DEAR – PROVIDING A DUSTY ENVIRONMENT FOR PLANETARY EXPLORATION ROBOTICS TESTING

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ABSTRACT

Planetary or asteroid exploration missions impose a unique constraint on exposed components: the operation in a dusty environment. A variety of effects can be observed, all depending on the nature of the celestial body a space system is operated on. On Mars, dust transported through the atmosphere builds up layers on the solar panels, reducing their efficiency, and dust storms distribute dust particles over all exposed surfaces. On the Moon, the lack of atmosphere prevents the transportation of particles by winds, but particles stirred up by the firing of the descent thrusters, by the wheels of a rover, by solar charging, or due to the interaction of instruments with the lunar regolith, also lead to a contamination of exposed surfaces. Compared to larger bodies, asteroids only have very little gravitational pull, thus resulting in them being surrounded by a dust cloud at all times, again creating a dusty environment for a space system to operate in.
In preparation of the ESA DEAR (Dusty Environment & Robotics) project, OHB System AG is currently setting up a test bench to perform environmental tests from early breadboards to qualification models (see Figure 1). This paper provides an overview of the capabilities and limitations of said test facility.

Figure 1: DEAR Testing Facility

1 DUSTY ENVIRONMENT AND ROBOTICS

Human and robotic exploration missions to the Moon, Mars, or other celestial bodies have become more important in recent years. Exploration missions of any kind face unique technical challenges related to the environment. Dust is, among others, one of these challenges as the hardware used for surface exploration needs to work reliably in its presence.
OHB System AG, together with Colandis GmbH, developed a test chamber for operation and test of spaceflight hardware in a dusty laboratory environment, using different kinds of dust simulants in a safe way.
Testing hardware in dusty environments usually imposes health and safety concerns on the sample materials used (e.g. [7]). Lunar regolith, for example, contains particulate matter (particles with an aerodynamic diameter > 10 µm) and also regolith simulants are prepared to match the particle size distribution (see Figure 2 and Figure 3). While such materials can be handled with certain care in laboratory conditions, it is not advised to stir them up without proper protection.

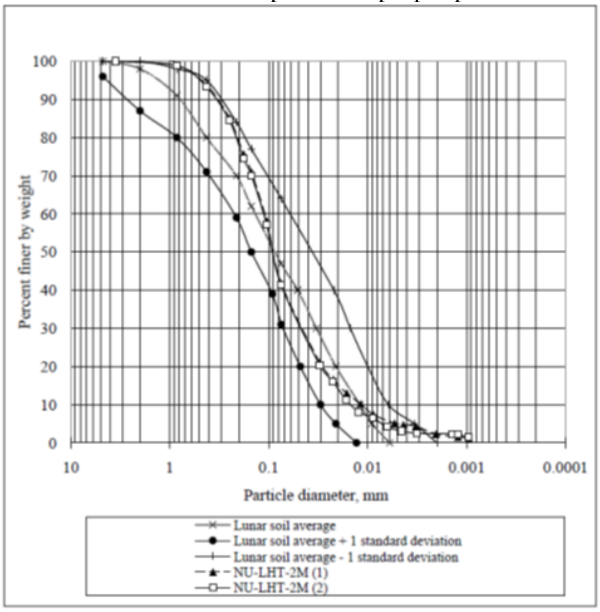

Figure 2: Lunar highland region soil average particle size distribution and distribution of NU-LHT-2M, based on Apollo 16 samples [1].

The DEAR (Dusty Environment and Robotics) Box

developed and available at OHB System AG is sealed in a way that allows hardware to be subjected to an environment containing particulate matter without imposing health threats on the operator.
The chamber shall be used for functional testing, ranging from early laboratory testing of concepts on breadboard level, to verification purposes during a qualification campaign, and also plausibility checks for already operational exploration hardware.

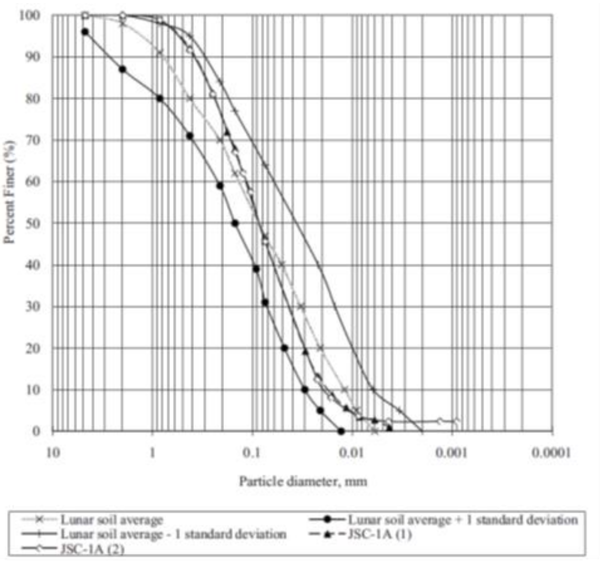

Figure 3: Lunar mare region soil average particle size distribution and distribution of JSC-1A [2].

A unique feature of the DEAR Box is that it not only holds an encapsulated volume for dust testing, but also is equipped with two adjustable fans, filter units, and flaps to simulate different events. It is possible to create a number of different air flow dynamics such as: a) a low but constant air movement simulating, for example, Martian dust storms, b) short but stronger wind events like dust devils, or c) even short, strong and directed blast events simulating backdraft from descent thrusters which stir up surface material prior to touchdown of a landing vehicle. This is not only relevant from a contamination point of view, but also the cleaning effects of such events can be investigated. Dust settling on solar panels, radiators, or optical surfaces impedes their performance. On Mars, cleaning events due to dust storms or dust devils have been observed in the past, partially recovering the performance (see Figure 4). Both effects, settling of dust on horizontal surfaces as well as cleaning events can be simulated in the DEAR Box.
Apart from various dust events, also the effects of dust contamination on wear can be analysed. The drive trains of mechanisms designed for sample handling or analysis need to be shielded against potentially abrasive dust particles and such shielding concepts can now be tested and verified in a controlled environment. Another important field of wear analysis are the effects of dust on EVA astronaut (Extra Vehicular Activity) suits. Especially regions of the suits exposed to relative motion (e.g. elbow- or knee-joints) can be impaired by abrasive particles.
A third field of investigation is the testing of recovery/cleaning methods on representative on-ground models (if available) to assess the feasibility prior to operating the methods on the flight hardware. Also the effectiveness of these concepts (e.g. electrostatic discharge or wipers) can be tested early to gain valuable inputs for the design process.

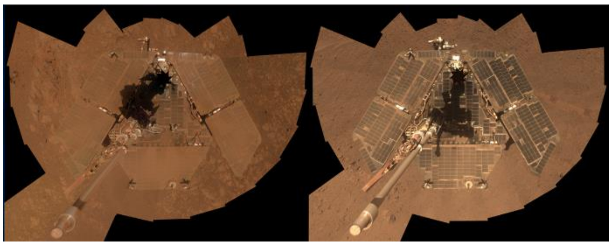

Figure 4: NASA Opportunity Rover in January 2014 (left) and after a cleaning event again in March 2014 (right) [4].

2 DEAR BOX DESIGN DESCRIPTION

The DEAR Box structure is built from aluminium profiles with surface elements made from PVC. The box consists of three separate volumes: the test compartment, the intake volume and the discharge volume. Outside air is moved into the intake volume through a powerful adjustable fan. The intake volume is connected to the test compartment through pneumatically actuated flaps on either side of the compartment. As long as the flaps are closed, the fan builds up pressure in the intake compartment which can be released into the test compartment by opening one or both flaps, thus creating a powerful blast. As long as the flaps are open and the intake fan is running, there is a constant adjustable air flow inside the test compartment as long as the discharge fan is operating. It moves air out of the test compartment and through a fine filter unit preventing dust from exiting. A schematic of the DEAR Box architecture is presented in Figure 5.
It is crucial to adjust both fans and their interaction with the flaps in a way to match the relevant behaviour for the test. Measuring equipment is available to experimentally adjust the settings prior to a test run, as the interaction of test hardware and air flow needs to be taken into account for each new test. Specifically, the redistribution of dust inside the test compartment as well as the sedimentation are measured by fine dust air counters which are also used for health & safety aspects.
The test compartment is 1200 x 800 x 800 mm³ (L x W x H). It has a stainless-steel sheet metal bottom and black PVC elements on the lateral sides above the flaps. For visual inspection, the front is equipped with a large safety glass window, and acrylic glass sheets have been inserted in each of the doors on the backside of the chamber. An aluminium bar is installed along the test compartment

which holds a 300 x 300 mm² interface plate providing a M6 hole pattern as a standard interface. The plate can be removed if a different interface is required, or the test hardware exceeds its size.
Ten feedthroughs are installed for cable diameters ranging from 1 mm to 16 mm in order to operate the hardware or GSE inside the test compartment. Unused feedthroughs can be closed in order to maintain the sealing of the compartment.
Special care has been taken to ensure that dust cannot exit the test chamber during operational test runs. The whole test compartment is sealed and all air leaving the test compartment has to pass the filter element. If sample materials containing particulate matter are used, a measuring device is available to measure the actual concentration of particulate matter inside the chamber, providing an indication of when all dust has settled and it is safe to open the cabinet doors.

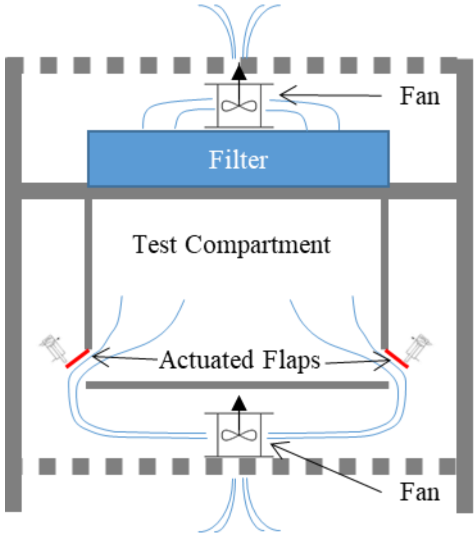

Figure 5: DEAR Box Architecture

Summary of Main DEAR Box Features

- Outside Dimensions: 1840 x 800 x 2040 mm³
- Test Compartment Dim.: 1200 x 800 x 800 mm³
- Filter F7 or ePM1 55%, efficiency > 80 % acc. EN 779
- 2x RZB LED Light Strip Lightning
- Large safety glass window on the front
- Double Wing Door with acrylic glass inserts at the back
- Access openings: 2x 580 x 800 mm²
- Standardized Interface Plate 300 x 300 mm², M6 threaded hole pattern
- Feedthroughs for 10 Cable Glands (from 1 mm to 16 mm each)

Specific upgrades (e.g. UV light, specific humidity, temperature) can be implemented if required.

3 Characterization and Testing

Initial tests have been performed to characterize the flow inside the test compartment and the corresponding sample transport. Tests were carried out with reference dusts, a mixture of natural calcium carbonate with a known particle size distribution. The available test materials and the test results are presented in the following sections.

Test Materials

Currently, four different test materials are available at OHB System AG, however, the use of other materials is possible as well. The available sample materials are:
- ISO reference dust eskal 60
- ISO reference dust eskal 150
- Lunar Regolith Simulant TUBS-T
- Lunar Regolith Simulant TUBS-M

ISO Reference Dusts eskal 60 and eskal 150

The reference dusts are used for a safe and quick characterization and for testing activities. The samples consist of natural calcium carbonate ($CaCo_3$) [4]. Their non-hygroscopic [4], insensitive to humidity [4] composition and stable [4] nature simplify sample handling and storage.
Reference dusts can be obtained with different particle size distributions. The particle sizes of the two available dusts are Gaussian distributed around 60 µm (eskal 60, see Figure 6) or 150 µm (eskal 150, see Figure 7).

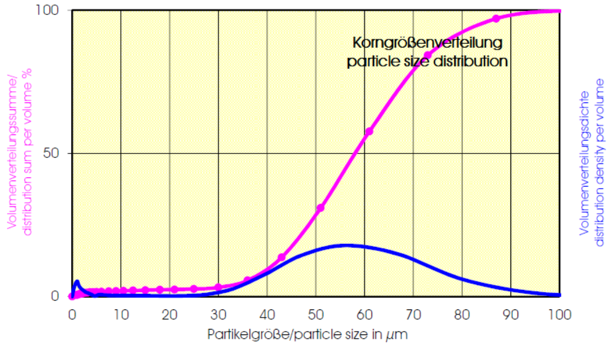

Figure 6: eskal 60 particle size distribution [4]

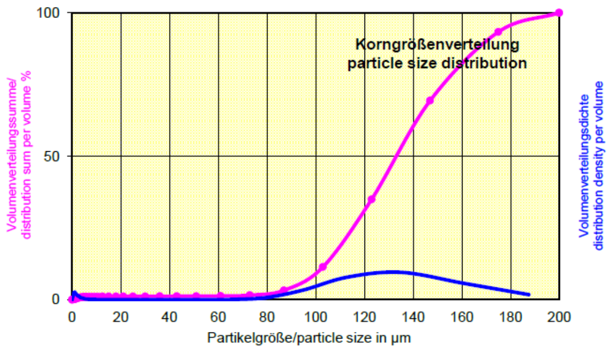

Figure 7: eskal 150 particle size distribution [5]

For health and safety reasons, the reference dusts do not contain particulate matter and therefore allow test or characterization runs with high frequency as it is not necessary to take special precautions prior to opening the test compartment after each run.

Lunar Regolith Simulants TUBS-T & TUBS-M

The TUBS-M and TUBS-T regolith analogue samples are available at OHB. They are manufactured by TU Braunschweig according to the international recommendations from the regolith simulant working group and as similar as possible to Apollo samples in chemistry, particle size distribution and particle shape [6]. To enhance scientific value, the simulants' characteristics in terms of chemical and mineralogical composition and bulk properties, are matched as closely as possible with real lunar regolith [6]. The cumulative particle size distribution for TUBS-T and TUBS-M is presented in Figure 8.

TUBS-T generally matches the average chemical composition of lunar anorthosites, the major lithologies of Lunar highland terrae [6] and is representative of lunar highland regolith particle size distributions. TUBS-M chemically and physically represents lunar maria region regolith [6].

TU Braunschweig, as manufacturer, can also adapt and tune the simulant composition to site-specific requirements, and detailed parameter studies and the inclusion of orange or green glass additives are possible [6].

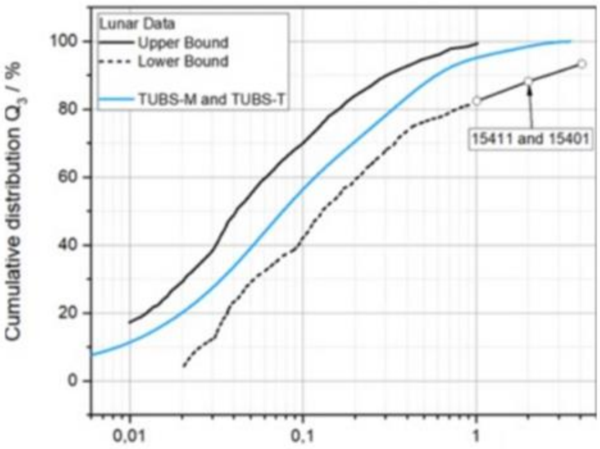

Figure 8: TUBS-M & TUBS-T Regolith Simulant Cumulative Distribution Characteristics [6]

It is important to point out that the regolith samples are sharp-edged fine dust which require special safety instructions and precautions. The health protection, but also the protection of hardware, test hardware and infrastructure are mandatory aspects. It is advised to run pre-tests with ISO dust standards.

Flow Characterization

The speed of the two fans providing air flow in the chamber can be adjusted continuously. During early operational tests of the DEAR Box it became apparent that for settings below 20-30 %, the fans produce an airflow too weak to pick up dust and therefore the range < 20-30% does not have practical value for DEAR Box operations. The highest 20 % of the operational fan-speed show unwanted behaviour in two regions: First, from 80 % onwards, the pressure in the intake compartment (see also section 2) is too high for the pneumatic flaps to open. And second, the airflow picks up dust quite efficiently, but most of the dust is pressed/sucked into the filter unit, leaving very little material in the test compartment during operations. So, the sensible operational range of the DEAR box lies between 30 % and 80 % fan speed.

Measurements of airspeed and direction have been performed at 60 locations inside the chamber for fan speed settings of 10 %, 30 %, 50 %, 70 %, and 90 %. Both fans were operated using the same speed setting. To minimize disturbances, all equipment was removed from the chamber except for the hot-wire anemometer (see Figure 9). Measurements were averaged over 3 minutes of continuous data acquisition at each of the 60 measurement locations.

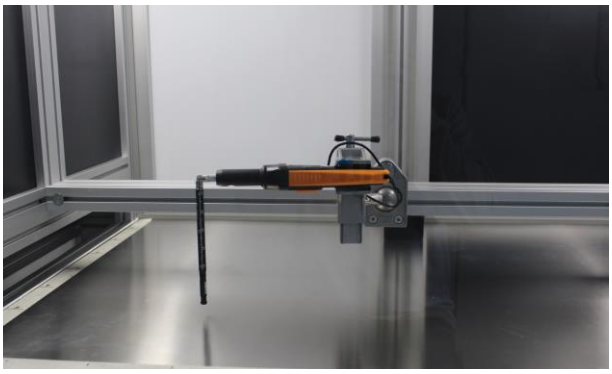

Figure 9: Flow Characterization using a hot-wire anemometer.

In principle, the measurements confirmed the expected flow characteristics. The results of all 60 measurements are presented in Figure 10. It can be seen that the general airflow direction does not change with the setting and that only the magnitude of the airflow is affected. However, it is also evident that the flow is not mirrored on the left and right side of the chamber but has an additional twist to it resulting in the X component of the flow to be positive near the doors and negative on the window-side of the test chamber.

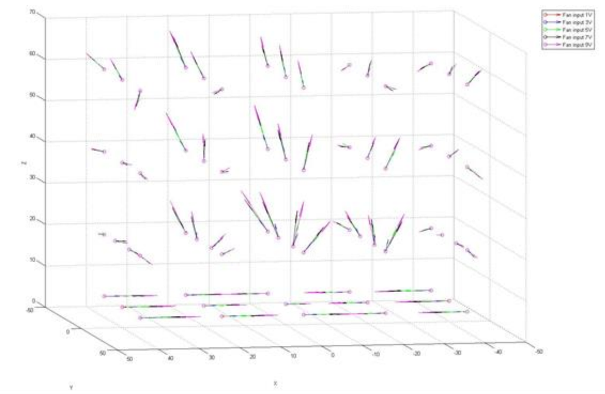

Figure 10: Stacked representation of all measured flow vectors. Vector length proportional to air speed.

The minimum and maximum air speeds achieved with each fan speed are presented in Figure 11.
Air speed results show that while the maximum air speed increases significantly with higher fan speeds, the minimum flow does not follow this trend in the same way. This is due to the fact that there are regions in the chamber, especially near the edges where the air generally flows with smaller velocities.
In other words, even for higher fan speeds there are always regions with moderate flow velocities.

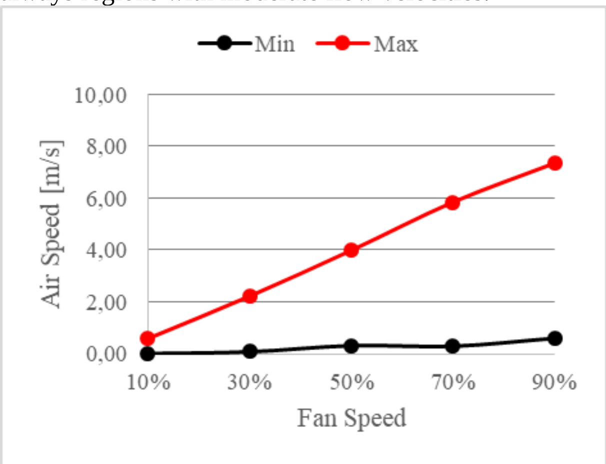

Figure 11: Minimum and maximum air speeds for different fan speed settings

Dust Distribution

The dust distribution capability of the DEAR Box was also characterized using ISO reference dust with a particle size distribution around 60 µm. For this test, the location of the test object was not varied. A 3D printed test cube was equipped with particle traps (adhesive foil) on 5 sides (all lateral sides and the top). 10 g of reference dust were distributed equally to four fixed pick-up points, located symmetrically in front of the flaps (see Figure 12).

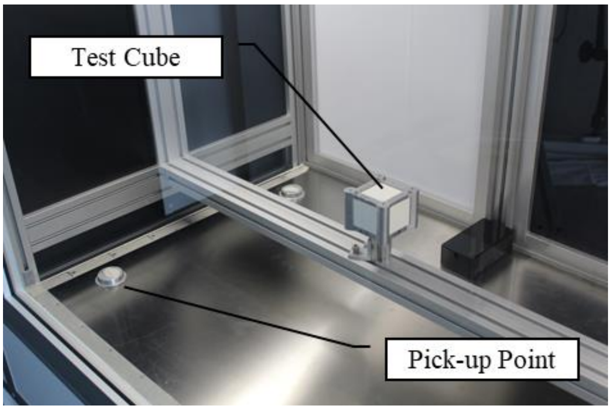

Figure 12: Test Cube and Pick-Up points

The tests were carried out with different fan speed settings ranging from 40 % to 80 %, covering the identified operational range of the DEAR box (see Flow Characterization Chapter).
After each test run, the particle traps were secured, labelled, and the chamber was cleaned to keep the amount of dust inside the chamber constant. New particle traps were used for each new test and new dust was distributed on the pick-up points.
The tests provide an indication on the amount of dust that is transported to a certain area inside the test compartment in a certain amount of time. The test cube was mounted centrally in a height of 25 cm (coordinates [0; 0; 25], see Figure 13). The tests were carried out in an automated and controlled way. Fan speed was set to the desired value and the fans were switched on. After 10 seconds acceleration time, both flaps were opened simultaneously and left open for 60 seconds. Afterwards, the flaps were closed and the fans were switched off after another 5 seconds.

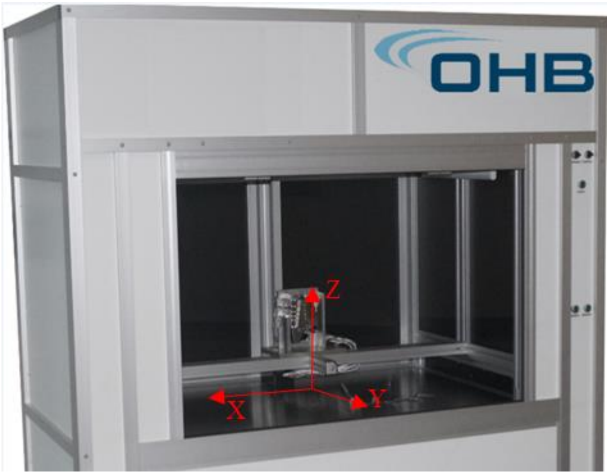

Figure 13: DEAR Box Coordinate System

The results for each test cube face are presented in Figure 14 to Figure 18. Even though visual examination showed that pick-up and distribution of dust inside the chamber improved with fan speed, the tests results do not follow this observation, as the detected particle quantities on the

foils have a tendency to drop between 50 % and 70 % of fan speed, rising again for the 80 % speed test. One noticeable result is that most particles adhere to the foils for the low-speed test at 40 % power. An explanation might be that the air speeds were not sufficient to remove already adhering particles accumulating more material over the 60 second testing period.
Generally, it can be deducted from the test results that lower fan speeds are beneficial for maximizing particle distribution on the test surfaces.

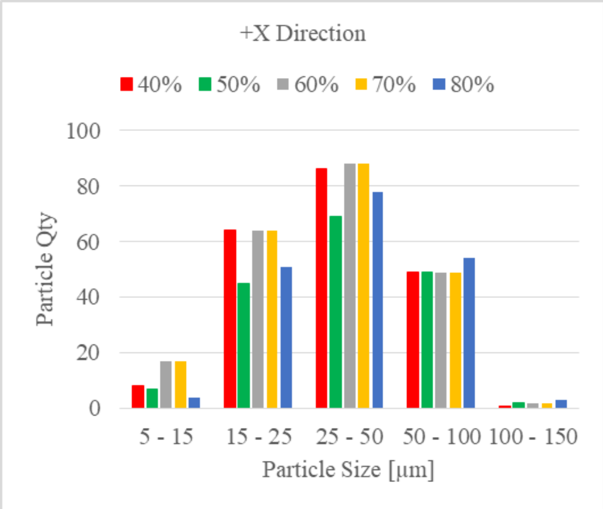

Figure 14: Particle quantity and size distribution for +X direction.

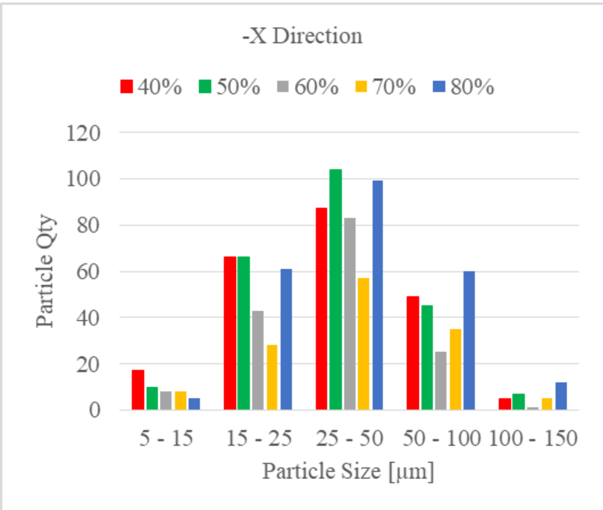

Figure 15: Particle quantity and size distribution for -X direction.

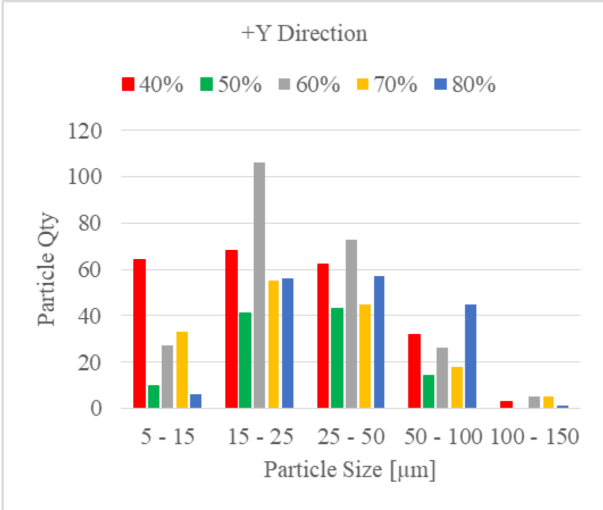

Figure 16: Particle quantity and size distribution for +Y direction.

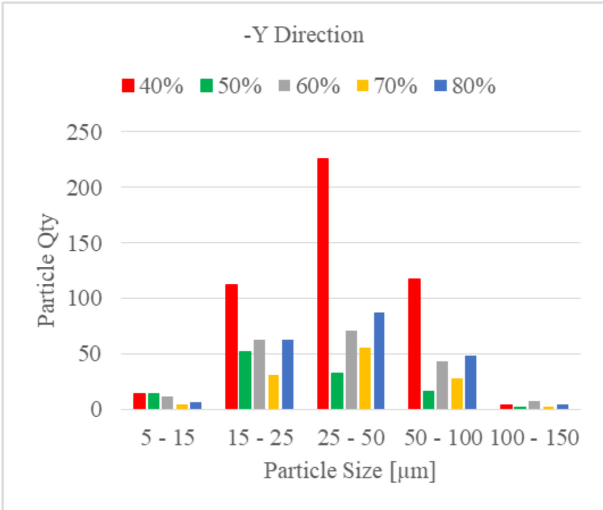

Figure 17: Particle quantity and size distribution for -Y direction.

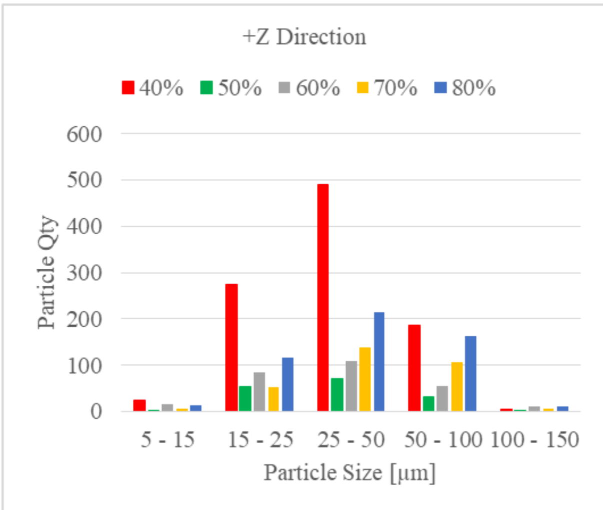

Figure 18: Particle quantity and size distribution for +Z direction.

4 CLEANLINESS AND CONTAMINATION

DEAR Box testing activities are closely followed by OHB System AG's cleanliness and contamination control group, as dusty environments are addressed as a contamination aspect at OHB. This covers engineering and design support, detailed investigations on contamination sources, transport phenomena and mitigations. Protection of critical hardware, passive by design, or active by cleaning, is one dominant aspect. *Cleaning* has to be separated into on-ground cleaning, and potential cleaning as part of the operational concept in space. The latter is much more difficult but improves the reliability of the mission until end-of-life by providing recovery potential for expected and unexpected events. The philosophy of the workflow is in brief:

1. Investigation of the contamination source (amount, chemistry and particle distribution);
2. Identification of transport phenomena (time, amount and frequency);
3. Assessment of the performance degradation to be expected with respect to the acceptable limits;
4. Identification of recovery possibilities in cooperation with the engineering support of OHB;
5. Analysis of out-times and risks.

All work is performed according to ECSS standards and generally ESA project conform. This covers the preparation of procedures, technical notes and reports. The experimental evaluation of the 5 key aspects above was the driver for the DEAR box development.

In addition to the design support, the cleanliness and contamination group offers a variety of measurement approaches to determine the dust contamination on the test hardware: Particle witness samples, particle rinsing samples, or active and passive particle stamps. The samples are either to be analysed directly at the OHB cleanliness laboratory or through the OHB partner network. Advanced methods of analysis like electron microscopy to identify scratches, or CT scan to investigate potential contamination of sealing, bearings or lubricants, are available through the OHB partner network as well.

5 DUSTY ENVIRONMENT APPLICATION RESEARCH

The DEAR box is currently foreseen to support the ESA Dusty Environment Application Research project (DEAR project, contract No. 4000132901), an activity led by Microelectronica S.A. and supported by OHB System AG.

The Dusty Environment Application Research project provides an experimental test area to systematically study the negative effects of lunar regolith dust on space relevant materials, sensors, actuators, mechanisms, solar cells, radiators, and instrumentation. The risk on performance in respect of motion, optical, electrical thermal, but also astronautic applications can be addressed. In the DEAR project, the development and evaluation of active countermeasure technologies for dust removal in a lunar environment shall be covered. Optical surfaces and airtight seals are the main targets due to their mission criticality. It is targeted to achieve TRL 4 for the demonstrators.

6 CONCLUSION

The DEAR facility aims at providing a volume where components can be subjected to various levels of dust contamination, where various simulants can be used, and where simulants containing particulate matter, particles with an aerodynamic diameter of less than 10 µm, can be used. Particles of such sizes are considered a health hazard when inhaled. The DEAR box available at OHB System AG provides a safe working environment. An enclosed and sealed volume of 0,8 m³ is available for testing. Two pneumatically actuated flaps, one on each side of the chamber, connect the test compartment to a second enclosed volume in which one fine-filter unit and one additional fan are located. The fan speeds, and therefore, the intensity of the airflow is adjustable. This, together with the various combinations of flap operations allows to simulate different scenarios. With a regolith simulant distributed in trays on the bottom of the chamber, a soft but continuous air flow will pick up and distribute smaller amounts of dust over a longer period of time, while a pressure build-up with closed flaps and the abrupt opening of them can create a short but intensive pick-up similar to what can be expected when regolith is stirred up, for example, by descent thrusters.

Tests with ISO reference dusts have been performed, showing that both the air flow directivity as well as the achievable air speeds are sufficient to cover the envisaged range of dust events. The dust distribution tests performed showed that a significant amount of dusts can be picked up from the sample trays and redistributed inside the test compartment. However, the correct setting of fan speed and the right amount of dust need to be derived experimentally based on size, shape and location of the test article/object, as these parameters interfere with the free flow measured and characterized during the initial tests. The results presented above provide a valuable starting point for such an activity.

7 Acknowledgments

The support of the DEAR project team and especially the support of the TU Braunschweig team with regolith simulant know how and samples shall be explicitly mentioned here.

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