

Uniform Dust Deposition System for Dust Tolerance Studies

Stephen Gerdtz
Nathan Jimenez
Patrick H. Dunlap, Jr.
National Aeronautics and Space Administration
Glenn Research Center
Cleveland Ohio 44135

Abstract

Future missions to the Moon will require mechanisms and materials to effectively and reliably operate in the presences of lunar regolith. One of the challenges of developing such technologies is terrestrial testing with lunar dust simulants. Dust has a stochastic nature of depositing and it can be difficult to accurately apply it to surfaces of interest. Deposition density, particles size distribution, and percent coverage are all factors that affect the quality of dust mitigation testing. Therefore, to enable such testing the dust mitigation and seals teams at NASA Glenn Research Center (GRC) have developed a system that can uniformly and repeatably deposit lunar simulants on a range of surfaces. Testing of the Dust Deposition System (DDS) and an associated simulant preparation methodology have quantified the levels of uniformity and precision for this system. Furthermore, the deposition system has been paired with automated micrograph capturing and machine learning image analysis to correlate the images of dust on a surface to deposition density (in g/cm^2). This correlation alleviates the need for tested samples to be accurately weighed with milligram precision and may be a useful tool for in-situ contamination evaluation on the Moon. This paper covers the design and validation testing for the DDS.

Introduction

A renewed interest in lunar exploration was initiated by the signing of Space Policy Directive 1 in December 2017 (Executive Office of the President 2017). The directive calls for NASA to lead an innovative and sustainable exploration program with commercial and international partners, and it helped lay the foundation for the Artemis program which will send the first woman and next man to the surface of the Moon. The Artemis program along with the Human Landing Systems (HLS) and Commercial Lunar Payload Services (CLPS) programs have spawned an array of development efforts for lunar surface assets. These assets range from human rated and robotic landers to autonomous mobile explorers and deployable towers. All these systems depend on the reliable operation of their mechanisms and components, which may be susceptible to performance degradations or failure due to dust.

Lunar dust has often been described as “...one of our greatest inhibitors to a nominal operation on the Moon” (Crotts 2014). This is because lunar dust has abrasive and electrostatic properties that can disrupt systems in various ways (Heiken et al. 1991). Meteorites impact the Moon constantly, fracturing rocks into fine particles called regolith that coat the top four meters of the Moon’s surface (Pieters et al. 2000). The lack of atmosphere and geological transport mechanisms (e.g., wind and rivers) on the

Moon means that there is no process to reduce the roughness of these particles, leaving them extremely angular and abrasive (Stubbs et al. 2005). An additional aspect to the challenge of lunar dust is the electrostatic charging of these particles due to interactions with the local plasma environment and solar electromagnetic radiation (Hood et al. 2021). This results in the regolith becoming electrostatically attracted to surfaces of the opposite charge making it very difficult to remove (Buhler et al. 2007). These conditions can cause the regolith to obscure optical systems, create extreme wear on astronaut's space suits, disrupt mechanisms and rotary systems, and compromise the critical seals needed for habitable volumes and effective Environmental Control and Life Support Systems (ECLSS) (Wood et al. 1991). The need to develop technology that can not only tolerate but thrive in the presence of dust is critical for the establishment of sustainable architectures both on the Moon and for destinations further into the solar system.

These risks associated with lunar dust were recognized as a top concern by NASA. As a result, NASA established a dust mitigation working group consisting of stakeholders and technology developers to work together to generate solutions for this problem (Winterhalter et al. 2020). One of the issues identified by this group was the difficulty in performing tests in a repeatable fashion when evaluating the effect of lunar dust on systems. Measures have been taken to standardize the testing of dust amongst the stakeholders in the community in the form of NASA Technical Standards like "Classifications and Requirements for Testing Systems and Hardware to be Exposed to Dust in Planetary Environments" (NASA 2021). However, dust is often applied to mechanisms or target surfaces in a much less controlled manner with spoons or by sprinkling it on by hand. Although these methods fulfill the requirement of contaminating a specimen, the amount of regolith deposited is often not measured, uniform, or repeatable. The creation of a system that can deposit a known amount of simulant per unit area at a known size fraction would create a reliable way of testing a vast array of mechanisms in a standardized way across the industry. The development and validation of such a system is the focus of this paper.

The Uniform Dust Deposition System (UDDS) was developed with the aim of producing not only a system but a series of techniques for depositing and characterizing dust simulant for stakeholders to have available for testing. One such technique outlined in this paper is the pre-processing of the simulant for testing. Preparation of the simulants is instrumental for deposition uniformity due to the sensitive nature of deposition physics to initial conditions. Once prepared, the simulant is loaded into the UDDS on a vibration plate that is then agitated using an electric motor by spinning an eccentric mass. The resulting deposition is a uniform column of particles of selectable size fraction which settles onto a desired target. The system then transfers the target to an inspection area where images of the surface are taken with a microscope to characterize the amount of simulant deposited. The analysis is completed using a trained machine learning algorithm that recognizes particles, counts them, and feeds back a percent coverage. The entire process occurs within a dry air glove box at a Relative Humidity (RH) of less than 1%. Furthermore, all components were designed such that the whole system could be introduced and operated in a vacuum chamber to better represent the lunar environment. Finally, this

paper outlines how the accuracy and precision of this system was evaluated through validation and verification testing.

System Requirements

As mentioned previously, testing with lunar regolith simulants can be a difficult task to undertake given the stochastic nature of granular physics. Many factors contributed to the system's design requirements to produce a reliable, repeatable, and safe technique for depositing dust. The main factors included accuracy of the deposition, uniformity of the deposition, particle size distribution (PSD), imaging resolution, relative humidity, operators' working environment, and throughput of test articles.

Accuracy and uniformity of the deposition were two of the critical design requirements. The desired accuracy for the system was based on previous research conducted by Oravec et.al, which determined that for size 2-309 silicone (S0383-70) O-rings the critical mass of dust contamination, was 6.3 mg ($\approx 1.5 \text{ mg/cm}^2$) (Oravec 2014). With the contamination to failure levels for seals being so low, it seemed an appropriate target for a system that needed to have a very high level of accuracy, so the UDDS deposition accuracy requirement was set at 1.5 mg/cm^2 . This high accuracy is also critical for solar panel and thermal radiator testing since their performance degradation is a function of contamination level (Kawamoto 2019).

The second critical design requirement for the UDDS was uniformity of the deposition on the target surface. For this requirement, the coefficient of variation of the percent coverage (i.e., the percent of the target surface area covered with lunar simulant) was the metric used. For the test data to be of use to a stakeholder, a dusted surface needs to have uniform layer of dust of a known particle size distribution (PSD) at a known concentration. To capture this need into a verifiable requirement images would need to be collected at several locations on the contaminated surface during testing. Each image would be analyzed for the percent coverage and the coefficient of variation for the collection of images would need to be less than 20%. This would allow for the assurance of uniformity across a range of deposition density levels since each would yield different percent coverages (i.e. higher density would result in higher percent coverage but also the chance for variability).

To produce a deposition with an accurate PSD the system would need to incorporate standard sieves procured from a manufacturer with a certificate of accuracy. The PSD could then be varied by switching out the standard sieves since they would contain varying mesh sizes. The sieves are used in conjunction with pre-processing and pre-sieving of the simulant to deliver the desired PSD. For example, for a desired PSD range of 150 – 250 μm , the simulant would need to be pre-sieved to remove all particles smaller than 150 μm (No. 100 sieve) and larger than 250 μm (No. 60 sieve). Then the pre-processed simulant would be placed into a No. 60 sieve when testing, ensuring all particles could pass through. To quantify the PSD and determine the uniformity of deposition on the target surface, a requirement for the imaging resolution was required.

The imaging requirement for the UDDS was a resolution of 10 μm with at least 100 pixels.

While considering requirements, the design of the Lunar Dust Adhesion Bell-jar (LDAB) system was explored. The LDAB is a system whose primary design criterion was to emulate the lunar environment thermally, atmospherically, and electrostatically (Gaier and Sechkar 2007). Based on the review, a decision was made to design a system with components compatible with a 10^{-6} Torr vacuum, like the LDAB, but the system would deposit simulants in dry air over a much larger area. Dry air is critical to a lunar dust testing environment since simulant can absorb moisture out of the air. Moisture in the simulant can then cause the finer particles to agglomerate after passing through a sieve while being deposited on a surface. This can cause an artificially large particle to form on the surface and can affect the quality of the tests (Yuan et al. 2014). To mitigate this phenomenon, it was decided that the simulant would be desiccated prior to use, and dry air at less than 1% RH would be pumped into the glove box before testing to purge the system.

The final requirements considered were operational ones related to human safety and throughput maximization. To comply with NASA and OSHA (Occupational Safety and Health Administration) standards for airborne silica, it was decided that the deposition would occur inside a commercially available glove box (MBraun UniLab Pro model). This eliminated the need for an operator to wear a respirator and had the added benefit of keeping the lab space free from lunar simulant contamination. As for throughput, the target test time was set to 30 minutes to allow for multiple depositions in one workday. Automation ensured the system would be available for numerous test campaigns for stakeholders as well as repeatability from test to test. The requirements of the UDDS in its current form are summarized in Table 1.

Table 1: Summary of Requirements.

Requirement	Specification
Deposition Level Accuracy	$\pm 1.5 \text{ mg/cm}^2$
Deposition Uniformity	<20% Coefficient of Variation of percent of area covered
Deposition Surface Size	60 cm diameter (24 in. diameter)
Test Article Height	15 cm height (6 in. height)
Atmosphere	< 1% RH
Vacuum (Compatibility)	10^{-6} Torr
Exposure Control	Glove box
Deposition Test Time	< 30 minutes
Simulant Size Fraction	20 μm – 1000 μm
Image Resolution	10 μm
Temperatures	Room Temperature (evolvable with heaters and cold plates)

System Design



Fig. 1: All-up System Inside Glove Box



Fig. 2: Deposition Sub-System

The UDDS is separated into three major sub-systems: the deposition sub-system, the transfer sub-system, and the imaging sub-system [Fig. 1]. The deposition sub-system is where the deposition sieves are mounted along with the eccentric mass motor which generates the vibration. The transfer sub-system consists of an automated spinning plate which sits on a mechanized rail system that allows for repeatable positioning of the target surface. Finally, the imaging sub-system houses the microscope and remotely controlled camera mounted on a rail with a motorized focus stage. Together these sub-systems function automatically to ensure quick and repeatable tests.

For a more in-depth description of the systems refer to NASA/TM-2021-0024128.

Deposition Sub-System

The sub-system consists of a frame which supports a vibration plate via four spring mounts, two standard sieves with a dust trap, and an eccentric mass motor. All components of the deposition sub-system are made of vacuum-compatible materials such as aluminum, 304 stainless steel, and 18-8 stainless steel. The spring mounts rest on an adjustable portion of the frame [Fig. 2] and allow the vibration plate to be agitated in isolation. The adjustability of the frame allows the operator to select different deposition heights or accommodate larger fixturing. A two-sieve architecture was adopted to improve the deposition uniformity and control the deposition rate. Both sieves are installed with the same mesh size to ensure all particles can pass through.

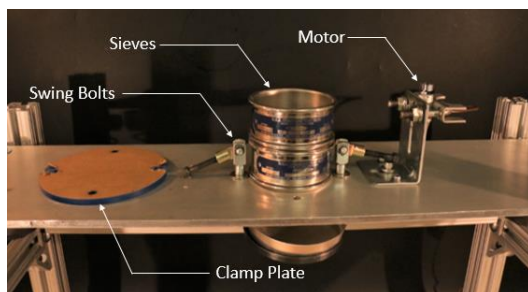


Fig. 3: Vibration Plate Top View

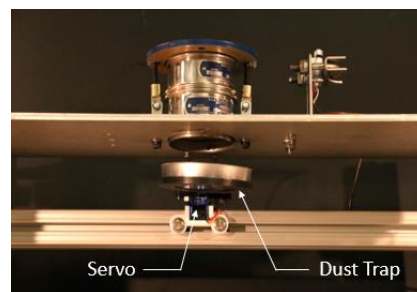


Fig. 4: Dust Trap

Another component mounted on the vibration plate is the eccentric mass motor and its mounting bracket. The motor is mounted such that the axis of rotation is normal to the top surface of the vibration plate creating a circular horizontal movement [Fig. 3].

To further increase the accuracy of the deposition sub-system a dust trap was added under the vibration plate beneath the openings of the sieves. The dust trap is mounted to a rigid point on the deposition system frame to eliminate any unwanted mass on the vibration plate and protect the servo motor from the vibrations. This dust trap consists of a servomotor connected to a lightweight arm which holds an aluminum cup [Fig. 4]. The cup catches any simulant that leaves the sieves before the eccentric mass motor is operating at the desired speed (e.g., ramping up from rest). The dust trap actuates only when the deposition is at steady state. Its actuation is quick enough to allow for immediate deposition on the target surface but slow enough to mitigate disturbance of the deposition column.

Transfer Sub-System

The transfer sub-system's function is to accurately position the target surface beneath either the deposition sub-system or the imaging sub-system in a repeatable fashion. A secondary role of the transfer sub-system is to help automate the deposition and characterization process and produce accurate and repeatable movements. The system consists of a pair of parallel rails which support a transfer carriage. On that carriage sits a spin plate where the target surface is installed. Both the rail and spin plate components are motorized using two NEMA 23 stepper motors connected to chain drives [Fig. 5]. All components of the transfer system are made of vacuum-compatible materials such as aluminum, 304 stainless steel, and 18-8 stainless steel.

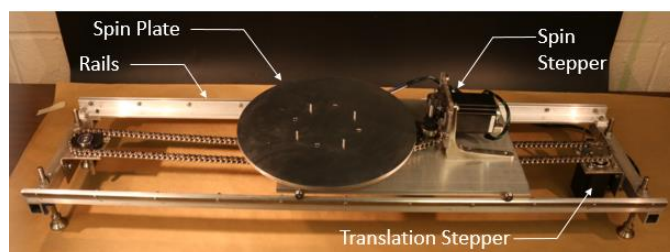


Fig. 5: Transfer Sub-System (Shown Outside the Glove Box)

The last component of the transfer sub-system is the spin plate. This plate sits on the transfer carriage and is driven by a chain drive connected to a stepper motor which also sits on the carriage [Fig. 5]. This plate has positioning pins for repeatable alignment of target surfaces and fixtures.

Imaging Sub-System

The imaging sub-system captures micrographs at various locations of the sample surface while it is still inside the dry-air environment of the glove box. A stereo microscope (Motic SMZ-171 model) capable of magnification levels from 7.5x -100x was coupled with a 10 MP microscope camera (Moticam 10+ model) to inspect the sample surfaces and obtain the desired micrographs. To protect the imaging sub-system from dust, a custom enclosure and stand were built around it [Fig. 6]. The bottom face of the enclosure features an optically clear 5 cm diameter quartz disc below the

objective lens to provide a clear sightline to the target surface. To illuminate the target surface, a ring light was mounted around the objective lens of the microscope.

To obtain an image with a depth of field larger than the microscope's lenses could offer (for example, the curved surface of an O-ring), a z-stacking capability was implemented. This was accomplished by attaching a NEMA 23 stepper motor to the focus stage of the microscope. To complement this capability and improve the automation of the testing the imaging system was tied to the transfer system's spin plate to allow rotation of the target surface. This rotation feature can be used when images of several locations of a target surface are desired. Once the imaging routine finishes an image stack the spin plate can rotate to a new prescribed area, and another stack can be captured. This is especially useful when testing deposition uniformity. All the stepper motors were controlled with the same software as the rest of the system on a control box outside of the glove box.

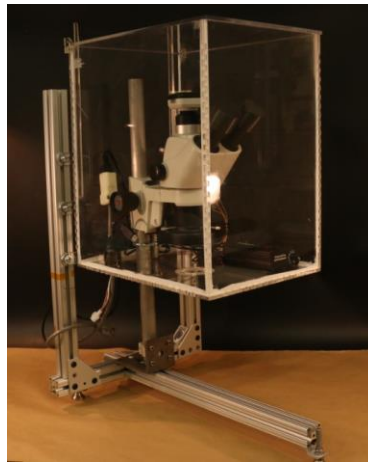


Fig. 6: Imaging Sub-System

The microscope, camera, and motor are used to capture several images of the target surface at varying focal distances. This creates an image stack which is post-processed using ImageJ software through the FIJI package. This entire process is summarized in NASA/TM-2021-0024128. An example of an image the algorithm would analyze is shown in Figure 7. To obtain sufficient image quality and confidence in the data, 100 pixels was set as the minimum resolution a single particle could be imaged with. This resolution then implies that the smallest diameter particle the current system can accurately identify is 8 μm which is less than the 10 μm requirement.

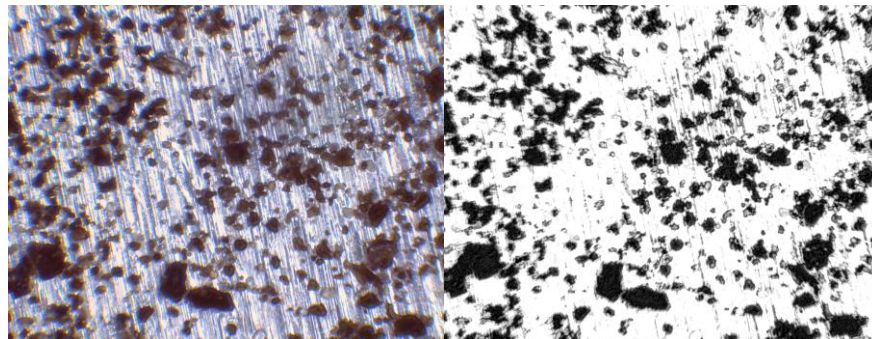


Fig. 7: JSC-1A on an Aluminum Tray at 50X Magnification.

Left: Focused Image, Right: Segmented Image

Peripheral Components

For the measurement of the RH and the temperature a Vaisala DMT340 sensor capable of reading RH from 0 – 70% ($\pm 0.004\%$ + 20% of reading) and temperatures from 0 – 80°C ($\pm 0.2^\circ\text{C}$) was used. The sensor's probe was mounted inside the glove box and was biased toward the upper middle of the back wall. Another instrument that facilitated testing was an Ohaus EX225/AD electronic balance also located inside the glove box. This device not only met the weighing requirements (220 g capacity with 0.01 mg readability) but was compact enough to fit inside the glove box. This capability improved the accuracy of the mass readings since the measurements were taken in a dry environment where, the samples would not absorb any atmospheric moisture.

Simulant Preparation

The simulant preparation process is outlined in the NASA-STD-1008 and NASA/TM-2021-0024128 and consists of four steps: sieving, drying, rolling, and storing [10]. To sieve the simulant, the guidelines of ASTM D6913 are followed to achieve the desired PSD using a mechanical tapping sieve (ASTM 2004). After the simulant been sieved it is desiccated in a vented oven which has been pre-heated to 110°C for at least 12 hours per ASTM (2010) standard D2216. After the simulant is dried sufficiently, it is placed in a sealed cylindrical container and rolled on a lab roller for 30 minutes. This allows the PSDs that were selected to recombine into a more homogenous distribution within the container. Experience shows batching the larger desiccated batch into smaller portions in separate containers helps to ensure that each test sample is insulated from passive separation due to settling. The simulant should be stored in a dry environment. Note that the samples tend to separate over time. To address this issue, the sample containers should be rolled again before use (even if just by hand) to ensure homogeneity. This batching process also helps expedite test flows by making separate, smaller containers of simulant available for every test.

Test Procedure

The test procedure for a typical deposition experiment is separated into three phases: pre-testing, testing, and post-testing. Before conducting any testing, the simulant is prepared by following the process in the “Simulant Preparation” section.

Pre-Testing

The pre-testing phase begins by ensuring that all appropriate safety controls are in place, particularly appropriate respiratory protection. Any equipment required for the test is placed inside the chamber and the atmosphere of the glove box is purged with dry air until it reaches less than 1% RH. After purging, the temperature and atmospheric pressure of the lab are recorded. Finally, the sub-systems of the UDDS (deposition, transfer, and imaging) are checked out, and dry runs are performed to ensure that they are functioning properly before the simulant is loaded.

Testing

The first step of the testing phase is to load the simulant into the sieves of the deposition system. After cleaning and brushing the sieves, the lower sieve is left in-place in the vibration plate, and place the upper sieve on a weighing dish. The simulant container is then selected and rolled at least 10 full rotations about its major axis, and the contents of the jar are deposited onto the center of the upper sieve. The upper sieve and weighing dish are then lifted together and gently swirled in a circular motion along the plane of the sieve mesh once to ensure that the simulant completely covers the mesh surface of the upper sieve. Finally, the upper sieve is stacked on top of the lower sieve on the vibration plate, and the sieve clamping plate is installed.

After the simulant has been loaded, the target surface is positioned on the carriage of the transfer system and is clocked in a known and repeatable fashion. This is particularly important for target surfaces that are larger than the 7.63 cm-diameter deposition area and require the surface to be rotated to deposit simulant on the entire surface. One way this is done is by having the fixture interface with alignment pins on the spin plate of the transfer carriage to enable exact manipulation of the large target surface with the stepper motors.

The actual test now begins by executing a homing routine for the transfer systems followed by a translation to the area under the deposition system. The spin stage is then triggered to start rotating the target surface. The deposition system is activated, and the routine runs for the prescribed amount of time. The translation system then moves the carriage under the imaging system where the microscope software is remotely triggered along with the rotation stage to image various areas of the target surface. After the deposition and imaging are complete, the fixture is moved to the home position where the target surface can be removed and weighed if desired. As mentioned earlier, the target surface is typically weighed inside the glove box to prevent the deposited simulant from absorbing atmospheric moisture from the lab. In the cases where the sample is too large or too heavy to weigh, the image analysis is critical to evaluating the deposition density (explained in greater detail in the validation testing section). The test sample can now be removed from the glove box through the transfer chamber for subsequent performance evaluations (e.g., leak tests on seals, transmissibility testing of glasses, thermal testing of radiators).

Post-Testing

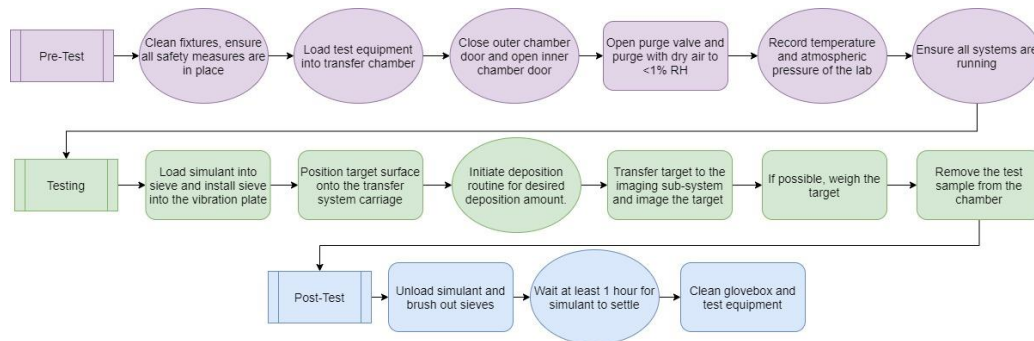


Fig. 8: Flow Chart of a Typical Test

The post-test phase begins with the unloading of the simulant from the deposition system's sieves. The excitation frequency for the vibration plate is dependent on the

vibrated mass. If there has been a significant change in weight of the simulant in the sieve, it is recommended that a new container of prepared simulant be used. When changing the simulant, the first step is to transfer all remaining original simulant in the sieves to a “spent” container. (Note, it is not economically practical to discard simulant; as long as it is recharacterized it may be used in the future). Brush the sieves to liberate any stuck particles. Next, the glove box is left to sit idle for a minimum of 1 hour to allow all the particles suspended in the air to settle and then surfaces in the glovebox are wiped clean using wipes and a vacuum cleaner (with HEPA filter) as needed. The entire testing flow is described pictorially below in Figure 8.

Verification and Validation Testing

Tests were performed to verify and validate that the UDDS can deposit lunar dust simulants in a uniform, accurate, and repeatable manner. The verification tests proved that the system can deposit simulant in a controllable fashion and were used to characterize the modal and electrical characteristics of the system. The validation testing then tuned the system to obtain desired deposition rates and densities.

Verification Testing

The main objectives of this series of tests were to find the harmonic frequencies of the deposition system and the ideal mass of simulant that should be loaded into the sieves. It was discovered that the test results were dependent on the specific motor and supplied voltage used in the system. There were three test series each with a different mass of simulant in the sieves (20, 25, 50 g). For every trial in the series a new batch of desiccated JSC-1A simulant ($<250\text{ }\mu\text{m PSD}$) was loaded into the sieves and vibrated for 10 seconds. The target surface for deposition was an aluminum weighing tray placed below a mask plate. The mask plate had a hole cut out in its center with a 5 cm diameter which allowed for the isolation of the central deposition area [Fig. 9]. The mass of simulant that was deposited on the tray was recorded for a range of duty cycles, where duty cycle is defined as the pulse width sent to the DC motor. For example, a 50% duty cycle meant that for a given time pulse the voltage of the voltage was set to full voltage for half of that pulse.

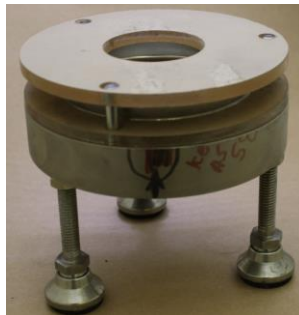


Fig. 9: Fixture for Verification Testing: Tray and Mask with 5 cm Diameter Opening.

The first step in this testing series was to find the “dead zone” of the 3V DC motor, the lower range of voltages at which the motor would not have enough power to rotate its mass. The duty cycle for the motor was increased gradually until the motor’s mass began to move slightly. Once that value was found (31% for the motor used) it was

hard coded into the deposition routine as the starting duty cycle. Each trial in the three mass-series then followed the same sequence of steps. First a target duty cycle was selected by starting at a value 4% above the dead zone for the initial trial. This was then increased by 2.5% for each subsequent trial. The motor was powered up to the dead zone duty cycle, steadily ramped up to the target duty cycle and was then held there for 5 seconds to allow the system to reach steady state. After the 5 seconds, the dust trap was opened, and the system deposited simulant on the tray for 10 seconds. After the 10 seconds, the dust trap would immediately close to prevent any continued deposition from reaching the target surface. The mass deposited on the tray was then weighed and recorded, the systems were reset, and the next trial was run. The same procedure was used for all three different masses of simulant in the sieves. The results of these trials are shown in Figure 10.

The harmonic frequency of the vibration plate was found whenever the deposited mass values greatly increased. This can be seen in Figure 10. During harmonic depositions, the flow of simulant out of the sieves was heavy and difficult to control. As noted from the figure, the harmonic phenomenon started to occur at a duty cycle of 59% for 20g of simulant and increased slightly as more simulant was added to the sieve. This agrees with theory since a larger mass requires more energy to reach the same level of excitation. The optimal duty cycle selected was 53% since it represented an output where all three curves had moderate slopes before reaching the first harmonic frequency [Fig 10]. The optimal sieve simulant mass selected was 25 g since it showed measurable levels of deposition while displaying a linear correlation between deposited mass and duty cycle.

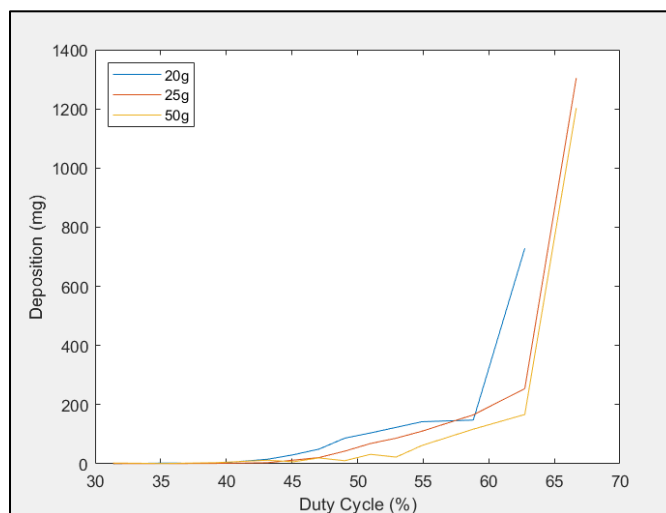


Fig. 10: Deposited Mass (mg) vs. Motor Duty Cycle (%) [10 second depositions] for Various Sieve Simulant Masses

Validation Testing

Once the system was characterized and the desired duty cycle and sieve simulant mass were identified testing was conducted to tune the system for desired deposition amounts. Two series of tests were conducted to validate the systems performance. The first series evaluated deposition accuracy by varying deposition time and the number of deposition runs to correlate the time rate of deposition to deposited mass.

The second series of tests evaluated deposition uniformity by relating the percent area coverage as measured by the imaging system to the actual mass deposited.

Deposition time testing quantified the accuracy and precision of the system. As noted earlier, the 53% duty cycle was selected along with a 25g mass of JSC-1A simulant (<250 μm PSD) in the sieve. The deposition time was the independent variable and was evaluated at 10, 20, and 30 seconds. The target surface for these tests was again an aluminum weighing tray installed under a mask with a 5 cm diameter opening. The dust mask covers and protects sensitive areas of the target surface while still permitting dust deposition in specific areas of interest. The test flow went similarly to the process described for the verification testing with the exception of deposition time. Repeats at every deposition time interval gave precision data, and the incremented time yielded accuracy data (a specific deposition mass).

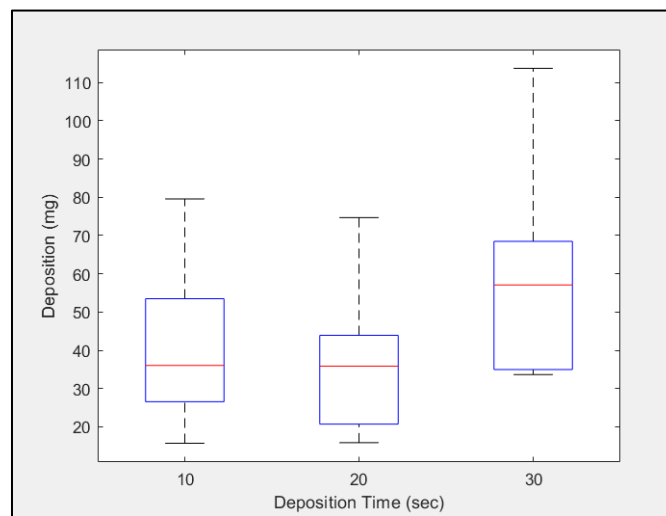


Fig. 11: Accuracy Testing: Box and Whisker Plot of Deposited Mass Trials for Three Deposition Times, Single Deposition Run

The results of this testing can be seen in Figure 11. For each time interval, the amount of simulant deposited varied, and the ranges obtained overlapped with each other. The standard deviations (SD) of the 10, 20, and 30 second trials were 18, 17, and 24 mg respectively, showing a moderate level of precision. Figure 11 also shows a weak correlation between the deposition time and mass deposited (accuracy) meaning there is some difficulty in hitting a prescribed deposition density in a single deposition.

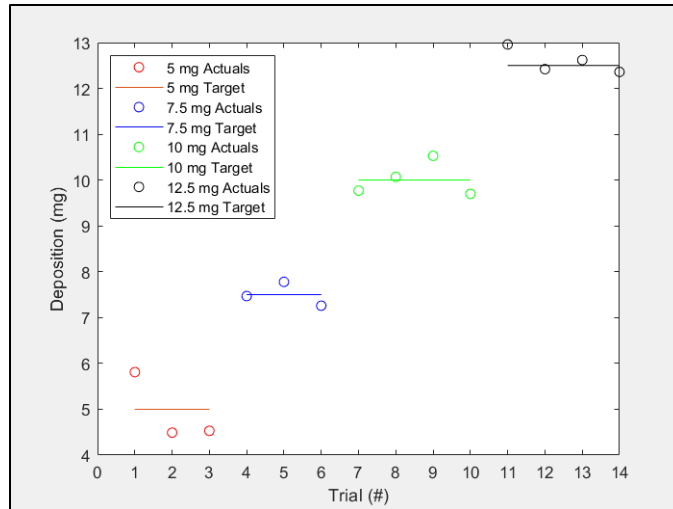


Fig 12: Accuracy Testing: Deposited Mass Trials with Multiple Deposition Runs

The second series of validation tests for the deposition system differed from the first series in the target (time versus mass) and process. In the first series, the process was a single deposition for a given time. In this next series of tests, multiple depositions were run to reach a target final mass. Four target masses were selected for the characterization tests: 5, 7.5, 10, and 12.5 mg. Three or four repeat tests were performed for each target value. The standard deviations were 0.613, 0.213, 0.327, and 0.234 mg for the 5, 7.5, 10 and 12.5 mg targets, respectively [Fig. 12]. This process works well for surfaces that can be weighed (i.e., small test articles such as O-rings). However, it is not suited for larger test articles. Therefore, the imaging sub-system was used to develop an analysis technique that could work for targets of all sizes.

The aim of the third series of validation tests was to obtain a correlation between the percent coverage value that the machine learning algorithm produced after analyzing dust deposition images and the actual mass of deposited simulant. To check uniformity, imaging data was captured during the trials performed for the first series of validation tests. After every 10, 20, and 30 second deposition trial the weighing tray was moved under the imaging system. The surface of the weighing tray was divided into five sub-sections, one in each quadrant and one in the center of the deposition area.

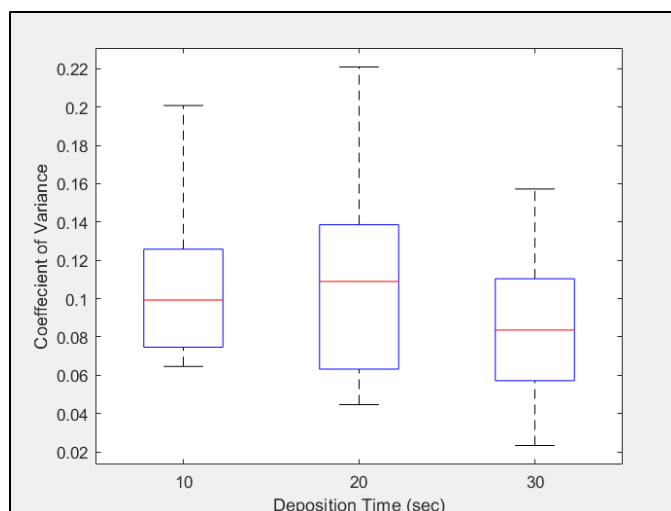


Fig. 13: Box and Whisker Plot Showing Coefficients of Variance for Various Percent Coverage of Trials for Three Deposition Times

A set of images was taken for each sub-section and combined into one high resolution, high depth of field image. The stacked image was then entered into a machine learning algorithm that was trained to recognize simulant particles, count them, and calculate the percent of the surface area that was covered by the simulant. The percent coverages for the five sub-sections were then averaged for each trial. The Coefficient of Variance (CV) of these values was calculated for each trial, and the CV values were plotted against the deposition times as shown in Figure 13. The low CVs indicate that there is a very uniform deposition throughout the trials independent of deposition time.

Next, the correlation for deposited mass versus percent coverage was evaluated. An R^2 value of 0.93 was calculated for the correlation between the percent coverage and the actual mass of simulant on a surface [Fig. 14]. This provided a high level of confidence in the ability to predict how much simulant (deposition density) was deposited on a surface using the imaging system to measure percent coverage. This capability is extremely important to have as there are often test articles too large or too heavy to be accurately weighed during dust testing. Furthermore, the standard deviation of percent coverage for all trials was always less than 6% with a mean of 3.5% across the data set. The deposition area for the characterization tests was a 5 cm diameter circle (20.3 cm² area). Regarding deposition densities, the average standard deviations for 10, 20, and 30 second depositions were 0.909, 0.889, and 1.213 mg/cm² respectively which were all low enough to satisfy the ± 1.5 mg/cm² requirement. The significance of a uniform deposition comes into play when testing technologies that must mitigate dust, and the excellent uniformity of the dust distribution observed will produce more meaningful testing results.

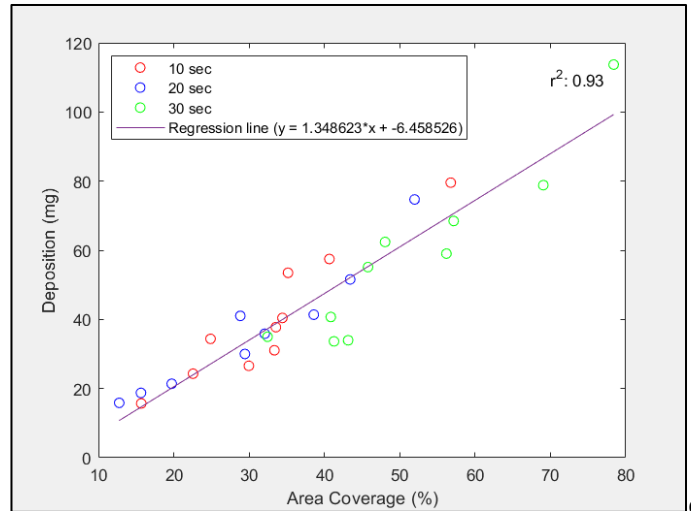


Fig. 14: Imaging Precision Results, Mass vs. Percent Coverage

Conclusion

The Uniform Dust Deposition System was developed at the NASA Glenn Research Center to provide repeatable, uniform, and automated deposition of simulants on surfaces of interest for dust mitigation testing. The system is capable of depositing simulants on test articles up to 60 cm in diameter and 15 cm high in a dry air environment with less than 1% RH while keeping users safe from aerosolized dust. The automation of the system allows for high testing throughput while not sacrificing test quality and allowing the user to reduce data in parallel. The additional development of a simulant preparation technique complements the repeatability of the deposition physics during testing. The system includes an imaging sub-system which leverages the power of machine learning to count simulant particles and measure their size thereby allowing for accurate predictions of surface deposition densities ($R^2 = 0.93$) from images alone. The coverage of dust on a surface was shown to be uniform ($CV < 0.11$) allowing developers to accurately evaluate the performance of their technology with a prescribed amount of lunar simulant, information which can be used to develop and refine models. The accuracy of the system is currently less than desired for a single deposition with a standard deviation range of $0.839 - 1.184 \text{ mg/cm}^2$ for a 5 cm diameter area. However, the accuracy can be improved by performing multiple deposition runs to build dust to a desired level. Testing has shown that a standard deviation of $0.076 - 0.227 \text{ mg/cm}^2$ can be achieved for a 5 cm diameter area using this technique.

Forward work has been planned to improve the single deposition accuracy of the system. The ultimate aim is to develop a system that can then be duplicated and used inside a thermal vacuum chamber that is currently being procured. However, the existing UDDS, and its potential expanded capabilities are expected to be valuable tools in the development of dust mitigation technologies for technology developers and scientists.

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