Dusty Environment and Robotics - Simulation and Optimization of the DEAR test chamber's internal air flow with respect to simulant pick-up and distribution

T. Tattusch (1), S. Ober (1), T. Maguire (1), R. Paul (1), A. Müller (1), V. Böhm (1), Prof. M. Pietras (2)

(1) OHB System AG, Manfred-Fuchs-Str. 1, 82234 Weßling, Germany; email: tim.tattusch@ohb.de:
(2) Hochschule München, Lothstr. 34, 80335 München, Germany; email: markus.pietras@hm.edu

ABSTRACT

This paper provides an overview of the capabilities, functions, and characteristics of the *Dusty Environment and Robotics Test Facility* (DEAR-Facility), a test facility available at OHB System AG to provide a save testing environment for hardware of different kinds (e.g., mechanisms, fabrics, coatings, optical components) in dusty environments. The focus lies on presenting the results of a computational fluid dynamics (CFD) analysis, which addressed specifically air flow inside the test chamber and its interaction with articles of various sizes. Predictions on special particle distribution and dwell-times are made to assist in the definition of test parameters representative of the expected mission scenario.

1 DUSTY ENVIRONMENT AND ROBOTICS

In recent years, human- and robotic exploration missions to the Moon, Mars, or other celestial bodies have become more relevant. 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 (see also [1]).

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.

A unique feature of the DEAR-Facility 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 1). Both effects, settling of dust on horizontal surfaces as well as cleaning events can be simulated in the DEAR-Facility.

Apart from various dust events, also the effects of dust contamination on wear can be analysed. The drive trains of mechanisms or joints of robotic arms 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.

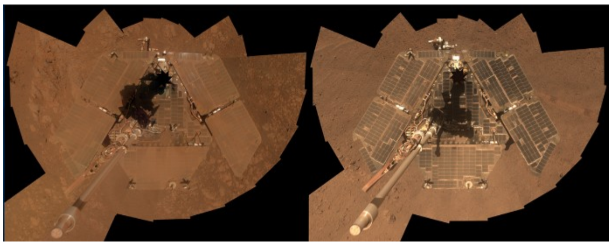


Figure 1: NASA Opportunity Rover in January 2014 (left) and after a cleaning event again in March 2014 (right) [5].

A main driver for setting up the DEAR test chamber was the provision of an experimental test area to systematically study the negative effects of regolith dust on space relevant materials, sensors, actuators, mechanisms, solar cells, radiators, and instrumentation. Instead of simply applying dust to a certain area, the operational scenario of a certain equipment is broken down in different of dust contamination:

1. Dust Generation
2. Dust Transport
3. Dust Accumulation

The method of dust generation is important to assess which kind of particles are likely to be generated. E.g., mechanically stirring Martian soil with the wheels of a rover is likely to move grains much bigger than those transported by Martian winds during dust storms.

Based on the assessment of the nature of the particles, the method of dust transportation (e.g., mechanically, atmospherically) in a mission specific scenario is taken into consideration as next step of the assessment.

Lastly, it is important to assess how dust can accumulate in certain critical areas (e.g., seals, optics) depending on the design of an equipment.

By assessing each of these aspects, the risk on performance in respect of motion, optical, electrical thermal, but also astronautic applications can be addressed, allowing for the development and evaluation of active countermeasure technologies.

As a result of the investigations mentioned above, sample materials with a smaller bandwidth in their grain size distribution can be selected to match the expected contamination of a certain area more closely, or to study the effects of particle sizes on certain parameters (e.g., performance) or technical features (e.g., seals). These tests allow to gain more knowledge due to the variability of parameters, than by testing solely with representative dust simulants (for more information refer to [1]). This enables the identification of critical particle sizes and allows for the definition of more precise design measures.

2 CLEANLINESS AND CONTAMINATION

DEAR-Facility 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-Facility 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.

3 DEAR-FACILITY DESIGN DESCRIPTION

The DEAR-Facility structure is built from aluminium profiles with surface elements made from PVC. Outside air is moved by an adjustable fan into the test compartment. Pneumatically actuated flaps on either side of the test compartment can be employed to block or direct the flow. With closed flaps, 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. With open flaps and running intake fan, there is a constant adjustable air flow inside the test compartment. A discharge fan moves air out of the test compartment and through a fine filter unit preventing dust from exiting. A schematic of the DEAR-Facility architecture is presented in Figure 2.

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 considered 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.

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.

Ten feedthroughs are installed for cable diameters ranging from 1 mm to 16 mm to operate the hardware or GSE inside the test compartment. Unused feedthroughs can be closed to maintain a sealed 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 passes 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.

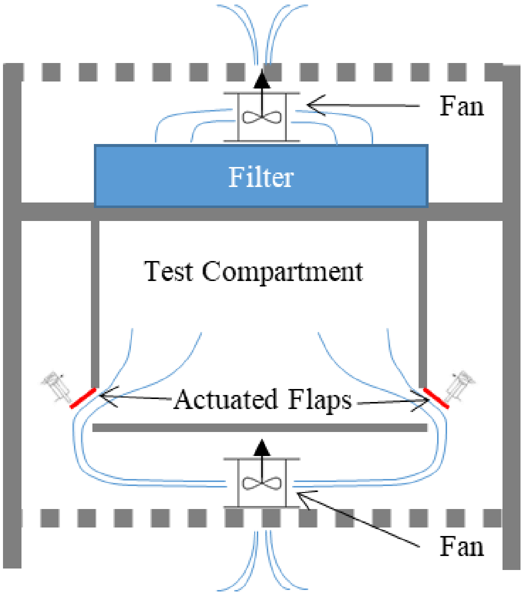


Figure 2: DEAR-Facility Architecture

4 Main DEAR-Facility Features

The characteristics of the DEAR-Facility are presented below:

- 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.

5 SIMULATION OF FLOW CHARACTERISTICS AND DUST DISTRIBUTION

To address the different scenarios addressed in section 2, the internal flow characteristics of the DEAR-Facility and their interaction with particles need to be understood in terms of particle distribution and particle dwell time inside the test compartment as, due to the nature of the DEAR-Facility design, particles eventually end up being filtered.

5.1 General information

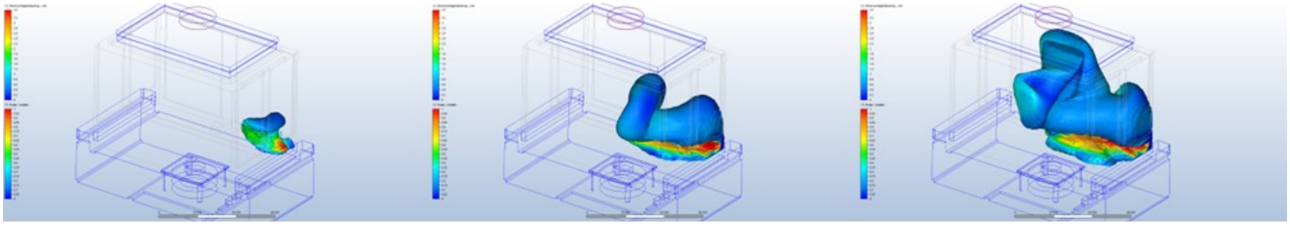
In order to understand and optimize the airflow and special distribution of the dust in the DEAR-Facilities test chamber, a computational fluid dynamics (CFD) simulation was created. The software used was Autodesk CFD. The goal of the simulation was to use it as an assessment for the movement and spread of dust particles at different airspeeds and particle sizes, not a highly accurate prediction of the movement of single particles. For this reason, short simulation runtimes were one of the main requirements, to be able to analyse a broad spectrum of settings and their effect.

5.2 Simulation setup

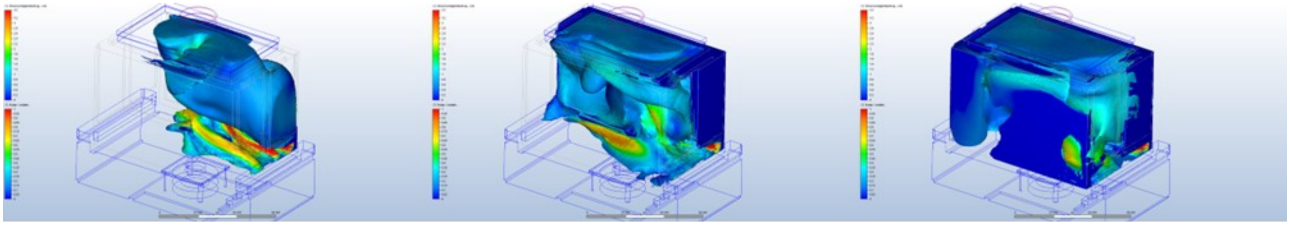
The point of interest was the internal test chamber, a simplified model starting from the intake at the lower fan and ending at the upper fan was determined to be representative. The fans were modelled using a centrifugal blower (lower fan) and an internal fan (upper fan), functions of Autodesk CFD. This way the effect of the fans gets modelled without the need for rotation regions, hence reducing the runtime. The filter acts as a resistance and was modelled as such. A mesh sensitivity study was carried out, the simulation results were compared to measurements taken at the DEAR-Facility with the main factor being the pressure loss from the intake up until the intake of the upper fan. Because of the focus on runtime, a mesh with an element size of 3cm was determined to be enough.

5.3 Airflow behaviour and dust distribution

The airflow in the test chamber is highly turbulent, mainly due to the geometry of the DEAR-Facility. This was visualized in the real world using a smoke generator and sewing thread. The second component defining the airflow is the lower radial fan. Due to its mechanics, it introduces a rotational motion into the airflow, this vortex propagates into the test chamber and shapes the airflow. The resulting airflow does not converge to a steady state; hence a transient solver was required to visualize the airflow and dust distribution.
For the dust distribution dependent on time, a scalar was introduced into the simulation at the special coordinates of the simulant pickup points. This scalar marks the air that went through the pickup points, functioning like simulations showing smoke spread. The scalar allows for a change of the air properties due to saturating the air with dust, because of the low amount of simulant used currently this change is estimated to be negligible. This scalar does not account for the reduction of simulant available in the pickup point or for the different behaviours due to particle size.



Time Step 0.5s
Time Step 1.0s
Time Step 1.5s



Time Step 2.0s
Time Step 3.5s
Time Step 5.5s

Figure 3: Theoretic dust distribution simulation results for an exemplary sample pickup-point using 40% fan speed

Figure 3 shows the simulation results for an exemplary pickup point using 40% fan speed and a scalar range of 0.1% to 100%. Within 5 seconds the simulation suggests a total contamination of the test chamber, with varying levels of concentration. By including a test body in the simulation, the effect of the placement of the test body and the pickup points can be estimated with respect to changes in the contamination on specific parts of the test body.

Besides the special distribution, the dwelling time of dust particles in the test chamber is an important parameter. This dwelling time was estimated using weighted particle traces, with different diameters. Autodesk CFD creates these particle traces by using the streamlines at discrete timesteps and adapts them to account for the weight and aerodynamic effects, but the time dependence due to turbulent airflow is not considered. Figure 4 shows the analysis of the dwelling time dependent on particle size and airspeed. To get an averaged value and reduce the influence of a single favourable or unfavourable flow, the particle traces emanate over the whole width of the flaps. Each value is averaged by using 19 particle traces at 5 discrete time steps.

For this analysis the material density used correlates to the density of the TUBS-T regolith [3], with 2.71g/cm3. The selected particle diameters are the median values of the particle ranges from the analysis presented in [1].

The simulation results estimate, that for particles with a diameter of less than 32 µm, once airborne, only short dwelling times are achieved. This means that with the current setup, to achieve prolonged exposure to particles with a diameter smaller than 32 µm, a continuous injection of particles is required. For brief exposure pickup points with a limited amount of regolith are sufficient.

The particle traces for the majority of 122 µm and a significant portion of 74 µm do not leave the test chamber in the calculated timeframe, so looking at the dwelling time for those particle sizes does not lead to conclusive results. However, when looking at the estimated behaviour, a clear change can be observed with a change of airspeed. This is shown in Figure 5

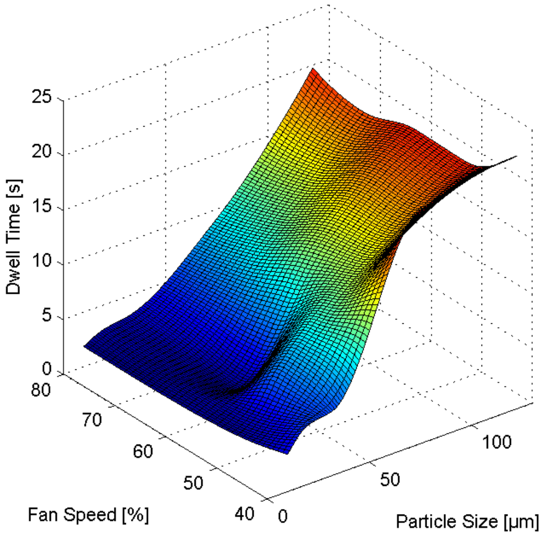
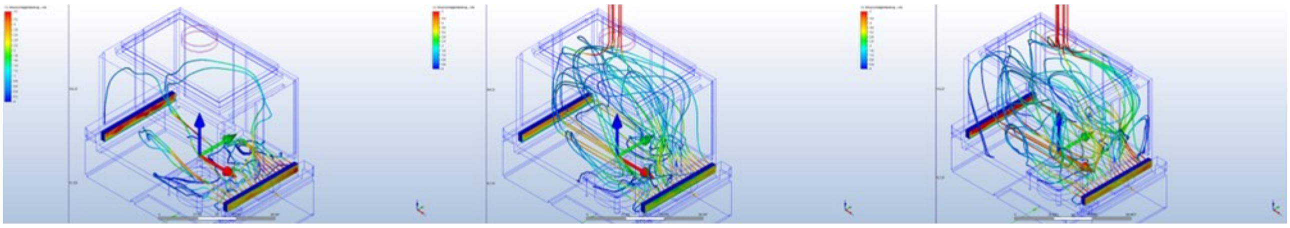


Figure 4: Theoretic dwell time of dust particles inside test compartment.

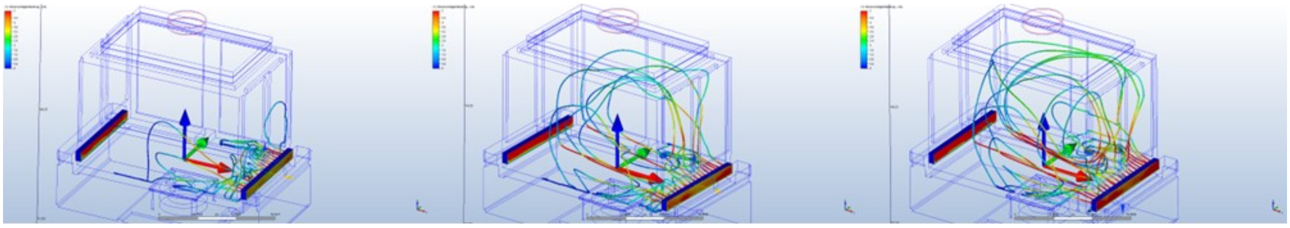
For lower airspeeds, the conditions to lift these particles occur very infrequently, and persist not long enough to push these particles into the filter. With increasing airspeed, the conditions for lifting them are increased, until similar behaviour to the smaller particles can be observed (see 74 µm for 80% fan speed).



Power 60% - Particle Ø 74 µm
Time Step 4.0s

Power 70% - Particle Ø 74 µm
Time Step 4.0s

Power 80% - Particle Ø 74 µm
Time Step 4.0s



Power 60% - Particle Ø 122 µm
Time Step 4.0s

Power 70% - Particle Ø 122 µm
Time Step 4.0s

Power 80% - Particle Ø 122 µm
Time Step 4.0s

Figure 5: Theoretical particle traces inside the DEAR-Facility test compartment; for 74 µm and 122 µm particles

5.4 Continuous particle injection

As presented in section 5.3, the analysis results indicate that while particles are distributed within the whole test compartment, the dwell times of especially small particles is low and thus a continuous supply of particles is required to maintain exposure.

For this reason, a particle dispersion device was installed that allows to continuously inject sample material. The device is placed outside the test compartment, loaded with particles, and a hose is fed through the existing glands into the chamber and secured at the desired location of injection. The rate at which particles are dispersed through this hose can be adjusted, which allows to set parameters according to the specific testing requirements.

The particle dispersion device can also be used when effects of contamination are to be assessed in scenarios that do not involve atmospheric transport of particles. Particles can be sprayed reproducibly at desired locations areas and the effects can be studied.

6 CONCLUSION

The aim of the DEAR facility is to provide an environment where the effects of various levels of dust contamination on equipments or components can be studied. The CFD analysis carried out provided significant insights in the interaction of particles with the air flow, allowing for an improved understanding of the expected environment in terms of particle distribution and dwell time inside the test compartment.

The inclusion of the simulation in the planning phase of testing scenarios allows for better adjustments of the facility settings, such as correct fan speed for the particle distribution of the used regolith and selection of the regolith injection method. Further, the placement of the test body and its effect on the spread of dust and the occurring level of concentration at the test body can be estimated beforehand. This reduces the time needed and uncertainties regarding the tests.

In addition, the implementation of a particle dispersion device increases the variety of test scenarios as the air flow created by the facilities fans is no longer the sole means particle transport. With the particle dispersion device, particles can be applied reproducibly to specific areas of interest.

7 Acknowledgments

The support of the DEAR project team and especially the support of ESA shall be explicitly mentioned here.

8 REFERENCES

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