Experimental Study of Rotor-Sand Ground Interactions Utilizing Scaled NASA Dragonfly Model

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As part of the NASA's New Frontiers Program, the Dragonfly mission is dedicated to exploring Saturn's moon, Titan. Equipped with eight co-axial rotors and an array of instruments, the lander will explore the geological and chemical characteristics of Titan's surface. Titan's dense atmosphere and low gravity, while ideal for flight, showcases the challenges associated with Dragonfly's octocopter configuration. The forces that are thrusted from the rotors can cause the particles to be provoked, resulting in erosion, dune formation, and visibility concerns. These occurrences are of interest, as they can be studied to understand Titan's environmental and geological dynamics. To investigate these aspects, an experiment was performed utilizing a scaled accurate model of Dragonfly. The model was placed in a box containment creating a controlled environment where the rotors were able to be powered. The octocopter model was placed on layers of sand and attached to the surface while the rotors were activated. This rotor-based method allowed for the measurement of sand concentrations to be captured on the body and the movements away from the lander. Cameras were used to record the particle mobilization thus gathering the qualitative data related to the erosion of the sand and the formation of dunes. The experiment contributes to an understanding of Titan's surface dynamics, focusing on the effects of Dragonfly's rotors, while simulating certain environmental conditions.

I. Nomenclature

ESC	=	Electronic Speed Controller
g	=	grams
RPM = $Kv \times V$	=	Revolutions per Minute
Δ	=	Change
Kv	=	Motor Velocity Constant
V	=	Voltage

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II. Introduction

On January 14, 2005, as part of the Cassini's mission by NASA (National Aeronautics and Space Administration), the Huygens probe landed on Saturn's moon Titan. The probe was able to record data regarding both terrestrial and environmental characteristics of Titan, both quantitatively and qualitatively [1]. Following Cassini's success, interest in exploring Titan grew due to its unique environment. NASA created the New Frontiers missions to promote space exploration to other bodies in the solar system. In 2016, NASA announced their New Frontiers 4 message, these missions were to explore "ocean worlds… Understand the organic and methanogenic cycle on Titan, especially as it relates to prebiotic chemistry; and…Investigate the subsurface ocean and/or liquid reservoirs, particularly their evolution and possible interaction with the surface." (Lorenz et al. [2]). In these announcements two different bodies were mentioned, one being Titan. Many different collaborators, beginning with John Hopkins Applied Physics Laboratory and NASA, were all aiming to send a lander to Titan. Due to the data gathered by Huygens, Titan houses interesting characteristics that make it possible for a lander to have the ability of flight. This idea was examined by different vehicles configurations, but ultimately the idea of an octocopter was chosen due to its technical capabilities and versatility (Lorenz et al. [2]). Presently, the mission is progressing and aims to send the lander in the upcoming years.

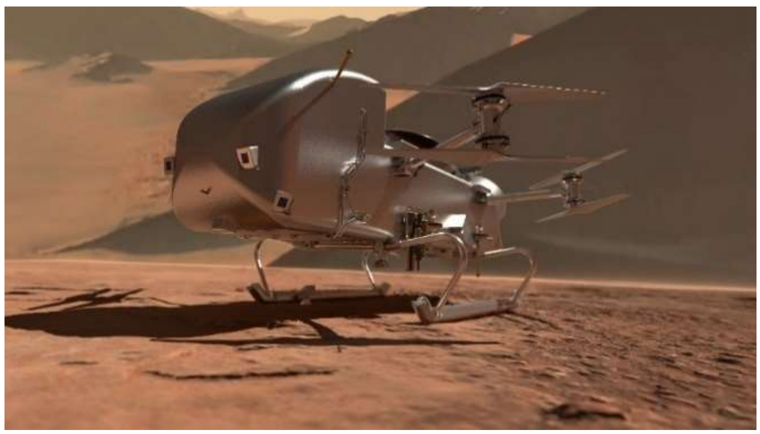


Fig. 1 Lander Concept Image [3]

The lander, named Dragonfly (Fig. 1 Lander Concept Image [3]), houses many instruments capable of performing various tasks; Dragonfly can measure meteorological characteristics and capture images of Titan. Dragonfly's eight coaxial rotors allow it to easily relocate to different sites due to Titan's unique environment.

Table 1. Titan's Environment

Property	Surface Value[a]
Diameter	5150 km (larger than Mercury)
Surface gravity	1.35 m/s^2 (1/7 Earth)
Distance from Saturn	1.2 million km (20 Saturn radii)
Rotation period (Titan day or Tsol[b])	15.945 days (same as orbit period around Saturn)
Atmospheric pressure	1.47 bar (note: Earth surface pressure = 1.01 bar)
Atmospheric temperature	94 K
Atmospheric density	5.4 kg/m^3 (4× Earth sea level air)
Atmosphere composition	95% nitrogen, 5% methane, 0.1% hydrogen, many trace organics
Speed of sound	195 m/s
Atmospheric viscosity	6×10^{-6} Pa-s (~3× smaller than Earth air)
Obliquity	26° to Sun (equatorial plane is ~ Saturn ring plane)
Surface illumination	~1000× less than Earth (or ~1000× full moonlight) predominantly in red and near-IR light; visibility near surface ~10 km

[a]Atmospheric properties vary with altitude; surface values shown here.

[b]Tsol, Titan solar day.

Fig. 2 Astronomical Details of Titan's (Lorenz et al. [2]**)**

Based on these characteristics [2], Dragonfly takes advantage of the lower gravity and the density of the atmosphere. However, Titan's surface is composed of hydrocarbon particles, that are sand-like and form dunes on the surface of the moon [4]. While it is worth studying the surface of Titan for pre-biotic life, the surface influences Dragonfly as well. Dragonfly houses external instrumentation, which are affected by phenomena in the environment. The activation of all eight rotors causes air forces to promote mobility of the particles, which leads to erosion and dune mobility. This is worth exploring, specifically for entry, descent, and landing sequences which is the goal for this experimental study.

The idea of studying particle mobility and rotor-ground effects is documented in previous literature, focusing on military helicopters. This is because military helicopters operate in regions where sand can cause a phenomenon known as brownout. In the brownout phenomena, the rotor downwash excites the particles and causes a dust cloud that can completely enclose the helicopter (Fig. 3 Brownout Phenomena on UH-60 Helicopter [5]).

a) Helicopter flight downwash   b) Helicopter landing brownout

Fig. 3 Brownout Phenomena on UH-60 Helicopter [5]

In Ref. [5], this phenomenon is studied experimentally with helicopters, and observing the particle dynamics. Different processes shown in (Fig. 4 Particle "Entrainment" [5]) caused by wind forces are explored and connected to the wind produced by the moving rotors.

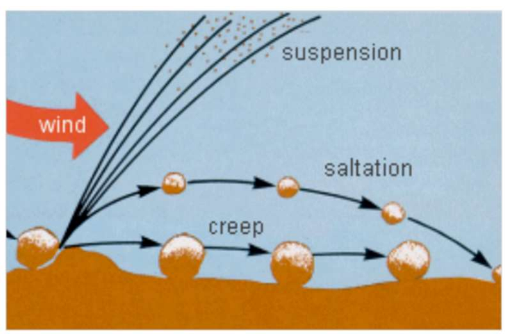
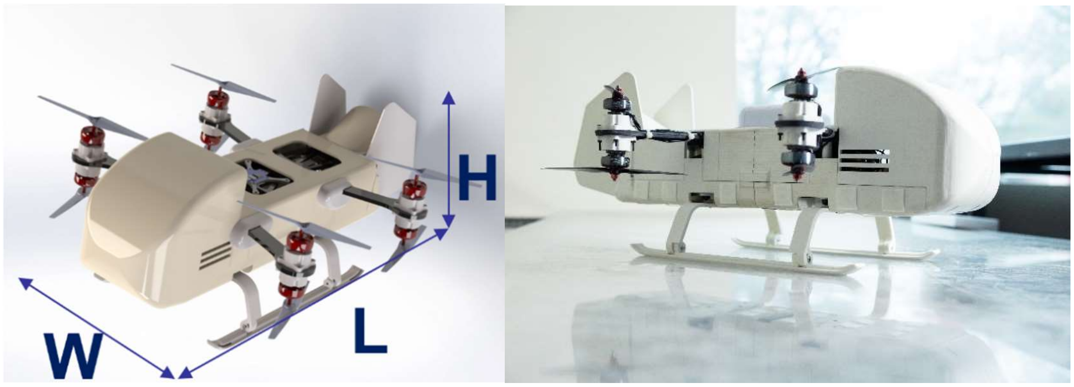


Fig. 4 Particle "Entrainment" [5]

When defining "entrainment" [5], the rotor downwash causes smaller particles to be suspended and join to become larger particles, which can include granular material. Regarding helicopters and brownout, the downward flow causes the flow to form an enclosure, creating a cloud or fog around the vehicle [5]. Based on Wadcock et al., this is worth exploring, because of the literature covering this topic, and the effects brownout has on helicopter operations[5].
Brownout can cause low visibility problems to both instrumentation and the pilot. This concern can be explored in other rotorcraft configurations, such as Dragonfly. Titan's conditions can also promote similar granular flow as brownout. Titan's density and gravitational characteristics allow Dragonfly to excite the surface particles. The idea is to characterize this mobility and observe the erosion of the particles as well as dune formation on the surface of Titan.

III. Methodology

A. Design and Manufacturing of a Lander Model



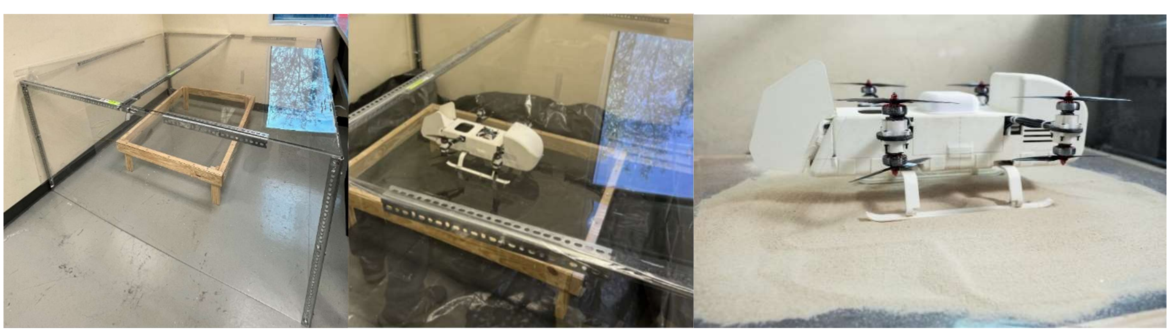
a) Scale render of lander model b) Physical model of Dragonfly lander built

Fig. 5 Dragonfly Lander Model

The Dragonfly lander model has three major design aspects, the scale of the drone, the frame, and the body. The lander is 0.62 m x 0.41 m x 0.25 m, in length, width, and height, without propellers. It features a three-dimensional printed polylactic acid body, 7-inch diameter bi-blade propellers, and utilizes hobby-grade electrical components. The drone is a 1/8th scale model of NASA's Dragonfly lander. This scale is optimal for a balance between ease of manufacturing and aerodynamic consistency. The structure of the internal frame is similar to modern commercial carbon fiber drone frames. The unique attributes with this design, when compared to other commercial drones of similar scale, include mounting points for landing legs, coaxial motor arms, and mounting points for an external body. The external body is an incredibly important aspect of this design and is crucial for properly analyzing the model's aerodynamics.

B. Sand Enclosure

Following the model's construction, the next step in the experiment was visualizing sand mobilization. Although capable of flying, the experimental model needed to be stationary on a flat surface to capture the downwash effect from the rotors onto the sand. Additionally, to avoid the sand escaping and spreading throughout the laboratory, an enclosure was built to contain the drone and the operations following rotor activation. The enclosure is made from acrylic and steel corner brackets. The brackets hold the acrylic sheets in place, and the acrylic sheets allow for the operator to see inside the box. The overall box is 6 ft x 6 ft x 3 ft in length, width, and height, meaning the corner brackets are 6 ft tall. To attach the drone model to an elevated surface, a wood table was built using a plexiglass top. The table has a surface area 4 ft x 3 ft. The setup for the enclosure is shown below in Fig. 6 Lander Enclosure with Table Surface (a).



a) Table and box construction b) Heavy-duty tarp c) Sand filled surface

Fig. 6 Lander Enclosure with Table Surface

For ease of work, a heavy-duty tarp was placed inside the enclosure, which allowed for recycling the sand used and ensuring safety of the work area, shown in Fig. 6 Lander Enclosure with Table Surface (b). The sand that was used was polymeric sand, commonly known as paver sand. This type of sand was preferrable due to its light granular characteristics and dryness. At first, the sand contained substantial amounts of dust, which was removed by a dry sieve. Then several layers of sand were placed on the plexiglass surface, after which the drone was placed on top. Displayed in Fig. 6 Lander Enclosure with Table Surface (c).

C. Thrust Measurement Stand

To obtain the RPM values when sand mobility commenced, onboard electronics were utilized. The lander has a flight controller manufactured for commercial drone use; the operator can then customize the options for the drone utilizing the flight controller. In the setup, the flight controller was set to throttle only to prevent any changes in the eight rotors and to prevent different speeds. This flight controller is soldered directly to a receiver which connects to a radio transmitter, which is how the operator pilots the drone. Eight ESCs are soldered to the flight controller, two of which can send telemetry to an onboard video transmitter. The video transmitter connects to an external monitor where the telemetry, including the voltage, throttle percentage, and RPM values were displayed. After obtaining these values, the next step performed was calculating thrust force per throttle increment. This was done by using a thrust stand, in Fig. 7 Motor Thrust Stand.

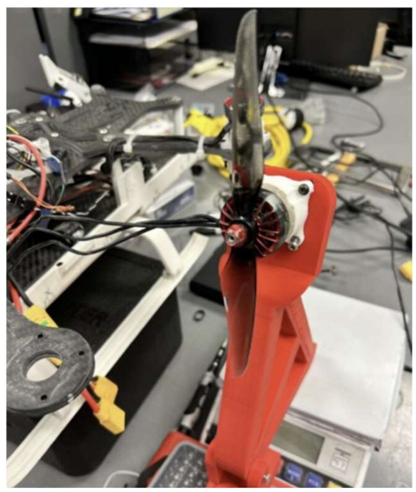


Fig. 7 Motor Thrust Stand

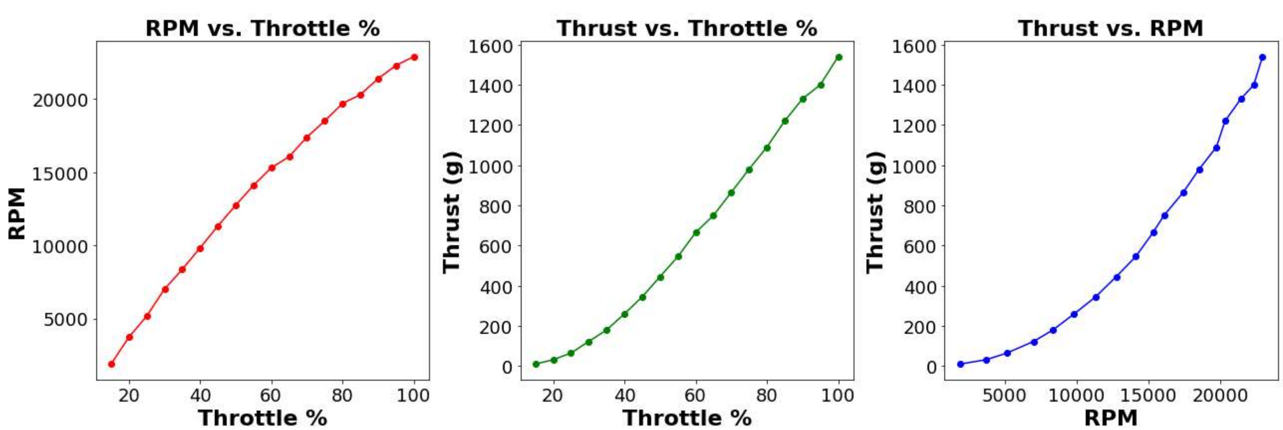
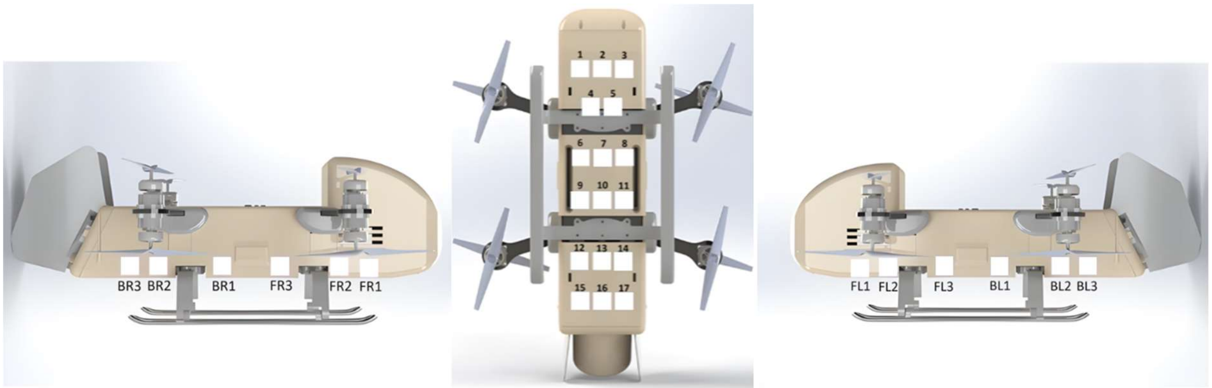


Fig. 8 Throttle %, RPM, and Thrust (g) Relations

D. Gathering of Particles at Different Locations

To measure where the sand concentrated at distinct locations, double sided adhesive was placed, through the bottom sections, following a side and middle pattern, and the lower lateral sides. The locations are displayed in (Fig. 9 Adhesive Locations on Model Lander.)



a) Right Lateral Side b) Bottom Side c) Left Lateral Side

Fig. 9 Adhesive Locations on Model Lander

Once the drone was prepared for sand testing, the model was placed on the sand bed. Since, the purpose was to analyze when sand started to move, see the incipient RPM, some non-tested trials were performed. It was found that at 30% throttle the sand started to move. Two additional ranges were added for the experiment, being 25% and 35% throttle. Following that, to begin gathering of data, the drone was powered and brought to the respective throttle percentage. Once at the throttle percentage, the drone ran constantly for 10 seconds. After 10 seconds, the double-sided adhesive was measured using a scale (Fig. 10 Sand Weighing Method using Scale). This process was repeated twice.

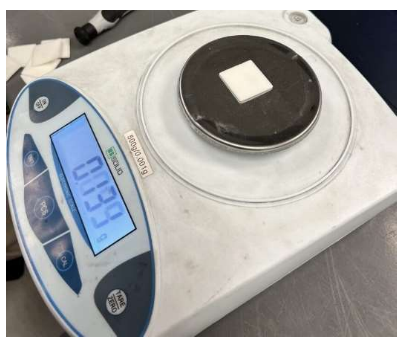


Fig. 10 Sand Weighing Method using Scale

IV. Results

E. Sand Concentration at Different Locations & Throttles

After the pieces of adhesive were weighed, the value from the scale was recorded. Using Microsoft Excel and Python code to process the data collected for the sand concentration at different locations and throttles percentages. The average of the two trials was taken, and to visualize the concentration, a color gradient was used to denote a difference in weight. Green meant lower concentration, while red is the highest concentration. The results are shown below:

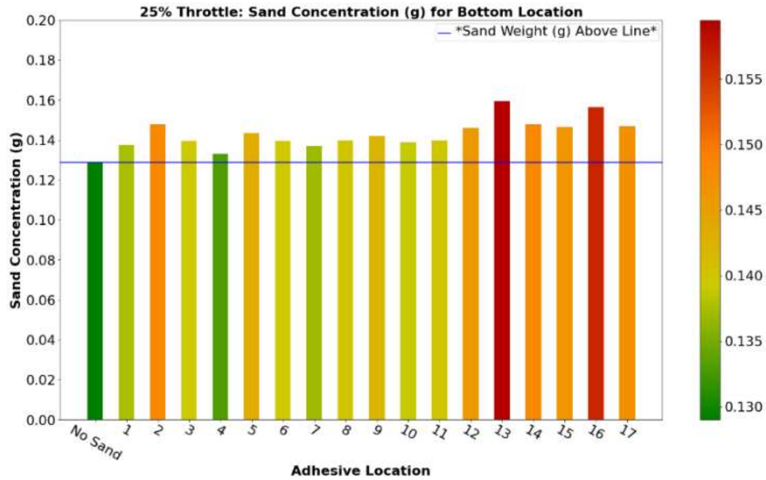


Fig. 11 25% Throttle Bottom Side Sand Concentration

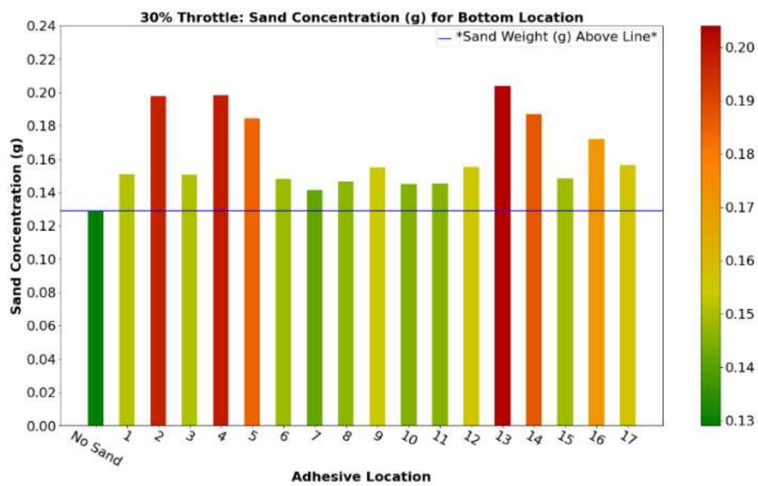


Fig. 12 30% Throttle Bottom Side Sand Concentration

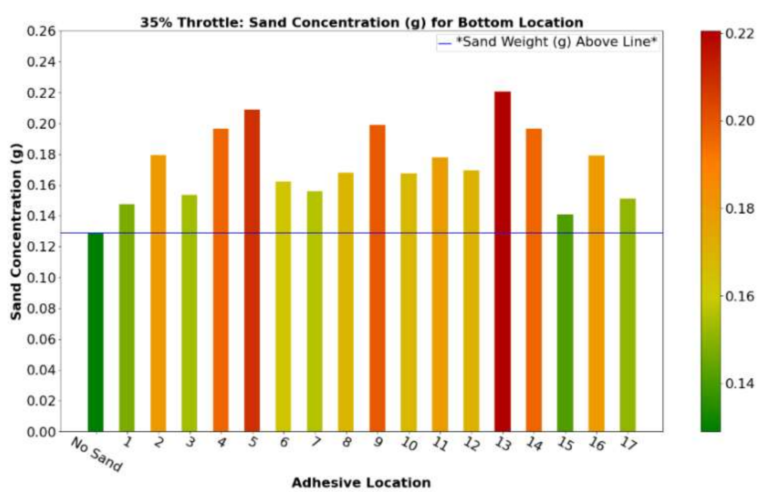


Fig. 13 35% Throttle Bottom Side Sand Concentration

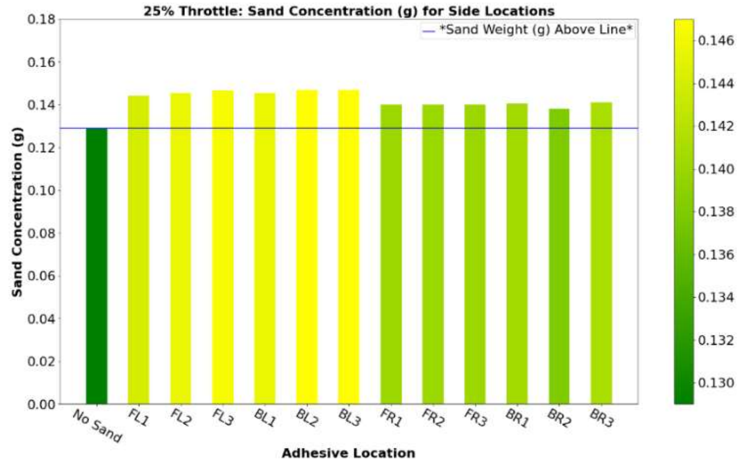


Fig. 14 25% Throttle Lateral Side Sand Concentration

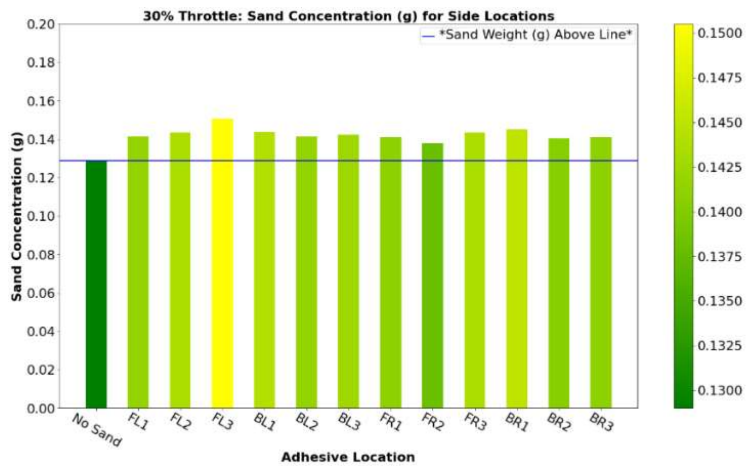


Fig. 15 30% Throttle Lateral Side Sand Concentration

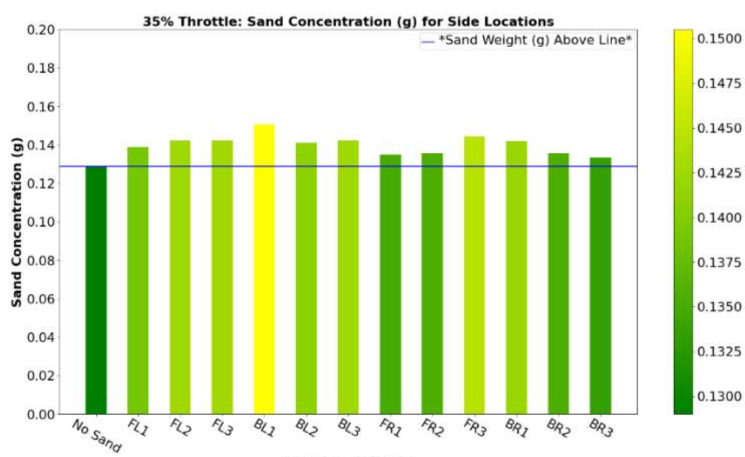


Fig. 16 35% Throttle Lateral Side Sand Concentration

V. Discussion

F. Location Visualization

Based on the data gathered, as throttle increased, more sand got added to the adhesive locations. At 25% throttle the amount of sand was minimal but notable due to the light top surface particles of the sand. At 30% throttle, where the incipient RPM occurred, a larger quantity of sand was gathered. At 35% throttle, the adhesive appeared to begin reaching a limit for gathering the concentrations of sand but gathered a larger number of sand particles in comparison to 30%. This is most noticeable in the bottom section of the drone. However, on the sides, smaller amounts of sand were gathered, often no sand was gathered. To visualize where the sand concentrated the most, the average of the concentration and the throttles were taken. The location is then marked by the color gradient mentioned in E. Sand Concentration at Different Locations & Throttles.

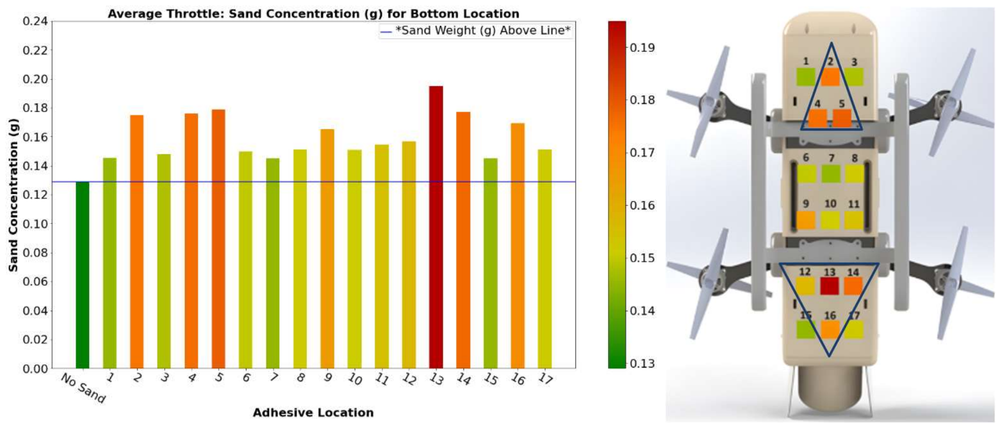


Fig. 17 Average Throttle Sand Concentration at Bottom Locations

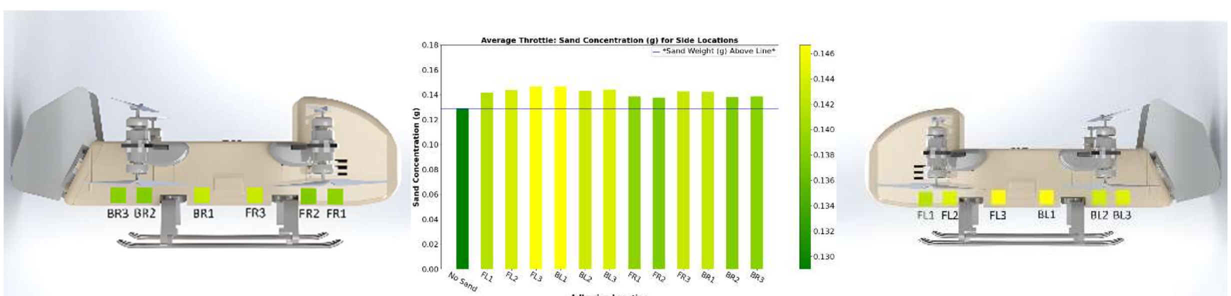


Fig. 18 Average Throttle Sand Concentration for Lateral Sides

For the bottom locations, the sand was concentrated mostly on the front-middle part and the back-middle part. Specifically at locations, 2, 4, and 5 for the front and 12, 13, 14, and 16 for the back. At the exact bottom middle there was a smaller concentration rather than the front and back. In addition, location 13 got the most concentration of sand for the bottom portion. As shown in Fig. 15 and Fig. 16, the sand accumulation at the side locations did not collect as much sand in comparison to the bottom portions. However, it should be noted that the port side of the drone received additional sand rather than the starboard side.

G. Errors and Uncertainties

RPM Error was calculated using the following equation:

$$Error\ \%_{RPM} = \frac{RPM_{observed} - RPM_{expected}}{RPM_{expected}} * 100\% \tag{1}$$

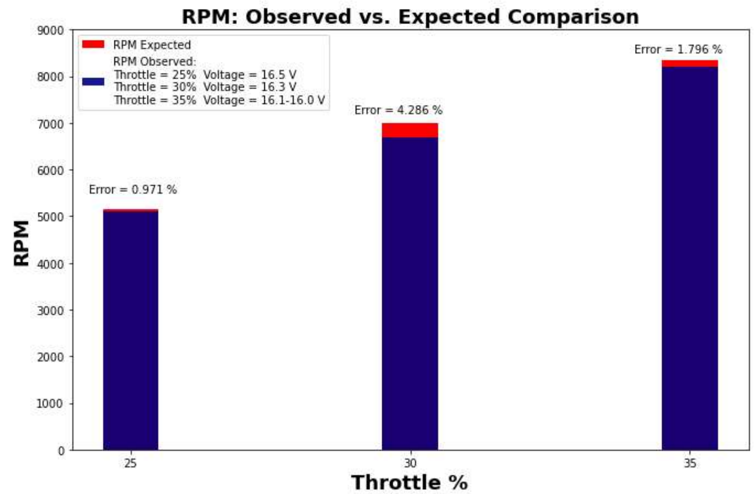
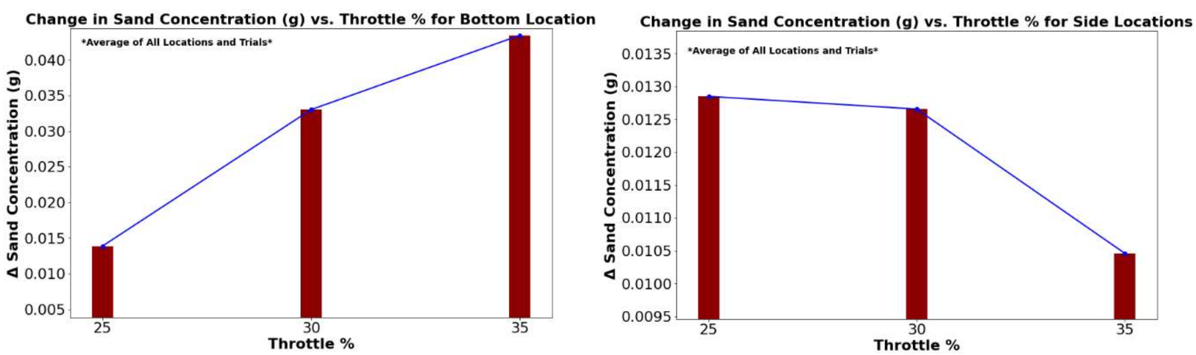


Fig. 19 Calculated RPM Error % Difference



a) Bottom b) Lateral

Fig. 20 Changes in Sand Concentration per Throttle %

Throughout this experiment three possible sources of error were encountered. Differing voltage within the three different throttle settings, interference between the coaxial rotors, and oversaturation of the double-sided adhesive cells.

An error noticed once the trials concluded was a degrading effect on motor RPM as compared to the isolated test stand data. The possible causes of this effect (Fig. 19 Calculated RPM Error % Difference) are a gradual drop in voltage between trials, as well as interference between the coaxial rotors. Although RPM is directly related to the voltage the motor receives, this alone cannot fully explain the full extent of the error. If voltage alone was responsible for the differing RPM, then the percentage error between trials 30% and 35% would be expected to increase. Instead, the percentage error drops by 2.49%. Therefore, there must be a phenomenon that is unique in intensity to the 30% throttle trial, to account for the large spike and subsequent drop between trials 25% to 35%. The only other factor in this system not represented in the single motor test stand trials is the motor's coaxial configuration. The coaxial configuration has a known interference effect due to the difference in pressure caused by the lower motor pulling air from the upper motor.

A separate issue observed when processing the data was an oversaturation of the adhesive squares (H. Gathering of Particles at Different Locations). These adhesive squares have a set area that particles can adhere to which can result in oversaturation if the squares are exposed to a large number of particles for a prolonged period. Therefore, if the number of particles causes an oversaturation of a particular square, then the square will cease to continue recording data. These phenomena served as a direct cap to how high the RPM could go during the trials. The drop in the Δ sand concentration (Fig. 20 Changes in Sand Concentration per Throttle %) between trial 30% and trial 35% is believed to be a result of this issue.

VI. Conclusion

To conclude, analyzing particle movement is important to understanding the brownout phenomena utilizing different rotorcraft configurations and non-Earth characteristics. Understanding these can help to identify critical locations for instruments. By powering the lander, both scaled and real, these can influence the environment around them. By mobilizing the particles on the respective surfaces, the particles create movements and erosion. By using these technologies and rotor-based techniques, one can characterize these aspects of the environment around the drone; even measuring the mechanical and meteorological characteristics of Titan and the effects these have on the lander. To further explore these topics additional imagery will be utilized, and validated by computational fluid and aerodynamic models, as well as literature.

Acknowledgments

An appreciation is sent to the Florida Space Institute (FSI) for providing the space and equipment necessary to run this experiment. The authors of this paper are thankful and hope to continue collaborating and furthering scientific research.

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