Pneumatic Sampling in Extreme Terrain with the Axel Rover

Yifei Huang
Mentors: Joel Burdick and Melissa Tanner

Abstract

Some of the most interesting regions of study in our solar system lie inside craters, canyons, and cryovolcanoes, but current state-of-the-art rovers are incapable of accessing and traversing these regions. Axel is a minimalistic rover designed for extreme terrains, and two Axels with a central mother system form a four-wheeled rover to efficiently traverse flat ground. Upon approaching the edge of a crater, Axel detaches from the mother system and travels down the cliff guided by the unwinding tether. However, scientific study of extraplanetary terrains requires instrumentation inside the Axel rover. We aim to develop a simple and reliable sample acquisition and caching system that could retrieve multiple samples from various sites before returning them to the mother system where more sophisticated instruments could perform further analysis. For simplicity and robustness, we propose a pneumatic sampling system which uses compressed air, guided with a nozzle, to blow soil into a sample canister. Numerous types of nozzles were designed, built, and tested. Different designs for nozzle deployment, sample caching, and pressure containment were considered. Finally, a prototype of the entire sampling system was built and evaluated for performance and feasibility.

1. Introduction

Some of the most interesting regions of study in our solar system lie inside craters, canyons, and cryovolcanoes. For example, satellite images of Newton Crater suggest evidence of water-like substances on Mars (Figure 1). However, when spectroscopy analyses were taken with the Mars Reconnaissance orbiter, no indication of water was found. [1] Sampling the soil is one way of better investigating this phenomenon. However, compared to relatively flat regions that are currently being traversed by rovers, these rocky areas pose a challenge to rover exploration and are referred to as “extreme” terrains. These terrains involve steep cliffs and rocky surfaces that reduce traction forces. Loose soil on slopes and cliffs will also make it harder for current state-of-the-art rovers to climb crater walls. Furthermore, rugged terrain make rovers more likely to tip over, and Mars Exploration Rovers (MER), such as Spirit and Opportunity, and Mars Science Lab (MSL) are not well suited to recover from such situations [2]. Specifically, Newton Crater consists of inclines of up to 40 degrees, while MER and MSL can reliably traverse 15 and 30 degree inclines, respectively. [3, 4]

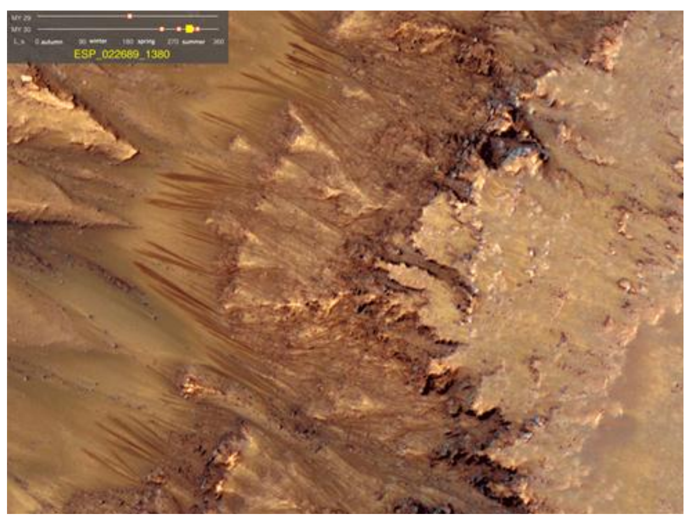

Figure 1. Flow of brines in Newton Crater in Mars. [1]

Figure 2. The Axel rover. (a) CAD model of Axel. The Axel rover is composed of two wheels , a central axle, and a tether arm, and a teather. (b) The DuAxel system consists of two Axel rovers and a central module. (c) Axel deploying one of its instruments. [2, 5]

1.1 The Axel Rover

The Axel rover is a minimalistic rover designed for these extreme terrains and is currently being developed at JPL in collaboration with Professor Burdick at Caltech (Figure 2a). It contains a tether and two wheels, and can be attached to another Axel to form a DuAxel system (Figure 2b). When approaching the edge of a crater, Axel can detach from the mother system and descend the cliff guided by the unwinding tether. Its paddle wheels generate more traction with the surface, allowing for more controlled movements through extreme terrain [2]. The robot does not have a preferred orientation, avoiding failure from tipping. The mother-daughter system allows for a lighter wheel since most of the electronics (i.e. energy source, scientific analysis, communication) can be placed on the mother system and communicated to Axel through the tether wire. This allows Axel room in each of its wheels for instruments, such as a laser spectrometer, thermometer, and microscopic imager. These instruments can be deployed as demonstrated in Figure 2c.

Although in-situ instruments can be sent to Mars for soil analysis, as demonstrated by the Mars Science Laboratory, samples returned from Mars are more desirable due to the much larger range and accuracy of instruments on Earth [6]. Therefore, we aim to develop sample gathering and caching strategies for Axel. Even if Axel is not used for a sample return mission, sampling techniques would be useful: the wheel drum is relatively small, and it would be advantageous for Axel to acquire separate samples in multiple locations before returning to the central module, where larger instruments would perform analyses on the soil.

Honeybee Robotics is developing both a powder and a coring drill that are customized for the Axel system. Therefore, we will aim to sample types of soil that Honeybee is not targeting: loose regolith and wet soil. Wet soils are especially difficult to acquire and store. As Paul Backes recalled from previous NASA field tests, moist soil tends to stick to the sampling system, both contaminating and damaging the sampling system [7]. This problem was previously experienced by the Phoenix lander in 2008 when soil was stuck on Phoenix's scooper [8]. Furthermore, Mars has a thin atmosphere that has conditions close to the triple point of water, which further complicates acquiring samples containing water because it will sublime quickly. [9] Therefore, we will first focus on sampling loose regolith before addressing the problem of wet samples.

1.2 Pneumatic Sampling

We propose a pneumatic sampling system for acquiring loose regolith and moist soils. These systems rely on a compressed canister of gas to generate a pressure gradient that will create a force to lift loose soil from the ground to the sample container.

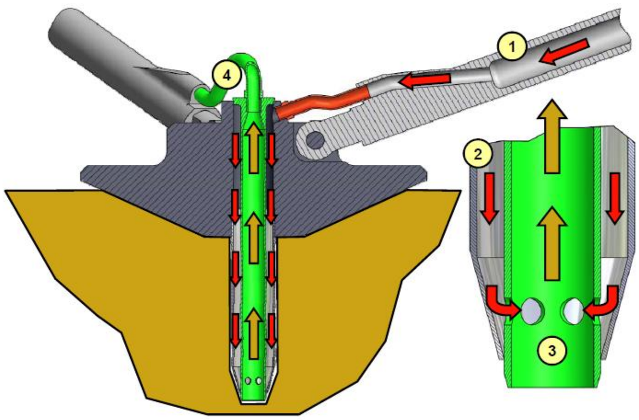

Figure 3. Schematic of a pneumatic sampling system. (1) A cylinder with pressurized gas is opened and releases gas. (2) The gas flows down the outside of the pneumatic probe. (3) Gas exits from openings into the inner tube and travels upwards, which is the path of least resistance. The upward traveling gas carries regolith with it up the tube. (4) The regolith and air follow the path into the sample canister [10].

A pneumatic sampling system's main advantage over other methods, such as scooping and drilling, is its simplicity, which is proper for keeping Axel a robust, minimalistic rover. A pneumatic system's simplicity results from the following characteristics:

1. Fewer actuators: actuation is only needed to (1) open/close the sampling containers, (2) open/close gas cylinder, (3) change the sampling containers.
2. Fewer moving components: soil is transported by pulsing pressurized air through the system, not generating mechanical movement. This reduces the risk for mechanical fatigue or failure.
3. Direct deposit: The system directly deposits the soil into the sample containers. The tubing system that the soil travels through would ideally be completely sealed from other parts of the wheel drum. A closed system prevents the contamination of other instruments inside the Axel wheel.

Other potential advantages of pneumatics would be the ability to sample water and ice, and acquiring samples with low cross-sample contamination. Water and ice sublime quickly on Mars because Mars conditions are near the triple point of water [9]. Compared with scooping and drilling mechanism, pneumatic systems provide for a smaller time period between exposure of the water/ice and confinement of the sample in a container, allowing less time for the water to sublime. Furthermore, cross-sample contamination can be decreased by using a puff of gas to remove the loose soil from the pneumatic tubing system.

Finally, using pneumatics is energy efficient. It has been previously shown that with 1g of gas compressed to 10psi (absolute), 5kg of soil can be lifted with an atmospheric pressure ~5torr, which is similar to conditions on Mars [9].

1.3 Initial Calculations and feasibility on Earth

Although pneumatic sampling has been proven to work on Mars, we will perform all of our tests on Earth, so it is necessary to confirm the feasibility of the concept under Earth atmospheric conditions. Simple, rudimentary calculations were performed to determine the required canister pressure and estimate the amount of soil lifted under ideal conditions on Earth.

Because the circular hole connecting the inner and outer nozzle tubes is small in diameter, we estimate that the flow is likely to be choked at high container pressures. We estimate that the canister need only be 27.8psi (less than twice the atmospheric pressure) to reach chocked flow conditions such that the air velocity will be the speed of sound.

$$\frac{P_{inlet}}{P_{exit}} = \frac{P_{inlet}}{P_{atm}} = \left(\frac{\gamma + 1}{2}\right)^{\frac{\gamma}{\gamma - 1}} = 1.89$$

$$P_{inlet:\,choked} = 1.89P_{atm} = 1.89atm = \sim 27.8psi$$

Then, the mass of soil lifted was estimated to be about 12g/s by considering the area of the inlets. However, this estimation does not account for aspects such as the friction between the flow and the nozzle wall, the multiphase nature of the flow, and gravity, so it is expected that the actual flow rate of soil is much lower. However, this estimate is gives us a much larger mass than we need: the estimated amount of soil needed to perform useful analyses is about 2 grams, so it is reasonable to expect that an adequate amount can be captured using the pneumatic sampling approach.

Compared to Earth, Mars would require much less compressed air per gram of soil lifted because atmospheric pressure on Earth is about 100 times that on Mars. For these reasons, we seek to use a pressurized container to push the soil instead of creating a vacuum to pull the soil because the vacuum will not generate as much lifting force as the pressure canister on Mars, although both might perform similarly on Earth.

2. Design

The design of our system involved the nozzle, for injecting pressurized air into the soil, a cyclone separator, to separate the pressurized air from the soils, a sample container, to store the soil, an instrument deploy mechanism, to place the nozzle into the soil, and a pressure release mechanism.

2.1. Nozzles

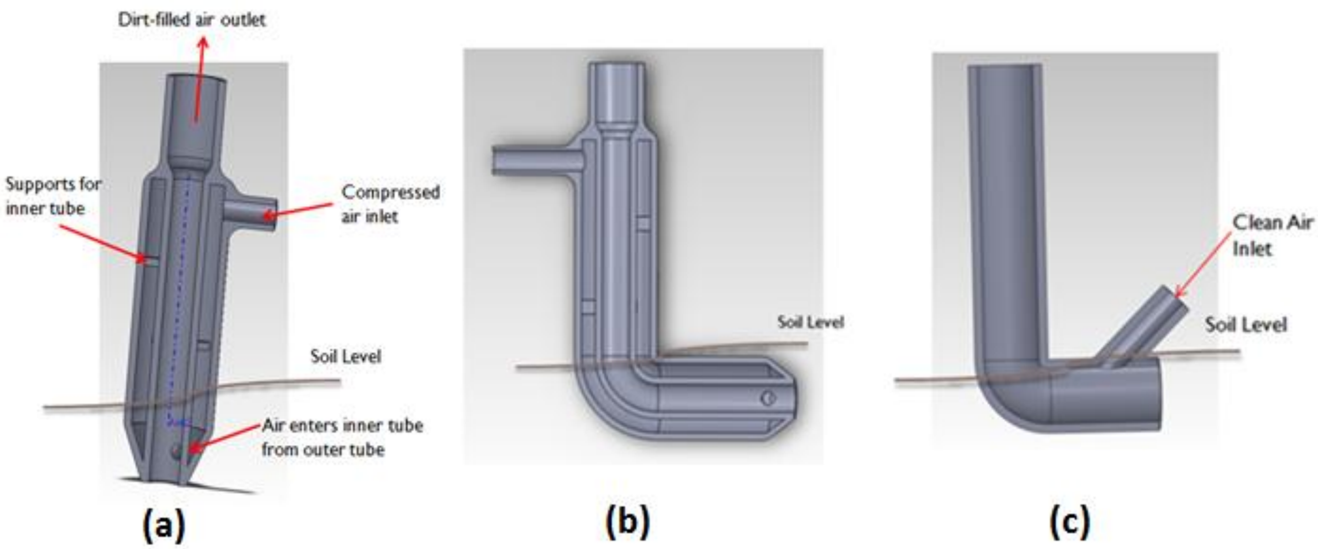

Figure 4. The first batch of nozzles. All nozzles had a soil outlet of 5/32in in diameter, and an air nozzle inlet of 1/4in in diameter.

We started with three main nozzle designs (Figure 4). Nozzle #1 was designed to resemble the design in Zacny et al. (2010) [10]. Nozzle #2 was similar to Nozzle #1, except that it contained a 90-degree bend, which experimented with a different method of soil penetration. While Nozzle #1 enters the soil directly perpendicular to the soil surface, Nozzle #2 uses the rotation of the Axel wheel to generate penetration soil, entering in a passage that is more horizontal, rather than vertical, to the ground. Nozzle #3 experimented with changes due to a slanted air inlet. All Nozzle had air-inlet sizes of 1/4in diameter, and soil outlet of 5/32in in diameter (based on tubing sizes available from the Caltech biology stockroom). All dimensions were chosen arbitrarily.

All nozzles were created on the 3D printer and tested with loose sand of about ~390μm in grain size. All of our tests used 25psi compressed air released for 2 seconds. Plastic tubing was used to connect the pressure inlet to the nozzle and the nozzle to an unsealed container. Duct tape was used to secure the tubing connection. The containers were unsealed to prevent the pressurized air from gathering in the sample container and regurgitating the sand back to the nozzle. All nozzles were dug ¾'' into the soil. To measure the mass of soil captured, the sample container mass was measured before and after each run. See Figure 5 for experimental setup.

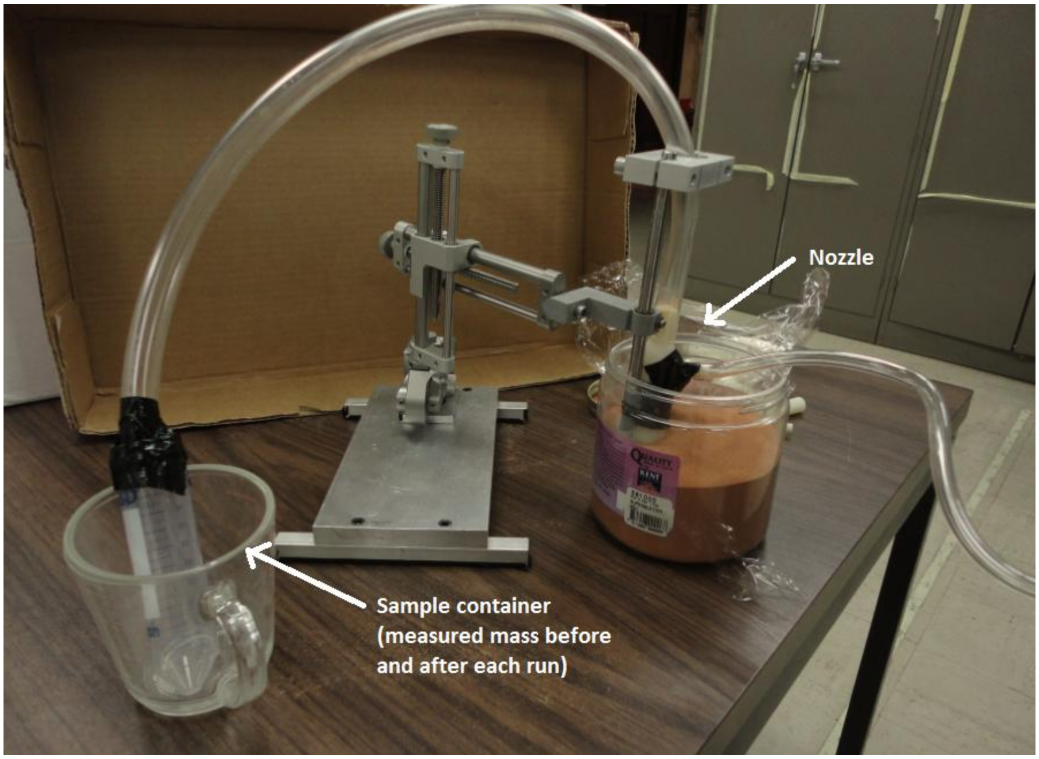

Figure 5. Experimental setup for nozzle testing.

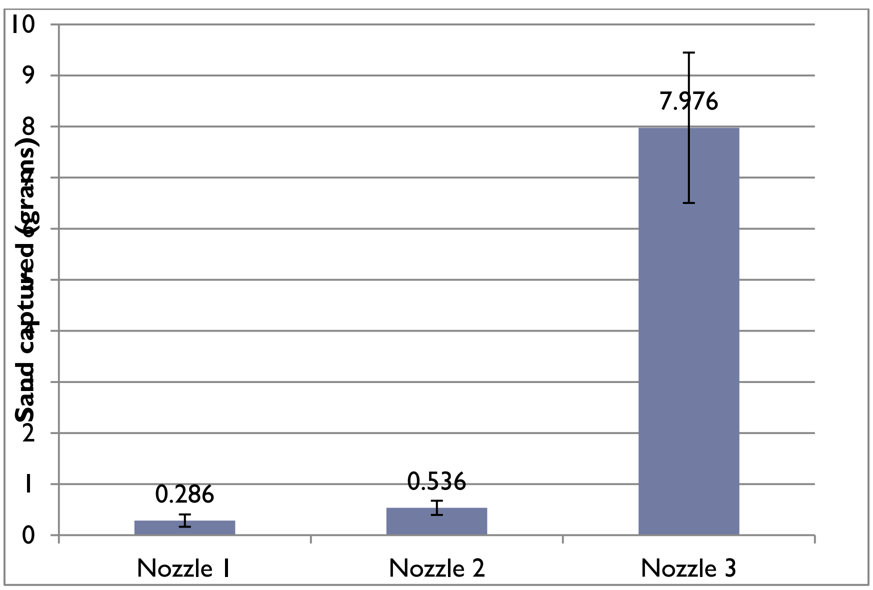

Figure 6. Grams of soil acquired for each of our initial nozzles.

From Figure 6, we see that Nozzle #3 performed much better because of the angled air inlet. In fact, when we attached the nozzles to an air supply, we saw that nozzles #1 and #2 blew more air out from the soil entrance than up through the soil exit, and Nozzle #3 did not have that problem. Furthermore, we conclude that the straight design is better than the curved design: particles lose momentum as they turn the corner and tend to fall back down into the nozzle instead of continuing up the tube into the sample container.

Tests were also performed with a curved nozzle like Nozzle #2, but with twice the original soil-inlet diameter (0.5in in diameter). This was able to acquire twice as much soil, probably because soil was able to fall into the nozzles opening more easily. Therefore, we conclude that nozzles with larger diameter were better, and designed any following nozzles to have a 0.5in diameter soil-inlet.

Our second batch of nozzles are straight, containing slanted air inlets and a larger soil-inlet diameter of 0.5in (Figure 7). After testing, it was discovered that Nozzle #5 performed much better than Nozzle #4, probably because some of the holes in Nozzle #4 were not completely embedded in the sand. In Nozzle #5, all the holes were embedded in the soil, and fewer holes mean that a larger force was pushing on the soil in each hole.

It was observed that most of the soil was lifted into the sample container was during the first second of pressure release. In this second, the soil that entered the nozzle during soil penetration is transported into the sample container. During the remaining time in which the air is released, the air captures only a few loose grains that are lifted up and into the nozzle by the fast air velocity. Therefore, we conclude that Nozzle #5 is a reliable nozzle since it is able to acquire an adequate amount of soil: 3±0.25 grams of sand (around 2 grams of soil is necessary for performing experiments and analysis).

Furthermore, we performed tests with outside dirt in addition to sand used in all previous tests. Outside dirt was most moist and sticky, requiring more force to separate and transport the dirt.

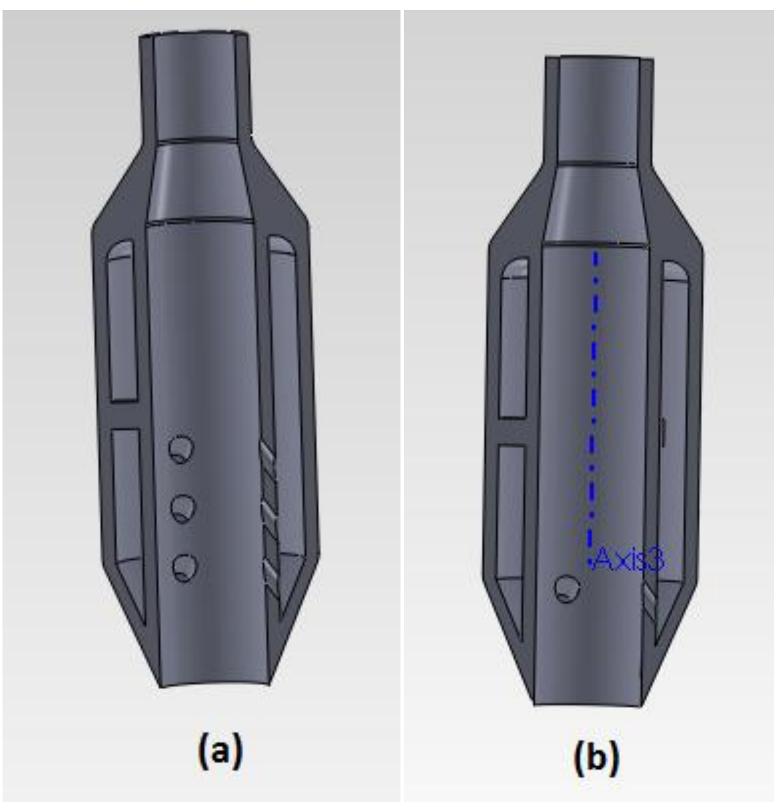

Figure 7. Nozzle (a) #4 and (b) #5 were designed with slanted air inlets. Nozzle #4 had three times as many holes as Nozzle #5.

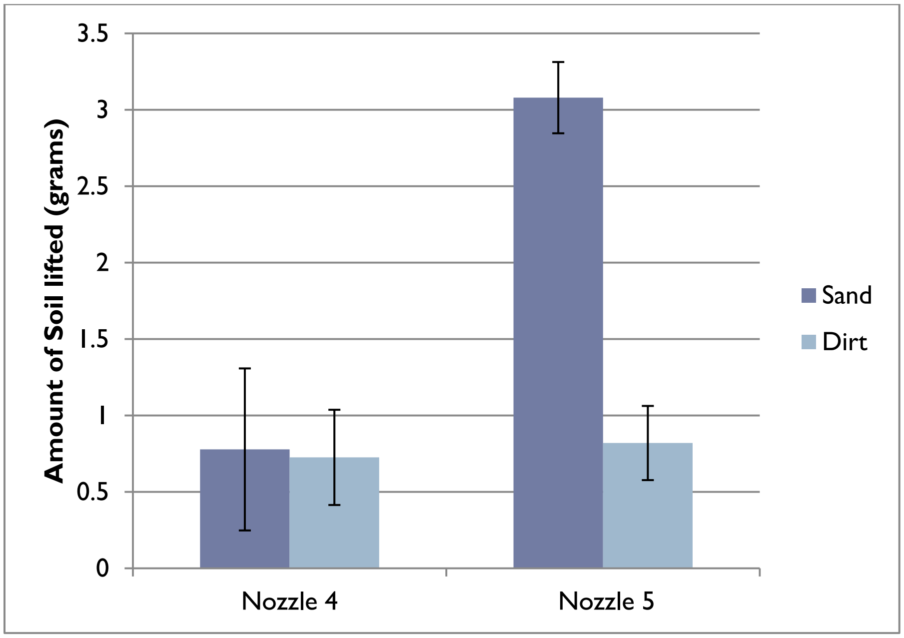

Figure 8. Nozzle #4 and #5 and their performance in sand and outside dirt.

2.2. Separator

Pressurized air cannot be contained in a sample canister because the buildup of pressure will cause air and dirt to be regurgitated to the nozzle opening. Therefore, a cyclone separator will be used to separate the compressed air, which will be removed from the system through a hole, from the acquired dirt, which will be deposited in the sample canister. In a cyclone separator, large particles have too much inertia to follow the curve of the cyclone, hitting the edge of the cyclone and falling to the bottom of the cyclone. Lighter particles are accelerated as the cyclone diameter narrows and gain lift, traveling up through an exit hole at the top of the cyclone [11].

We acquired a cyclone separator design from Honeybee Robotics, which was 3D printed and used in benchtop testing (Figure 9).

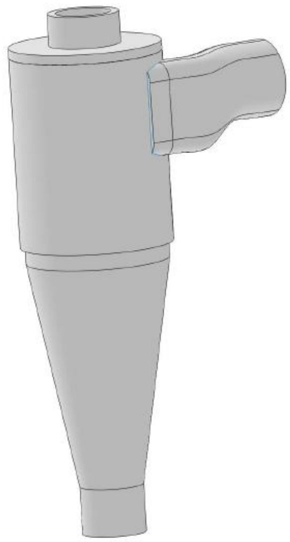

Figure 9. Cyclone separator.

2.3. Sample Container

A sample caching mechanism was devised to reduce complexity by minimizing actuation with springs. Figure 10 illustrate the sample caching concept. The cyclone will be lowered into the sample container, where holes in the cyclone will deposit soil into the sample container. Afterwards, the cyclone is raised, and the restoring force of the spring will seal the sample container. The sample container was constructed in four parts in the 3D printer, as shown in Figure 11. Other methods that create hermetic seals were considered, such as shape memory alloy caps and solder seals, but were deemed too complex since they required heating and cooling system. [12]

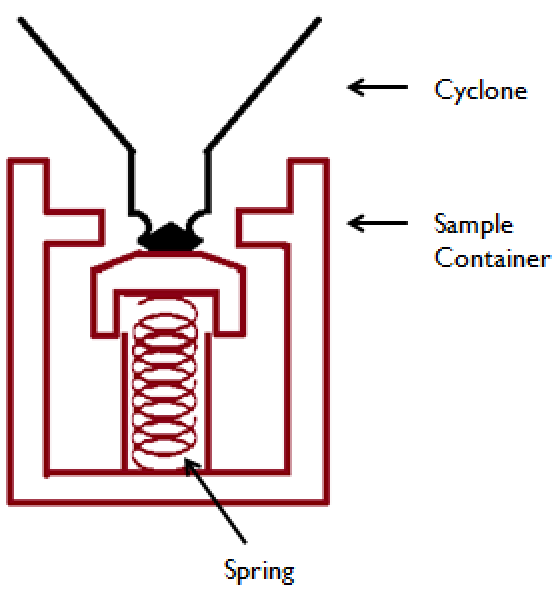

Figure 10. Schematic demonstrating the concept of the sample caching mechanism.

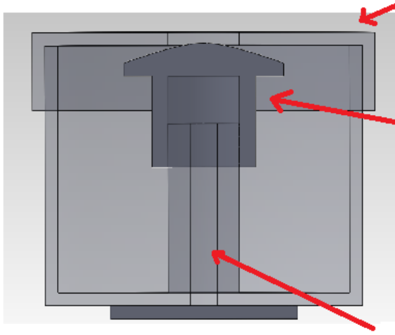

Figure 11. Sample container CAD.

2.4. Instrument Deploy

An instrument deploy mechanism is necessary to keep the original Axel instrument deploy cover from encountering the soil. If the cover comes into contact with the soil, and soil sticks to the instrument cover, the cover may not close properly. Therefore, a vertical extension of the original deploy mechanism is necessary.

We propose a second 4-bar linkage coupled to the original. This eliminates the need for a second actuator located on the plate of the instrument deploy mechanism. Mars conditions can be extremely cold, and it will be difficult and expensive to engineer motors for such conditions. A coupled 4-bar linkage eliminates the need for such motors. Furthermore, preliminary calculations demonstrate that adding this additional 4-bar linkage allows the penetration system to withstand more vertical force (89N as opposed to 60N) because of the smaller arm length of the new system.

The new 4-bar linkage will be coupled to the original through 4 total gears, 2 which are located on the rods connecting the bars on the plate (of 9/16in in pitch diameter), and 2 to bridge the distance between the first 2 gears (of 5/8in in pitch diameter).

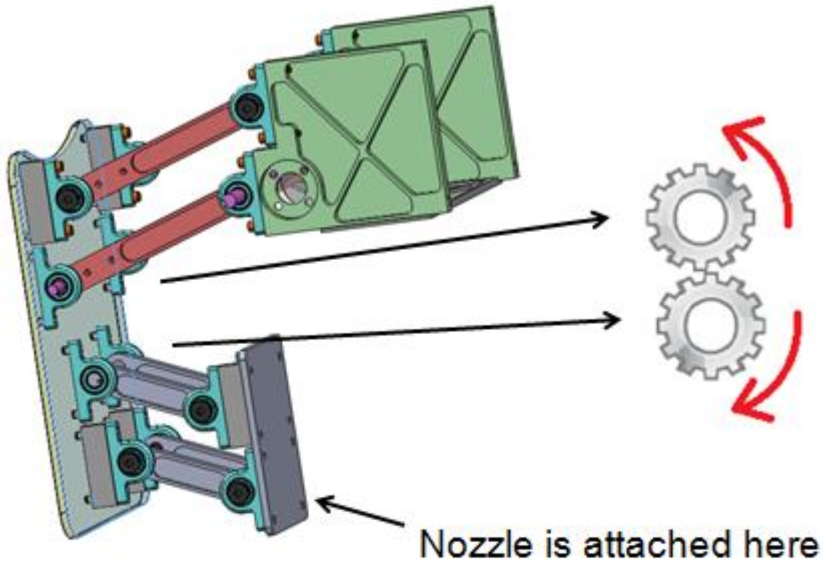

Figure 12. The proposed instrument deploy mechanism adds an additional 4-bar linkage to the original instrument deploy mechanism. The movement of both 4-bars is couple through gears.

2.5. Pressure Release

In order to transport pressurized air to Mars, a small pressure container and an actuated pressure release mechanism is necessary. To do so, we used a compressed 20g CO_2 canister (usually used to refill deflated tires, from the local bike shop: Velo Pasadena) to contain our pressurized air. A regulator (50033 NR-14 Regulator from http://www.lelandltd.com/) and a bushing (50037 from http://www.lelandltd.com/) were used to lower the pressure from >100psi to ~25psi. Plastic tubing was used to connect the regulator outlet to a solenoid valve (Part 5760T123 from Mcmaster Carr). A circuit was used to open and close the solenoid valve, and a toggle switch turned on/off the circuit (Part 7343K184 from Mcmaster Carr). See Figure 13 for a schematic.

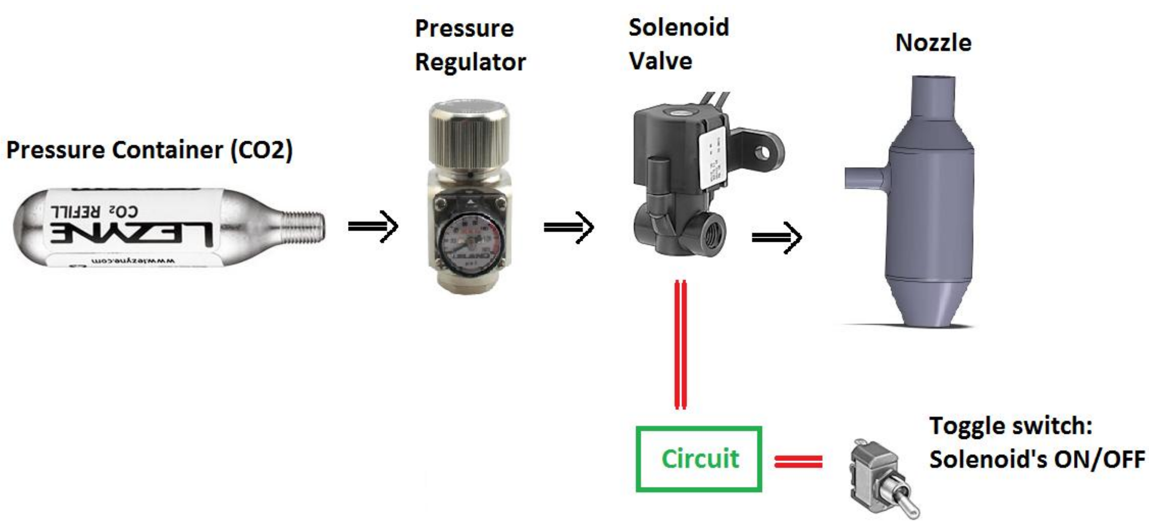

Figure 13. Schematic of the pressure release system.

2.6. Benchtop Test System

We developed benchtop test stands to demonstrate our mechanisms. The stands were built to imitate the movement that the mechanism would perform had they been embedded inside the Axel rover. See Figure 14 for the instrument deploy and sample caching mechanism.

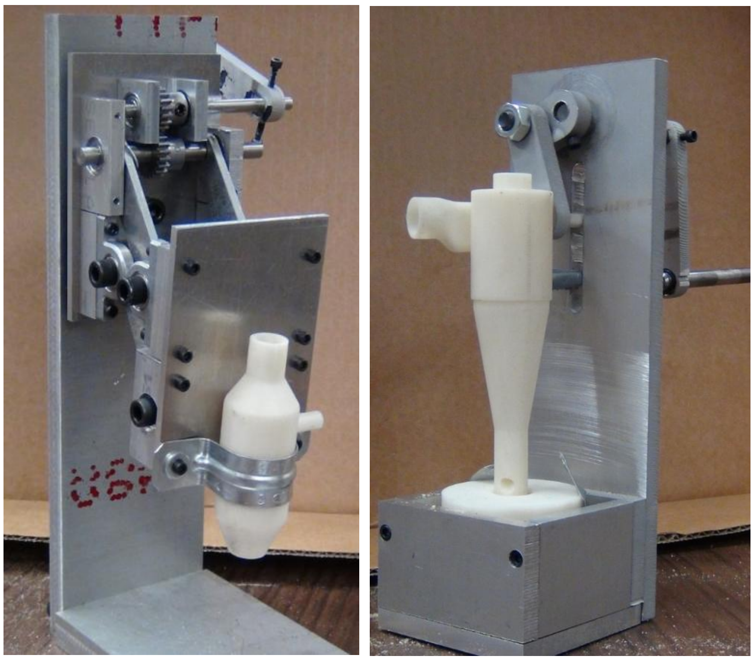

Figure 14. Benchtop systems were built to test the (a) instrument deploy and (b) sample caching mechanisms. Both were built to mimic their designed functions on the Axel rover.

3. Results and Discussion

With the benchtop system, and using the CO_2 container instead of pressurized air from the wall, we performed runs of the pneumatic sampling system. For both tests, 25psi compressed gas was released, and sand of ~390um in diameter was used. Nozzles were lowered 1in into the soil. It was found that the system was able to acquire less soil using the CO_2 can than the pressurized air from the wall. This may be due to the different type of compressed gas, or fluctuating reading s with the CO_2 regulator.

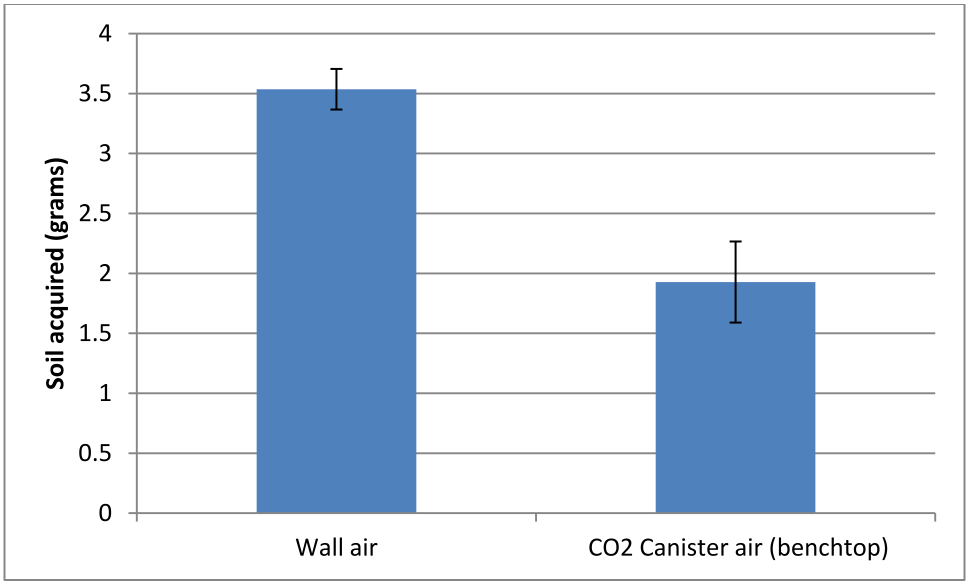

Figure 15. CO_2 canister air is able to retain less air.

Cross-contamination of the pneumatic system was tested. Using the ~390um sand from previous nozzles tests, it was found that less than 1% of the mass of the soil captured by the sample container remained inside of the nozzles. However, if the pneumatic system is instead used to uplift outside dirt instead of sand, over 100% of the soil mass captured by the sample container is retained inside the nozzle and cyclone (Figure 16). Outside dirt tends to remain in clumps and stick to the sides of the nozzle or cyclone. The contamination level largely depended on the design of the cyclone opening that was used. Cyclone with Figure 17a opening, due to its small holes, allowed more dirt to become stuck inside of the cyclone than the cyclone with Figure 17b opening. Therefore, a better design for the interface between the cyclone and sample container is needed to prevent this contamination. It is preferable that the cyclone opening is one large hole to minimize the contamination which arises from dirt sticking onto the sides of the cyclone opening.

Figure 16. Dirt is retained inside the cyclone because the cyclone exit opening is too small.

Figure 17. Two different cyclone designs: (a) This cyclone is designed to interface with our specific sample container, and has small, slanted holes. (b) This cyclone has one large opening at the very bottom.

The amount of soil acquired was compared for our sampling system for (a) Cyclone 17a, (b) Cyclone 17b, and (c) no cyclone. Figure 18 shows that using no cyclone acquires more sand, but, by observation, the system tended to spray much more soil and dirt out of the sample container than systems that used a cyclone. However, if we can engineer a method to dispose of the dirt that escapes from the sample container with the pressurized air, a cyclone may not be needed.

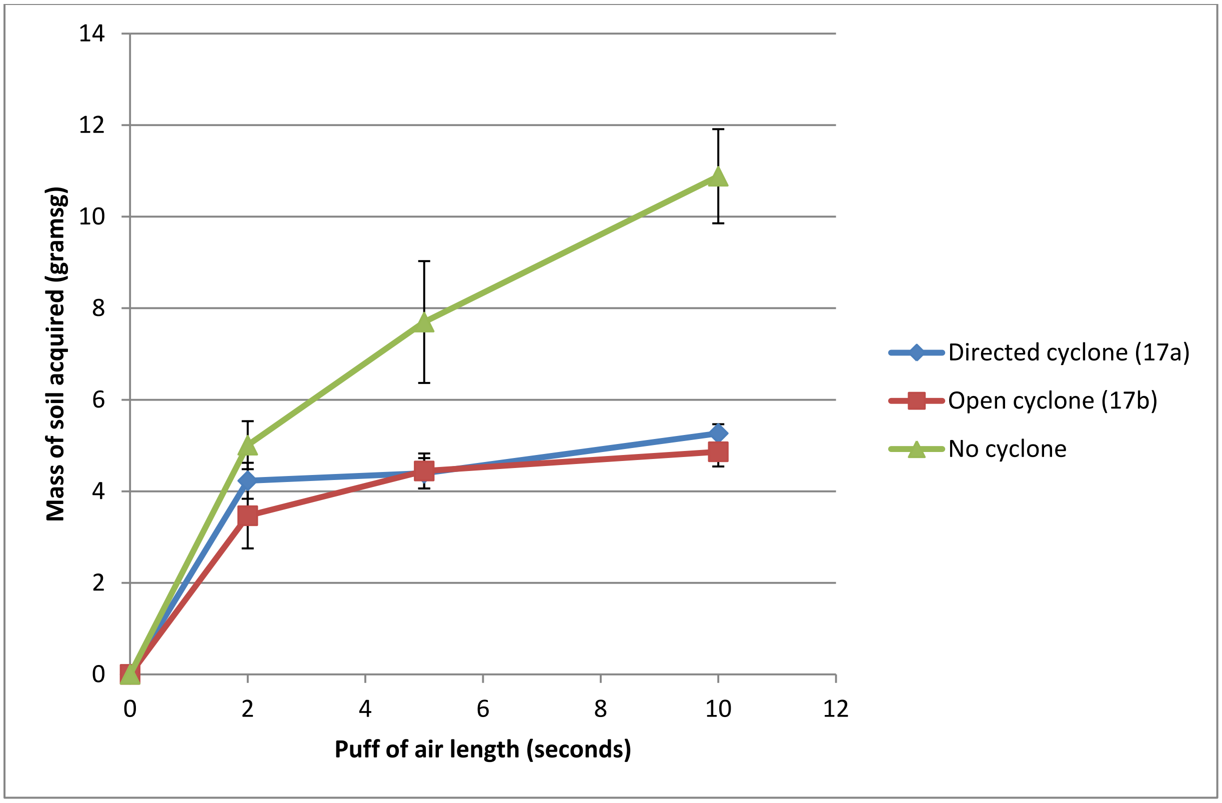

Figure 18. The effect of the length of puff of air (25psi) on the mass of ~390um sand acquired. The same experiment was performed with 2 different cyclones, and once with no cyclone at all.

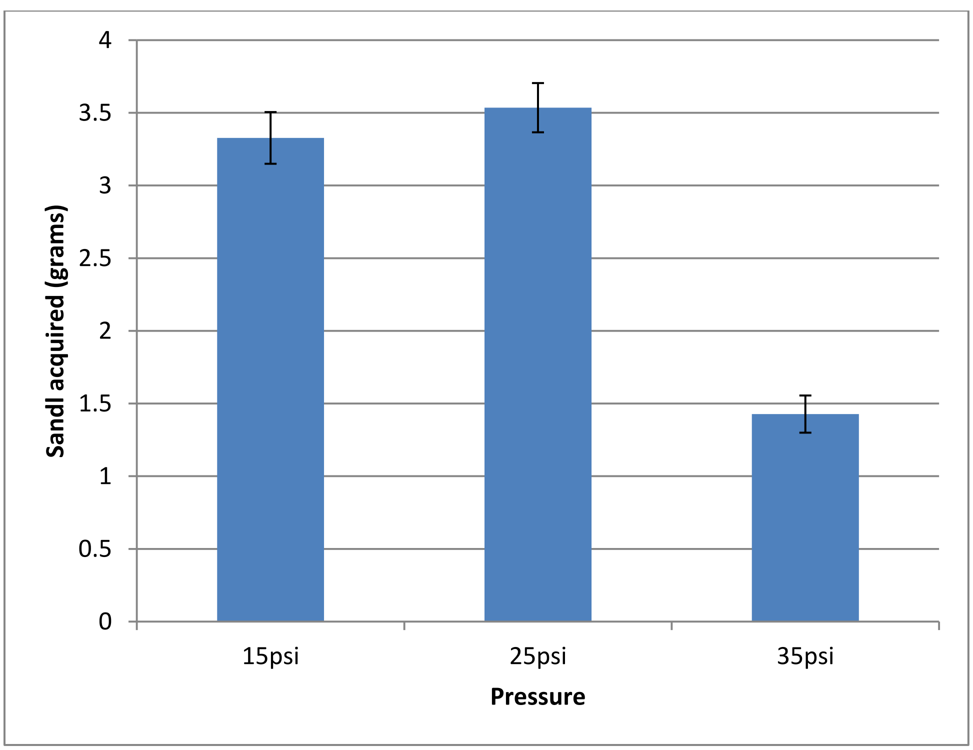

Figure 19. The effect of pressure on the mass of soil acquired.

The effect of pressure was analyzed. Intuitively, more pressure would increase the mass flow rate, pushing more soil into the sample container. However, results indicate that amount of soil acquire decreases when the pressure is too high. It is likely that the pressure build-up inside the sample container and nozzle is too high: the amount of air entering the pneumatic system is much greater than the amount leaving through the cyclone. Therefore, to avoid the unstable situation, air is pushed out through the bottom of the nozzle, pushing soil out into the environment instead of up into the sample container.

The pressure container limits the number of sample that can be attained with Axel. Each container of 20g of CO_2 has been observed to last through 8-10 puffs of ~2 seconds each. Therefore, in order to acquire more samples, the pneumatic system would require a larger pressure container. Perhaps, a pressure container exchange mechanism could be developed, which has the potential to acquire an unlimited number of samples.

Lastly, it would be beneficial if Axel could acquire multiple samples in different locations before returning to the central module. This requires a sample exchange and storing mechanism inside Axel. Further work will need to be placed in this area of system design.

4. Conclusions

Pneumatic sampling has been shown to be a feasible sampling method for future rover missions. It is fast and simple: a switch to turn on or off the pressurized air supply is sufficient actuation for acquiring one sample of soil. Although nozzle and instrument deploy mechanisms perform sufficiently well for preliminary demonstration with soil and sticky dirt, designs for the cyclone-sample container interface needs improvement to prevent contamination. Future work also includes developing sample exchange and pressure container exchange mechanisms.

5. Acknowledgements

I am very grateful to the Keck Institute of Space Studies and the Caltech Summer Undergraduate Research Fellowship program for funding this project. Special acknowledgement goes to Mr. Richard Cox for donating to the Frank W. Wood SURF fund, which directly contributed to this project.

Furthermore, I would like to thank my main mentors for the summer: Melissa Tanner and Professor Joel Burdick. There were many other people that guided me through the design and testing process: the JPL Axel team, Kris Zacny from Honeybee Robotics, Paul Baukes and Paulo Younse from JPL, Professor Bethany Elhmann and Professor Melany Hunt.

6. References

[1] Webster, G., Cole, S., and Stolte, D. (2011). NASA Spacecraft Data Suggest Water Flowing on Mars. *Mars Reconnaissance Orbiter News*, 242. Retrieved from http://www.nasa.gov/mission_pages/MRO/news/mro20110804.html.

[2] Nesnas, I.A.D., Matthews, J.B., Abad-Manterola, P., Burdick, J.W., Edlund, J.A., Morrison, J.C., Peters, R.D., Tanner, M.M, Miyake, R.N., Solish, B.S., & Anderson, R.C. (2012). Axel and DuAxel Rovers for the Sustainable Exploration of Extreme Terrains. Journal of Field Robotics, 1-23.

[3] Mahaffy, P. (2012). Curiosity rover. NASA Goddard Space Flight Center. Retrieved from http://ssed.gsfc.nasa.gov/sam/curiosity.html

[4] Hoover, R. (2011). Image and Data Analysis at the Final Four MSL Landing Sites. USPR Internship Report. Retrieved from http://usrp.usra.edu/technicalPapers/jpl/HooverMay11.pdf.

[5] Tanner, M. (2012) Extreme-Terrain Sampling KISS Proposal. Keck Institute for Space Studies: Student Led Mini-Program Proposal.

[6] Zacny, K., Beegle, L., Onstott T., and Mueller R. (2012). MARSVAC: Actuator Free Regolith Sample Return Mission from Mars. Concepts and Approaches for Mars Exploration, 4263.

[7] Backes, P. Notes from meeting with Paul Backes: June 21, 2012.

[8] Strickland, E. (2008). Mars Phoenix Lander Wrestles with Sticky Dirt. Discover Magazine. Retrieved from http://blogs.discovermagazine.com/80beats/2008/07/29/mars-phoenix-lander-wrestles-with-sticky-dirt/

[9] Zacny K. and Bar-Cohen Y. (2009). Drilling in Extreme Environments. Wiley-VCH.

[10] Zacny K., McKay D., Beegle L., Onstott T., Mueller R., Mungas G., Chu P., and Craft J. (2010). Novel Method of Regolith Sample Return from Extraterrestrial Body using a Puff of Gas. IEEE Aerospace Conference 5.

[11] Ingham, D.B. and Ma L. (2002). Predicting the performance of air cyclones. International Journal of Energy Research, 26-7, p. 633-652.

[12] Younse P., de Alwis T., Backes P. (2011). Sample Sealing Approaches for Mars Sample Return Caching.