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Simulating and evaluating regolith propagation effects during drilling in low gravity environments

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Abstract. This research is comprised of virtually simulating behavior while experiencing low gravity effects in advance of real world testing in low gravity aboard Zero Gravity Corporation's (Zero-G) research aircraft (727-200F). The experiment simulated a drill rig penetrating a regolith simulant. Regolith is a layer of loose, heterogeneous superficial deposits covering solid rock on surfaces of the Earth' moon, asteroids and Mars. The behavior and propagation of space debris when drilled in low gravity was tested through simulations and visualization in a leading dynamic simulation software as well as discrete element modeling software and in preparation for comparing to real world results from flying the experiment aboard Zero-G. The study of outer space regolith could lead to deeper scientific knowledge of extra-terrestrial surfaces, which could lead us to breakthroughs with respect to space mining or in-situ resource utilization (ISRU). These studies aimed to test and evaluate the drilling process in low to zero gravity environments and to determine static stress analysis on the drill when tested in low gravity environments. These tests and simulations were conducted by a team from Texas A&M University's Department of Construction Science, the United States Air Force Academy's Department of Astronautical Engineering, and Crow Industries

Keywords: space regolith; space construction; zero gravity; space drilling; computational design; static stress analysis

1. Introduction

With the recent increased federal attention and budget for space exploration for efforts like returning to the moon as a space base for propelling missions to Mars, operating in low gravity environments is a challenge that needs further investigation by engineers. Working with experts in other tangential fields like construction science, researchers will eventually best be able to master the architecture, engineering, and construction that will be needed to establish lunar or Martian bases. This work's aim was to simulate conditions for experiments in low gravity environments

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prior to physically flying the experiments in a Zero-G aircraft. Due to the expense and difficulty associated with real world physical low gravity simulation on earth, it makes sense that reliable computer simulations are preferable to physical tests.

2. Literature review

As the quote from the father of rocketry, Konstantin Tsiolkovsky stated, “Earth is the cradle of humanity, but one cannot remain in the cradle forever.” While Tsiolkovsky passed away 23 years before NASA was established, NASA celebrated their 60^{th} anniversary in 2018 and are seeing a resurgence as they collaborate with industry like SpaceX, Boeing, United Launch Alliance, and Blue Origin (among others). Space operations trace their roots to October 4, 1957 when the Soviet Union successfully launched Sputnik I. It was the world’s first artificial satellite and was about the size of a beach ball. The satellite was 58 cm or 22.8 inches in diameter and weighed 83.6 kg or 183.9 pounds and took 98 minutes to orbit the Earth on its elliptical path (Garber 2013). After several months from the launch of Sputnik, the U.S. formed NASA to develop space programs on October 1, 1958. President John F. Kennedy unveiled the commitment to execute Project Apollo in 1961 in a speech on “Urgent National Needs” (Garber 2013). In 1964, NASA pilot, Joseph Walker, conducted the first flight in the Lunar Landing Research Vehicle (LLRV), known for its unusual shape as the “flying bedstead.” (Petty 2013) A realistic simulation that was critical for landing a spacecraft on the Moon in the Apollo program was provided due to the development of two LLRVs and three Lunar Landing Training Vehicles (LLTVs). The controls design data base for the lunar module were provided by the LLRVs. The Apollo program resulted in American astronauts’ making 11 spaceflights and culminated with the moon landing in 1969. While Neil Armstrong is the most famous, there were 12 astronauts who walked on the moon and conducted scientific research there between 1969 and 1972 (Garber 2013).

2.1 Apollo mission history

Astronauts studied the lunar surface and collected moon rocks, which were brought back to Earth. The Apollo 8 was the first manned mission to the moon and Frank Borman, Bill Anders and Jim Lovell were its crew. However, Apollo 8 was not able to land on the moon and it could only orbit around it before coming back to Earth. The major landmark, which was yet to be achieved, was the first man landing on the moon on July 20, 1969 on the Apollo 11 mission. Neil Armstrong, Michael Collins and Buzz Aldrin were the crew members of the mission. Armstong and Aldrin walked on the lunar surface while Michael Collins remained in orbit around the moon. Neil Armstrong famously said “That’s one small step for [a] man; one giant leap for mankind” after the iconic moment.

However, Apollo 13 is amongst the most famous lunar missions because Apollo 13’s mission was to land on the moon, however, the spacecraft had a problem *en route* and NASA famously engineered how to safely bring the astronauts back to Earth by applying rapid designs relayed from Earth. However, Apollo 13 still orbited around the moon and landed back on earth safely despite the problems encountered. The journey from 1968 to today shows us the challenges and developments made by mankind to develop space resource and utilization. (Launius 2006). For autonomous moon bases and Martian bases to be constructed, great strides will need to start with small steps.

2.2 In-Situ Resource Utilization (ISRU)

Moving forward to modern space research and future endeavors, if humans are to conduct long-term operations in space, they will need to use the resources already there. The study of harvesting resources in place in space is known as in-situ resource utilization (ISRU). The knowledge of the physical properties of space regolith is essential for developing successful ISRU. NASA scientists developed earth-based tests to evaluate space regolith and that protocol is the process followed in this research. The eventual goal is to advance ISRU system-level technology readiness to provide human mission commodities such as propellant, fuel cell reactants, and life support consumables (NASA 2018). The ability to use space resources to create useful products and infrastructure, through ISRU covers a wide range of potential applications, technologies, and technical disciplines. To manage and focus the wide range of possible ISRU applications and their development within NASA, NASA's Chief ISRU Engineer, Gerald Sanders, typically divides ISRU into six main areas of interest: Resource Assessment, Resource Acquisition, Resource Processing/Consumable Production, *In Situ* Manufacturing, *In Situ* Construction, and *In Situ* Energy (Sanders 2013). The development and flight of systems and capabilities in these six main ISRU areas requires expertise and knowledge from multiple science and engineering disciplines spread across three NASA Mission Directorates: Human Exploration and Operations, Science, and Space Technology (HEOMD, SMD and STMD).

As human space exploration evolves toward longer journeys farther from our home planet, ISRU will become increasingly important. Resupply missions are expensive, and as astronaut crews become more independent of Earth, sustained exploration becomes more viable. Also, to obtain the mass, cost, and risk reduction benefits of space resource utilization and to prevent overdesigning or the need to redesign/recertify hardware, mission architectures and elements need to consider the availability of ISRU products from the start of the design and development process (Chepko 2009). To minimize resources, duplication of work, and development schedules, NASA created capability leadership teams (CLTs) as a means to better understand and focus NASA's workforce, technology and system development, and planetary mission plans across NASA Centers and Mission Directorates. For travel in space, as on Earth, we need practical and affordable ways to use resources along the way, rather than carrying everything we think will be needed. Future astronauts will require the ability to collect space-based resources and transform them into breathable air; water for drinking, hygiene, and plant growth; rocket propellants; building materials; and more (Fong *et al*. 2017). Mission capabilities and net value will multiply when useful products can be created from extraterrestrial resources. Some of the most promising space-based commodities that could enable substantial reductions in the mass, cost, and risk of human space exploration include oxygen, water, and methane. These products are critical for sustaining crew and for space propulsion and power systems. They may be derived from space resources such as the carbon dioxide-rich Mars atmosphere and water deposits based in lunar, Mars, and asteroid soil (also called regolith).

2.3 Regolith

Deposits of water and other useful volatiles, which are substances that evaporate easily at moderate temperatures, are not yet fully characterized, and work remains to understand their accessibility (NASA 2018). Perko and his team of researchers introduce surface cleanliness as a parameter to describe soil particle surfaces with different adsorbate thicknesses (Perko *et al*. 2001)

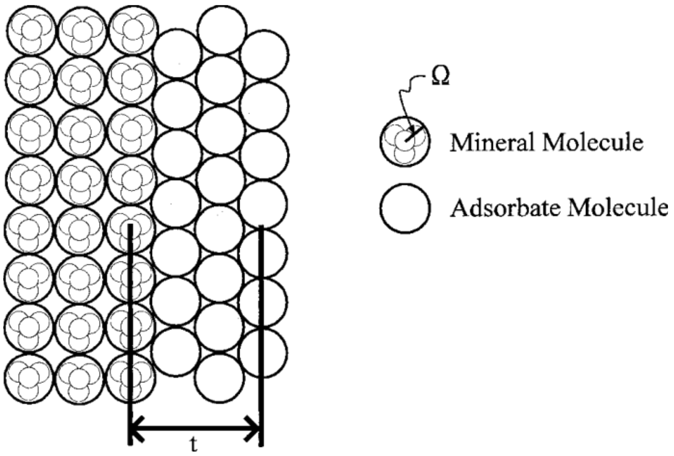

Fig. 1 Measurement of adsorbate thickness (used with permission)

(See Figure 1). A physical-chemical model is developed to determine surface cleanliness and its effect on lunar soil shear strength. Surface cleanliness, *S*, is defined as S = Ω/t where Ω = diameter of an O^{-2} ion ($1.32 * 10^{-10}$ m, 1.32 A°); and *t* = adsorbate thickness. According to the way *t* is calculated, *t* is the distance from the center of the outermost mineral.

The properties of lunar regolith is mentioned in, the data is collected from various returned samples and evaluated through remote sensing by previous lunar missions (Carrier *et al*. 1991). The bulk of the regolith is a fine gray soil with a density of about 1.5 g/cm3, but the regolith also includes breccia and rock fragments from the local bedrock (Papike *et al*. 1982). According to King, lunar soils lack organic matter and clays compared to terrestrial soils. It contains abundant amounts of glass and have much higher relative densities (Kring 2006). Lunar soils accumulate at a rate of ~1.5 mm/million years. It is dominated by <1 mm particles as the mean particle sizes are between 40 to 130 µm. The moon has a representative specific gravity of 3.1 and a bulk density that ranges from 1.45 to 1.79 g/cm3, depending on depth. It's relative density is greater than 65% and quickly exceeds 90% within ~1/2 m of surface and it's porosity ranges from ~44 to ~54%, decreasing with depth. The Cohesion of soils in inter crater areas is greater than that on interior crater walls but less than that on crater rims. Solar wind implants large quantities of H and He and trace amounts of other elements. Continued reworking by micro meteorites of the hydrogen-enriched soil particles causes melting, and the reaction of H with FeO forms H20 vapor and submicroscopic metallic Fe grains in the result in agglutinate glass. This process continues until the surface layer is buried by fresh ejecta or is broken up by a large crater. Trenches and core tubes into the regolith reveal that it is stratified with to the micrometeorite and solar wind environment (Meyer 2003) many buried soil horizons.

Various penetration tests have been accomplished to discover properties and behavior of lunar soil (Figure 2). The study by NASA Kennedy space center demonstrated the surface penetration of equipment into massive volume of icy regolith that is formed in low-pressure conditions inside a vacuum chamber. A cryostatic chamber which has 15 kg of icy regolith is mixed with water vapor and cryo cooled stimulants such as JSC 1-A, BP-1 and soda lime glass beads. (Mantovani *et al*. and Swanger 2014) Experiments and Scanning Electron microscopy conducted on plagioclase component of the lunar simulant NU-LHT and highlands plagiosclase grains obtained from Apollo 17 mission indicates that the shear contact properties of both particles varied substantially. The

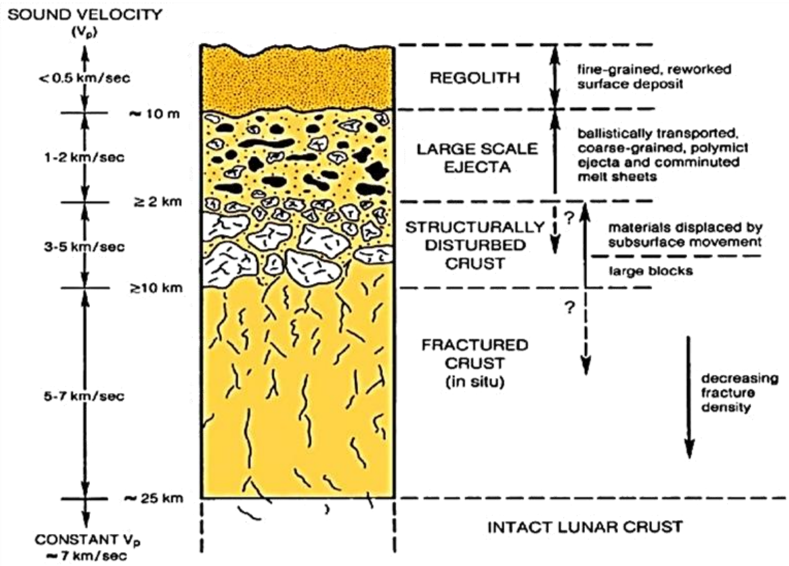

Fig. 2 Soil properties on moon (Hörz *et al*. 1991) (permission requested for use)

normal contact stiffness of the simulant ranged from ≈ 0.2 to 0.9 MN m^{-1}, compared to a range of 0.1 to 0.44 MN m^{-1} for the lunargrains (Cole 2010). Lunar soil contains dry silty sand. This is stated by the fact that thick layers of adsorbed gases, which coat and lubricate soil particles on Earth, are absent in the ultrahigh vacuum on the Moon.

2.4 Challenges

The difference between the atmospheres on the inner planets and moons is enormous, which results into modifying processes on these planets surfaces varying from Earth. Chemical and physical processes on most extraterrestrial bodies in the Solar System are limited by the lack of water. But polar solvents like sulphuric, hydrofluoric and hydrocyanic acids, and ammonia, methanol and hydrazine could replace water. Moreover oxygen, is not present as free O_2 on nearby planetary bodies, but can be available in ozone (O_3) and CO_2. On rocky bodies, oxygen is abundant in tightly-bound oxides such as SiO_2, Fe_2O_3, MgO and Al_2O_3, but it requires very high-energy processes to be reduced. Even without water and molecular O, a variety of energy sources drive chemical reactions: thermal, osmotic and ionic gradients, solar wind, magnetospheric energy and radioactivity are among the most important (Makuch 2006).

2.5 Problem statement

Ultimately, the physical process of drilling into regolith will create debris, more commonly referred to “spoils” when disturbing soils here on earth. It is unknown how this debris will behave when created in various low gravity environments. In order to further understand how it will behave, and to anticipate designing ways to capture more of the debris for more efficient ISRU, this research sought out first documenting its behavior. Because real world low gravity experiments are typically cost prohibitive and rare, research was first accomplished towards simulating regolith’s behavior in low gravity environments through a variety of software platforms.

Fig. 3 Drill with highlighted stress points

3. Methodology

The purpose of these experiments was to gain more knowledge about space effects on in-situ construction techniques. Initially, the drill rig model parts were designed in Solid works software. The Solidworks™ file was imported to Fusion 360™ for the stress analysis and simulations. These analyses were done to achieve accurate propagation flow of the dust regolith when drilled in low to zero gravity, amount of stress induced on the model when it is utilized and the stability of the model when used in Zero G flight under extreme conditions. Static Stress analysis is done on the drill with gravitational acceleration acting in Earth, Mars and Moon. The handle of the drill is locked and the force is applied on the stress pressure points, highlighted in Figure 3 to develop the stress analysis in Fusion 360™.

The stress analyses were conducted in Fusion 360™. Due to Fusion 360's inability to develop simulations of dust propagation, software like Coupi™ software and Autodesk CFD were considered for the process. Finally, Coupi™ (Controlled Objects Unbound Particles Interaction) was considered to develop simulations of the dust propagation by the drilling process via discrete element modeling (DEM).

3.1 Discrete Element Modeling (DEM)

According to Kulchitsky *et al*. (2014), resistance forces during boulder extraction from an asteroid were considered to develop simulations of the dust propagation by the drilling process. DEM is a first principle computational method to simulate the behavior of solids, individual particles, and particle aggregates (bulk solids) using physical interaction rules between the particles. The DEM is extensively used for modeling of granular materials and powder technology. The actual particle count involved in the process of dust propagation during drilling exceeds the capability of any model to track each particle individually by many orders of magnitude. To address this issue, larger particles that represent the group of actual particles need to be used. The size of the particles in DEM analysis can be considered as a "resolution" of the model. To achieve the correct results of bulk behavior, contact mechanics laws between these large particles used in simulations need to be adjusted. The post analysis of the results also needs to include the micro-

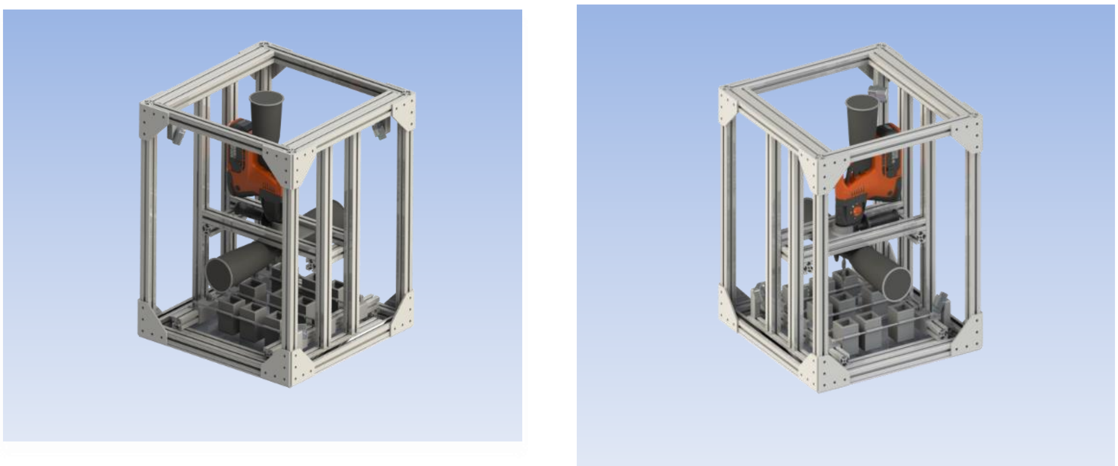

Fig. 4 a) and Fig. 4 b) Drill rig sectional view

macro transition from modeled particle parameters to the actual particles behavior. This multi-scale approach is known as "coarse-graining" and is widely used (Weinhart *et al*. 2016).

3.2 Drilling simulation modeling steps and stages

The drilling simulation include the following stages:

1. Particle bed creation. At this stage the CAD triangulated model of the experimental container is imported and filled with the particles. The particle linear size varied from 100 micron to 2 mm. Each particle is represented by three partially overlapping equal spheres with their centers forming an equilateral triangle and all three spheres have a single common point – the center of the particle. Using such tri-spherical particle shape instead of spheres allows taking into account a possible particle interlocking process while keeping the shapes simple enough to avoid too much computational overhead. Particles are gravitationally deposited under normal Earth gravity with no cohesion into the container.

2. Particle bed adjustment. At this stage some particles are removed from the top of the container to create an even surface. Then, the particle properties are adjusted by adding cohesion and adjusting friction between particles to the desired value.

3. Gravity adjustment. At this stage gravity is gradually linearly by time reduced to the target values such as Mars, Moon, Asteroid or 0 gravity.

4. Drilling. The tip of the drill is imported from the CAD triangulated model. The constant angular velocity and constant drilling velocity is applied to the drill to allow it to move into the particle bed.

After the last stage is completed, the results are analyzed to restore the velocity field of the particles that left the container. The stress within the material, the stress evolution on the container walls, and forces and torques applied to the drill tip are restored.

4. Results

The results of the static stress analysis done are given below.

Table 1 Drilling environment details

Type	Earth	Mars	Moon
Gravity (m / s^2)	9.807	3.711	1.62
Force applied (N)	88.2	33.4	14.58

Table 2 Material details

	Materials	
	UHMW, White	Steel, High strength, Low alloy
Density (lbmass / “^3)	0.03396	0.2836
Young’s Modulus (psi)	124877	2.901E+07
Poisson’s Ratio	0.42	0.287
Yield Strength (psi)	3046	40001
Ultimate Tensile Strength (psi)	5497	64977
Thermal Conductivity Btu / (s “ F)	5.337E-06	6.286E-04
Thermal Expansion Coefficient (/F)	1.111E-04	6.667E-06
Specific Heat Btu / (lbmass F)	0.5047	0.1146

Table 3 Mesh and adaptive mesh refinement

Mesh	
Average Element Size	
Solids	3
Scale Mesh Size Per Part	Yes
Average Element Size (absolute value)	-
Element Order	Parabolic
Create Curved Mesh Elements	Yes
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20
Adaptive Mesh Refinement	
Number of Refinement Steps	8
Results Convergence Tolerance (%)	2.5
Portion of Elements to Refine (%)	60
Results for Baseline Accuracy	Displacement, Total

Table 4 Final results

Name	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
	Earth		Mars		Moon	
Safety Factor	2.121	15	5.602	15	12.83	15
Von Mises (psi)	6.839E-04	18857	2.588E-04	7141	1.13E-04	3117
1st Principal (psi)	-2048	5222	-775.3	1977	-338.4	863.1
3rd Principal (psi)	-18860	1210	-7142	458	-3118	199.9
Normal XX (psi)	-18458	2125	-6990	804.4	-3051	351.2
Normal YY (psi)	-6140	4423	-2325	1675	-1015	731.1
Normal ZZ (psi)	-2454	2078	-929	786.7	-405.6	343.4
Shear XY (psi)	-6669	6677	-2525	2529	-1102	1104
Shear YZ (psi)	-1635	1846	-619	699	-270.2	305.1
Shear ZX (psi)	-1967	1591	-744.9	602.4	-325.2	263
Displacement (in inches)						
Total	0	0.003846	0	0.001456	0	6.356E-04
X	-0.002812	8.125E-04	-0.001064	3.077E-04	-4.646E-04	1.343E-04
Y	-2.555E-04	0.003766	-9.674E-05	0.001426	-4.223E-05	6.224E-04
Z	-3.116E-04	1.215E-04	-1.18E-04	4.602E-05	-5.15E-05	2.009E-05
Reaction Force (in lbforce)						
Total	0	0.003846	0	0.1476	0	0.06445
X	-0.002812 “	8.125E-04 “	-0.1147	0.07621	-0.05007	0.03327
Y	-2.555E-04”	0.003766 “	-0.04443	0.1019	-0.0194	0.04447
Z	-3.116E-04 “	1.215E-04 “	-0.09288	0.07899	-0.04054	0.03448
Strain (dimensionless)						
Equivalent	5.807E-10	8.469E-04	2.21E-10	3.207E-04	9.639E-11	1.4E-04
1st Principal	-7.083E-07	4.965E-04	-2.682E-07	1.879E-04	-1.171E-07	8.202E-05
3rd Principal	-9.166E-04	4.876E-07	-3.471E-04	1.846E-07	-1.515E-04	8.061E-08
Normal XX	-5.777E-04	2.159E-04	-2.188E-04	8.17E-05	-9.55E-05	3.566E-05
Normal YY	-4.603E-04	3.988E-04	-1.742E-04	1.509E-04	-7.604E-05	6.588E-05
Normal ZZ	-6.62E-05	1.964E-04	-2.505E-05	7.435E-05	-1.094E-05	3.246E-05
Shear XY	-5.918E-04	5.925E-04	-2.241E-04	2.244E-04	-9.783E-05	9.795E-05
Shear YZ	-2.377E-04	2.7E-04	-8.994E-05	1.022E-04	-3.926E-05	4.46E-05
Shear ZX	-5.26E-04	3.908E-04	-1.992E-04	1.48E-04	-8.695E-05	6.461E-05

Table 4 Final results (continued)

Contact Pressure (in psi)						
Total	0	2554	0	966.9	0	422.1
X	-1883	1141	-713.1	432.1	-311.3	188.6
Y	-2338	1880	-885.2	711.8	-386.4	310.7
Z	-1494	829.4	-565.5	314	-246.9	137.1

Table 5 Stress analysis details

	Earth	Mars	Moon
Factor of Safety			
	0 8	0 8	0 8
Von Mises			
psi	0 18857	0 7141	0 3117
First Principle			
psi	-2048 5222	-775 1977	-338.4 863.1
Third Principle			
psi	-18860 1210	-7142 458	-3118 200
Total Displacement			
inches	0 0.003846	0 0.001456	0 6.356E-04

5. Analysis

The results shown in Table 5 shows similar images (same colors) for all the analysis done. The factor of safety was kept the same in all environments. This suggests that the static stress on the drill will be similar on Earth, Mars and the Moon proportionally with the varying forces and gravitational acceleration experienced in the three environments in relation to the amount of gravity experienced in that environment. The results discovered using Fusion analysis suggests that the drill is capable to be used efficiently in the zero gravity flight. Still, the simulations of the dust propagation was not achieved as Fusion 360 lacks the ability to create such simulations. Therefore, Coupi was used to simulate the visual results of drilling into regolith. Further work needs to be done to mathematically compare the video of drilling onboard the Zero-G aircraft with the DEM simulations from Coupi. However, at first inspection, the simulation and the experiments were nearly identical. Per the researchers' hypothesis, the greatest amount of debris from drilling occurred during zero gravity flight, with less debris entropy in higher levels of gravity. Understandably, degree of drilling debris entropy and gravity are in this way, inversely proportional.

6. Conclusions

The similarity of results discovered via stress analysis with varying atmospheres provides data surrounding the strength and stability of the drilling device used in low gravity environments. The feasibility of the drill model is going to be further analyzed with data gleaned from the Zero G research flight. The limitation of Fusion 360™ for simulating the propagation of regolith particles when drilled is overcome by the use of Coupi™ which works for particle DEM. Finite Element Analysis through Fusion 360™'s static stress analysis tool is chosen as the best option to prove the Engineering Model's viability due to the complex nature of the structure and loads. Performing this analysis effectively by hand would have been impossible or incredibly challenging. Through many iterations of model modifications and analysis, the engineering model is expected to pass the g-load requirements and subsequently be permitted to fly. The strongest and weakest Factor of Safety (FoS) is produced by the 9 g and Earth load (1g) cases respectively. All other FoS values fall between 2.1 and 15.0. The maximum and minimum FoS change proportionally due to the varying gravitational acceleration considered during the simulation. The FoS is inversely proportional to the gravitational acceleration – that is to say that the lower the gravity, the higher the FoS. The FoS increases when the force of gravity decreases which is shown by lunar simulation with the least gravity having the maximum FoS. Additional work needs to be accomplished to compare the real world Zero-G drilling with the Coupi DEM simulations. Through many, many more experiments, the hope is that using this information will eventually lead to successful autonomous ISRU and space-based colonization on the moon and, eventually, Mars.

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