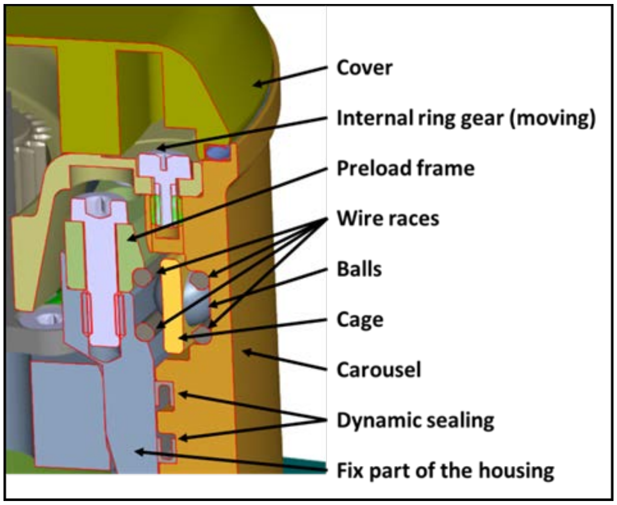

Figure 8. Wire race bearing and dynamic feed-through of the PSHS

To fully evaluate the dynamic feed-through, the integration and preload measurement of the wire race bearing was completed. For this the following integration steps were performed:

1. Open bearing and remove all bearing parts
2. Fill the plastic seal/seals with grease
3. Put the sealing's/sealing in there dedicated positions
4. Fill the space between the sealings or between sealings and labyrinths with grease
5. Reintegrate the bearing as described in the section before

The respective torque of both the bearing and the dynamic feed-through has been measured after these integration steps. As the friction torque generated by the bearing was measured in the integration step before, the additional torque resulting from the dynamic seals and the grease can be easily determined. These tests were only performed during ambient conditions (see Figure 6).

Table 3. Results of the torque measurements

PSDDS	**Max torque [Nm]**
Total	0.85
Preload bearing	0.27
Feed-through	0.58
PSHS	**Max torque [Nm]**
Total	0.86
Preload bearing	0.11
Feed-through	0.75

Compared with the PSHS, the preload in the PSDDS bearing is higher because the step range for the shimming was chosen too high and the required torque of 0.13 Nm could not be met, with either of the shims that have been used. As result, it was decided in co-operation with the supplier of the bearing that the combination with the higher torque will be used because it provides more safety during the vibration test. The only drawback of this solution is that a higher torque has to be provided by the drive-train but since the feed-through creates less friction torque this effect can be compensated. The lower friction torque of the dynamic sealing can be explained with the fact that in the PSDDS there is only one PTFE sealing, instead of two in the PSHS.

During the PSHS test campaign the leakage of the mechanism has been measured with a Helium leak detector. As the PSHS end-effector reaches into the ALD, the pressure must be applied on the outside of the mechanism. To achieve this, the setup was built in a way that the chamber and the inside of the mechanism are connected with each other and through this it was possible to create a vacuum on both sides at the same time with an additional vacuum pump. After this, the connection needs to be separated and the chamber is filled with 100-mbar Helium. When this condition is reached, the leakage measurement instrument is switched on and the measurement starts. This paper only describes the leakage measurements that were performed after the vibration and shock tests. The leakage measurements were done during qualification thermal cycling of the mechanism. In total, 8 thermal cycles were conducted and during the first, fourth and eighth cycle the leakage measurements were performed. For each cycle (1st, 4th, and 8th), leakage measurements were performed under the following conditions:

1. Ambient temperature, 100 mbar
2. Ambient temperature, 200 mbar
3. Ambient temperature, 100 mbar
4. 70°C, 100 mbar
5. 70°C, 200 mbar
6. 70°C, 100 mbar
7. -60°C, 100 mbar
8. -60°C, 200 mbar
9. -60°C, 100 mbar

The test results are shown in the Table 4.

Table 4. Results of the PSHS Leak Rate Measurements

Cycle	**Environment**	**Leak Rate [mbar*l/s]**	
	Temperature [°C]	at 100 mbar	after motion and 200 mbar
1st	20	5.6E-7	8.6E-7
1st	-60	2.8E-7	5.0E-7
1st	70	1.1E-6	1.6E-6
4th	20	3.7E-7	6.3E-7
4th	70	4.7E-7	9.8E-7
4th	-60	3.1E-6	3.2E-6
8th	20	7.5E-7	7.9E-7
8th	70	2.0E-6	2.0E-6
8th	-60	1.2E-6	1.4E-6

During these measurements, leakage peaks could be detected which were not present during the characterization test of the chamber without the mechanism. Therefore, it can be concluded that the peaks are caused by the dynamic seal of the PSHS. The peaks can be explained with the following physical effects:

- Helium absorbed or trapped inside the grease
- Helium penetration through the grease (e.g., bubble penetration)

Nevertheless, the peaks are a valid measurement and had to be taken into account for the overall leakage rate. Rates given in this paper are average rates over a measurement time of 30 min including peaks.

Conclusions and Outlook

The overall concept of the PSDDS presented in this paper and particular design decisions with regards to the three main challenges (pre-torque device, bearing concept, and dynamic feed-through) have proven suitable. The evaluation of the design was supported by test results obtained with the PSHS, which adopts the same design solutions under identical circumstances. The PSHS qualification tests were finished successfully, with satisfying results in all tests. Of special interest were the positioning performance tests, the leakage tests and the results of the roundness and evenness measurement. In the context of the PSHS, all requirements were fulfilled with the proposed design and material solutions, i.e., the PSHS mechanism is ready for the manufacturing of the flight model. Currently, a detailed qualification campaign of the PSDDS mechanisms is being carried out. The results of the PSHS campaign and the preliminary results of the PSDDS tests provide a strong indication that the implemented design choices will lead to a successful PSDDS qualification campaign fulfilling all specific functionality and performance requirements. The final results of the PSDDS qualification campaign will be presented at the AMS.

The four SPDS mechanisms will be sent to the mission prime TAS-I, where they will be completely disassembled and after the replacement of parts worn out by sample material, the extensive ultra-cleaning and sterilization process will be performed with a subsequent mechanism re-integration followed by integration into the ALD-Qualification model with all integration activities taking place inside an ISO3 AMC-9 glove box respectively an ISO7 HC clean room for parts outside the UCZ. After finalization of the integration process, the ALD system qualification campaign is carried out, in which, besides the standard test program (leakage, vibration/shock and thermal-vacuum), several blank samples are processed by the entire SPDS and analyzed by the instruments to investigate the cleanliness and performance of the entire system.

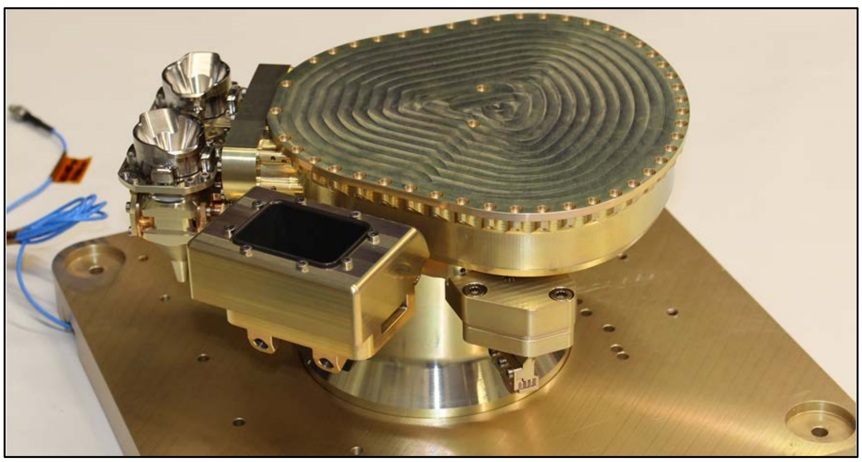

Figure 9. Final integrated PSDDS

References

1. Richter, Lutz., et al. “Progress Report on Development of the ExoMars Sample Processing and Distribution System (SPDS) and Related OHB Sample Handling Studies.” *ASTRA 2015*, ESTEC, Noordwijk, The Netherlands, 11-13 May 2015
2. Paul, Robert, et al. "Development and Testing of a „Backlash-Free“ Gas-Tight High Precision Sample Handling Mechanism for Combined Science on the ExoMars 2018 Rover, ESMATS 2*015*, Bilbao, Spain
3. Phillips, Robin., et al. Development of Brushed and Brushless DC Motors for use in the ExoMars Drilling and Sampling Mechanism. AMS 2012
4. Kannel, J. W. and D. Snediker. "Hidden Cause of Bearing Failure." *Machine Design* (7 April 1977), pp. 78-82.