Percussive Scoop Sampling in Extreme Terrain

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Abstract

Axel is a minimalistic cliff climbing rover that can explore extreme terrains from the moon, Mars, and beyond. To increase the technology readiness and scientific usability of Axel, a sampling system needs to be designed and build for sampling different rock and soils. To decrease the amount of force required to sample clumpy and possibly icy science targets, a percussive scoop could be used. A percussive scoop uses repeated impact force to dig into samples and a rotary actuation to collect the samples. Percussive scooping can reduce the amount of downward force required by about two to four times depending on the cohesion of the soil and the depth of the sampling. The goal for this project is to build a working prototype of a percussive scoop for Axel.

Figure 1: DuAxel in a field test at Black Point Lava Flow, AZ

Introduction

<u>Background</u>

Figure 2: Axel instrument bay with deployed instrument panel

The Axel rover has been designed and built in a collaboration between Caltech and JPL as a minimalist rover that can effectively cross extreme terrains and take measurements of nearby rocks using scientific instruments. Axel is a tethered two-wheeled rover that can be deployed from a separate robotics platform or from a second Axel rover and body, called "DuAxel" (Figure 1). This rover can traverse flat to semi-sloped terrain and the extreme terrain of interest. Axel is designed to be deployed at the edge of steep terrain, especially craters[1]. One area of interest that Axel could make accessible to researcher are craters that show new seasonal flow deposits hundreds of meters below the rim. An example of such reoccurring flow lineae deposits are found in the Centauri Montes regions on Mars but no significant traces of water has been found to explain it[2] (Figure 3). As of now, there have not been any missions that successfully collected and analyzed data from steep craters. But, DuAxel could arrive at the rim of these craters and Axel would then detaches, using a tether mechanism, and descends down the extreme terrain using cameras as guidance. To take samples of the terrain, instrumentation can be deployed from the instrument bay located inside each of the wheels. The instrument bay itself rotates with the body of the rover, independently of both the wheels and tether arm. Currently, the instrument bay hosts a thermometer, a micro imager, and a spectrometer.

Relation to other Work

Since Axel has been proven to work well in cliff terrain and more detailed path planning is now underway. The next step to increase Axel's technological readiness is to add more instrumentation capability. Therefore, JPL has commissioned Honeybee Robotics to build a coring and drilling tool for Axel and Caltech had four SURF students design and build additional sampling system during the summer. This project was one of them. Now that more sampling systems have been design, a sample handling system between different sampling systems and future instruments should be designed and the best strategy to sample should be analyzed.

Scope of Problem

To increase the scientific readiness of Axel, an effective sampling system is required. This project focused on collecting different types of soils. The most crucial restriction placed on this sampling system design is that the devices need to fit into the limited space of the instrument bay. With the current design of the instrument bay a deployable volume of 3.25" by 3.5" by 5" is available. Furthermore, the deployment mechanism in the instrument bay has been measured to exert 60 pounds of force.

Motivation

If Axel were to be send to Mars, brine ice layers might be a possible science target. Icy layers with salt content have been found under regolith including during the Phoenix mission. Furthermore, one possible explanation of the seasonal flow deposits found at the crater mentioned above is briny ice even though water has not actually been detected there by the Mars Reconnaissance Orbiter[2]. This icy soil will probably be cohesive and hard to break as experienced by the Phoenix lander, so the system designed will need a mechanism that can further break up the icy soil during acquisition[3]. This project focused on finding such a mechanism using a cam percussive mechanism to break up the ice and compact soils.

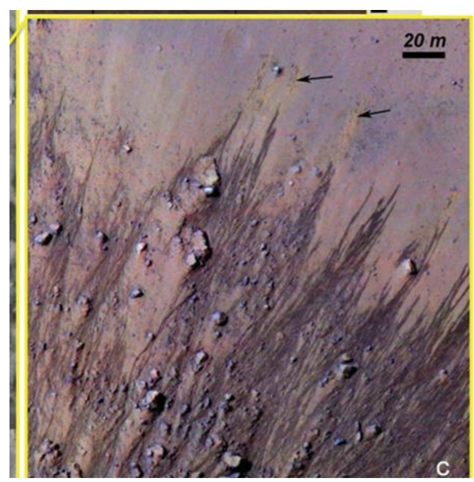

Figure 3: Enhanced photo of recurring slope lineae on Horowitz Crater[2]

Method

Previous research has proven that percussion has the potential of being effective[4]. However, the amount of force that these researchers used is even more than that Axel rover has available using the current configuration of the instrument deployment mechanism.

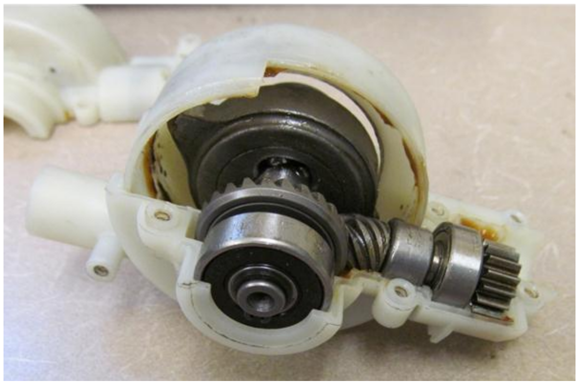

Figure 4: Dog clutch mechanism of hammer drill

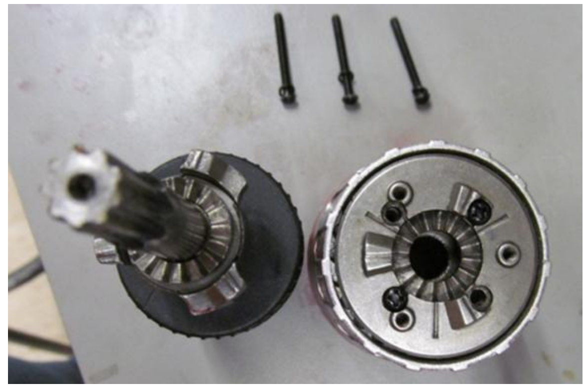

Figure 5: Impact mechanism from 12 V Craftsman Autohammer

Figure 6: Autohammer testing setup. Top: force sensor; middle autohammer with trovel; bottom icy sand.

Therefore, a new set of data has been collected in the force range of the current Axel rover using two different percussive mechanisms. Percussion continues to prove to be effective especially for increasingly compact and cohesive soils. While using these percussive mechanisms, the angle of impact has a less drastic effect on the force required than without percussion. However, in both cases data generally indicate that a smaller angle between the shovel and soil decreased the force required. During this project two different percussive mechanisms were used. One is a linearly decoupled hammerdrill and the other is an autohammer (also known as a nailer). Both percussive mechanisms have impact frequencies on the other of several thousand impacts per minute but the impact energy seems to differ more noticeably. The difference in percussion mechanisms affects force of digging required but it is most noticeable when testing icy soils. The autohammer allows for some digging and scraping of icy soils, while the hammerdrill cannot penetrate the ice soil.

Results

To verify the effectiveness of percussive scooping and pinpoint potential challenges, two different percussive mechanisms were tested on three different types of soil, angles of impacts, and depths. The first percussive mechanism was the dog clutch taken from a DrillMaster 18V Hammerdrill. A dog clutch mechanism uses two interfering disks to create percussion. To decouple the rotary motion from the percussive motion, a 3D printed part was fabricated and attached to the original holding the trovel so that once force was applied the percussive mechanism was activated (Figure 7). The second percussive mechanism is part of the Craftsman Autohammer (Figure 6). Since icy soils are of particular interest, the three different types of soil prepared were dry sand, wet sand, and icy sand. The wet sand was prepared by adding about 2.5L of sand and 1L of water into a box. The icy sand was prepared by putting the wet sand mixture into a

Figure 7: Percussive scoop prototype with force sensor (far left), hammer drill (center), and trowel (right).

freezer overnight. The depth was measured along the axis of the shovel by marking the different depths on the shovel itself, while the angle was measured using a protractor. The test was carried out with each percussive mechanism with all three soil types at different angles and depth. Some observation noted during the test is that the intensity of percussion is correlated to the amount of force applied. This is due to the fact that both mechanisms have compression springs between the cam mechanisms that are required to be engaged. This affects the increasing slopes of some of the depth vs. force graphs. However, it is impossible to measure how much the mechanism is engaged in the current configuration. Therefore, the compression springs should be regarded as a property of the make, model and percussive mechanisms.

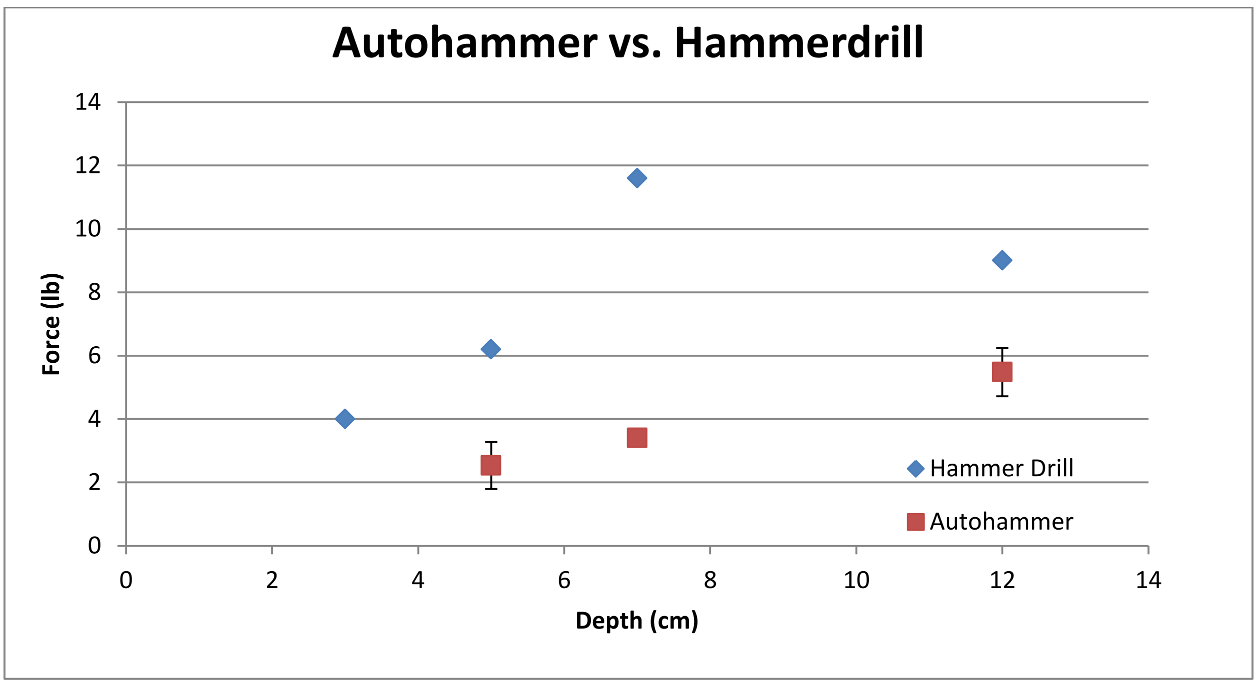

Figure 8: Comparison of autohammer percussive mechanism (red squares) to the hammer drill percussive mechanism (blue diamond) at 90 degrees angle in wet sand. In general, the autohammer mechanism requires less force to reach the same depth. Error bars are given for data using the autohammer since more than one trial were conducted.

In general, the autohammer requires slightly less force than the hammerdrill to reach the same depths sand (Figure 8). This suggests that higher impact energy used implies less force required.

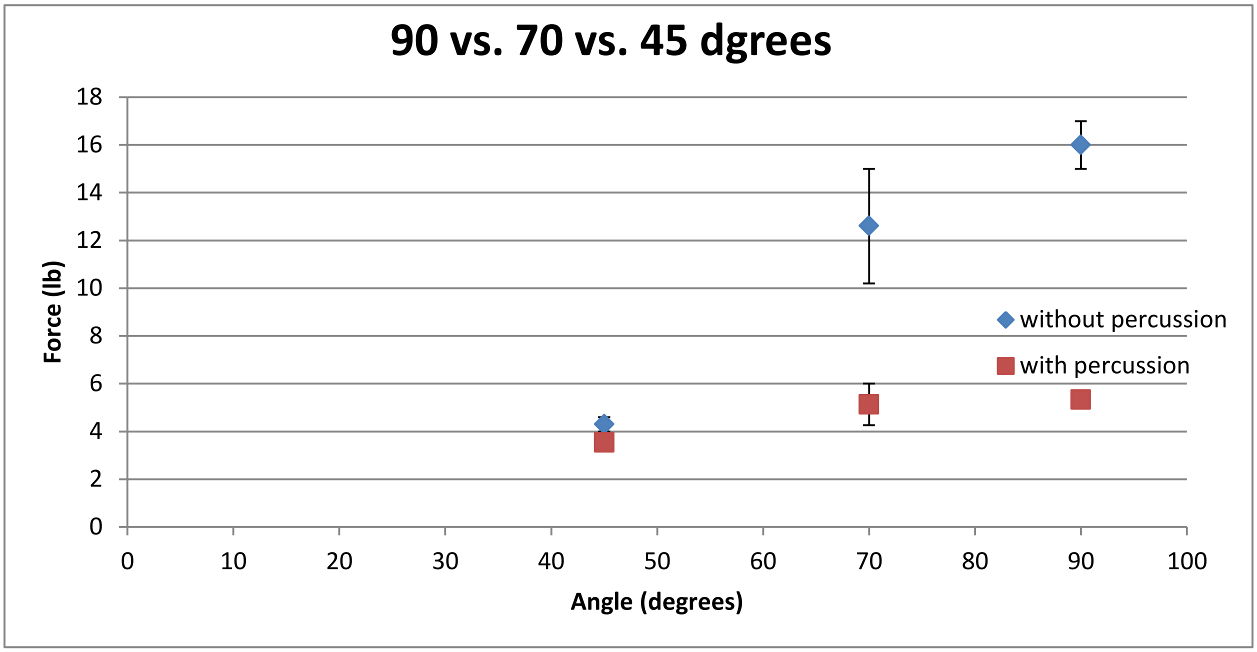

Figure 9: Comparison of force required for different angle of impact in dry sand using the autohammer percussive mechanism. Error bars are given using data of at least 2 different trials for each point of interested.

Figure 9, however, notes that the difference in force required is much less for percussion compared to without percussion. In general, the testing also has shown that a higher angle between the shovel and sand requires a greater force to reach the same depth.

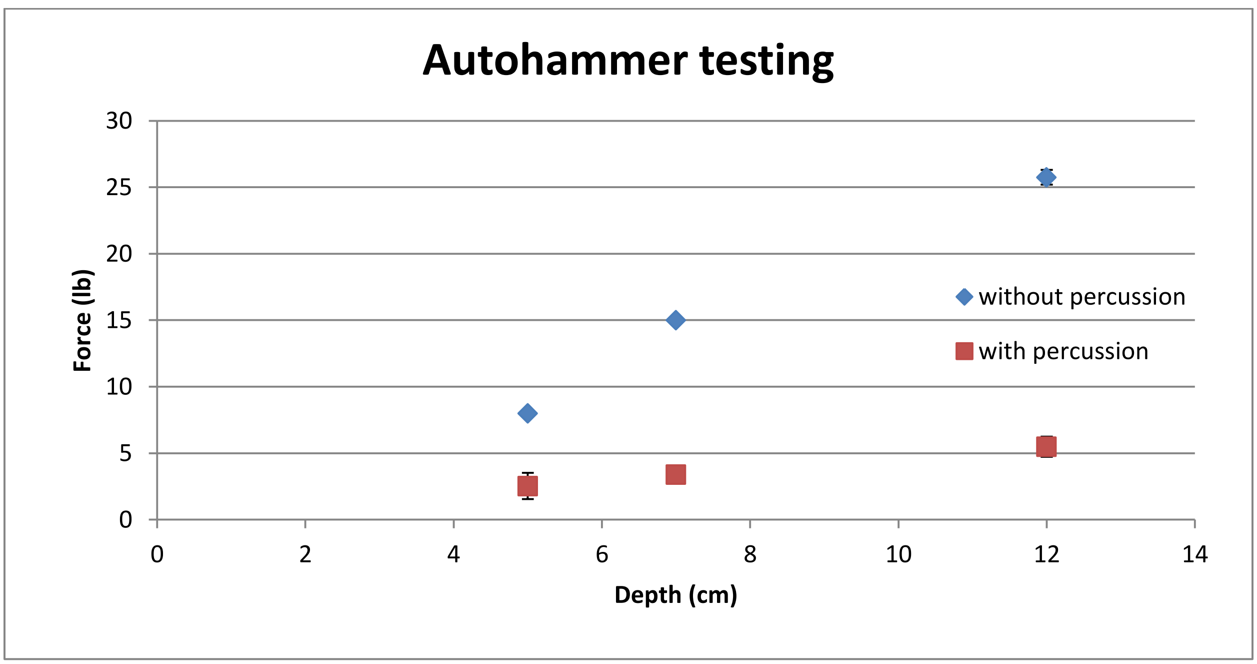

Figure 10: Depth of digging vs. force required in wet sand using the autohammer mechanism. Digging to a depth of 12cm at 90 degrees in wet sand requires 4.5 times less force with percussion. Error bars are given using data of at least 2 different trials for each point of interested.

The benefit of using a percussive mechanism can be up to at least 4.5 less force in as seen in wet sand using a the autohammer at 90 degrees (Figure 10).

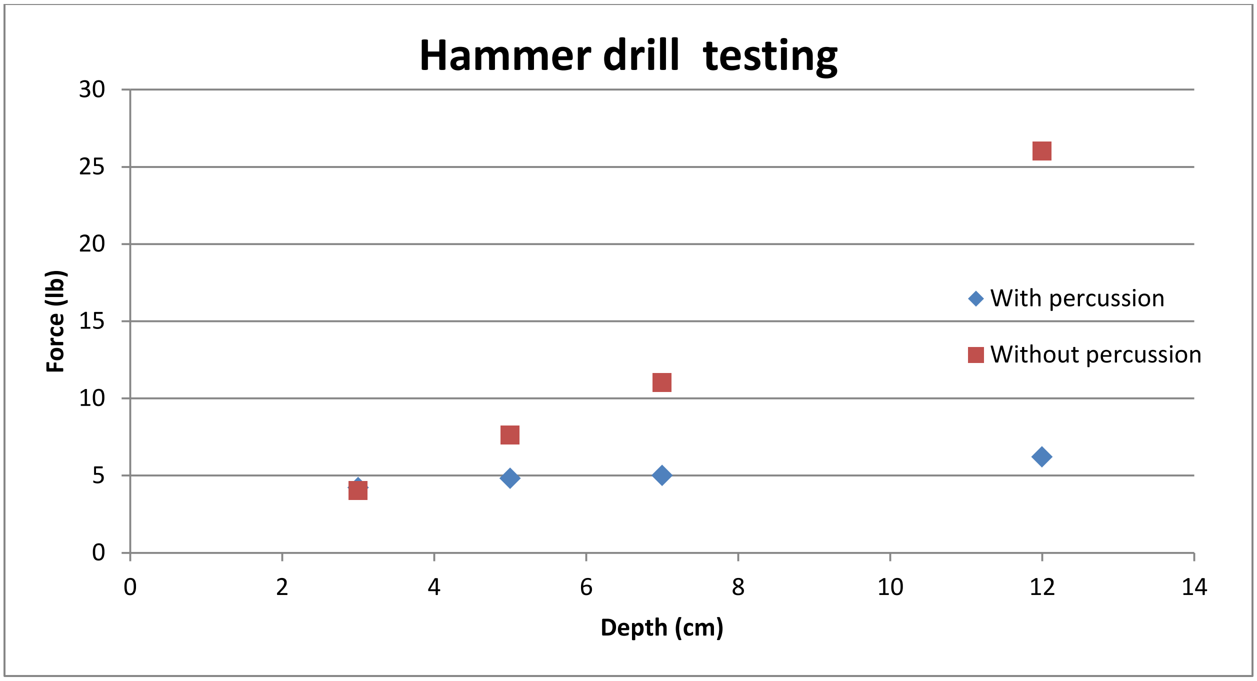

Figure 11: Depth of digging vs. force required in wet sand using the hammer drill mechanism. Digging to a depth of 12cm at 45 degrees in wet sand requires 4.2 times less force with percussion. Only one measurement taken for each point.

Similar results are also noticed at 45 degrees in wet sand using the hammerdrill, which allows for up to 4.2 times less force required (Figure 11). The hammerdrill mechanism does not allow for any ice collection in the range of force applied. Sometimes a small indent was made but not enough sand could be collected at any angles attempted.

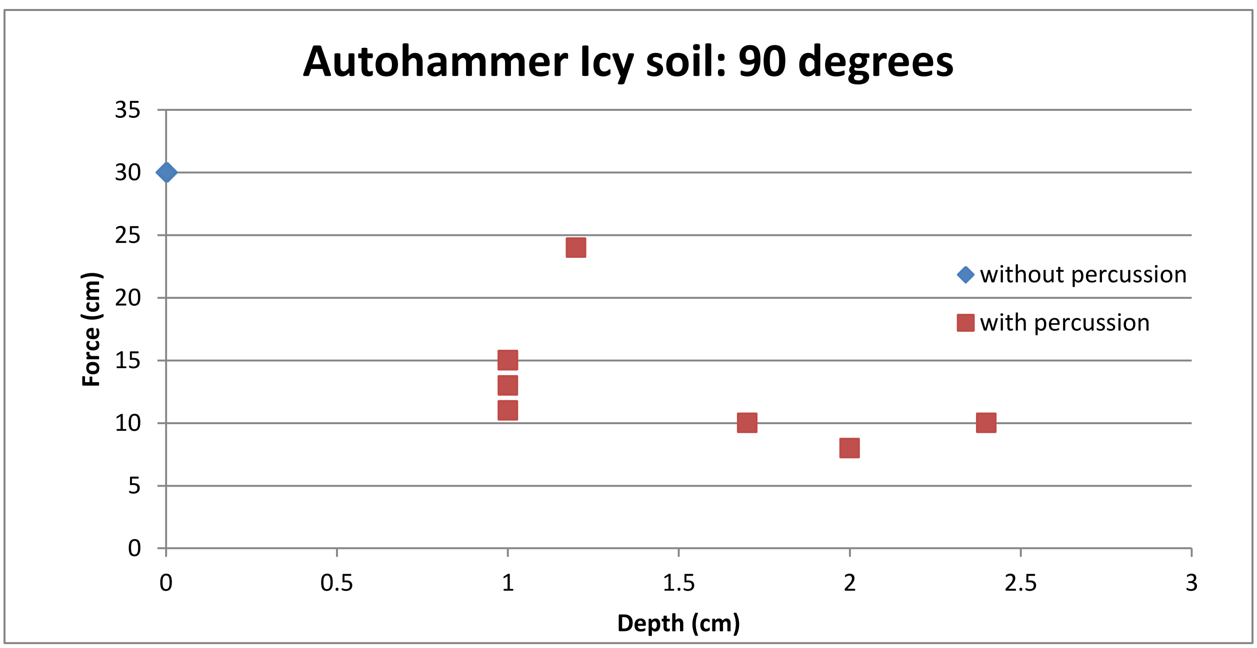

Figure 12: Icy sand testing using the autohammer at 90 degrees. Between 10 to 15 pounds of force are required to dig into the sample. No error bars are present since only one measurement was taken at each point.

Figure 13: 2 cm penetration into icy soil with a force of 58 N using the autohammer. Notice the clay like behavior of the sand and water.

The initial test in icy soil with the autohammer at 90 degrees shows that forces between 10 and 15 pounds are generally required to dig into the ice (Figure 12). However, it is quite difficult to remove the shovel without percussion. Another interesting observation is the interaction between the soil and the trovel with the autohammer in icy sand shows a fluid like behavior at the boundary (Figure 13). This can be avoided by a lower impact angle digging to a shallower depth (Figure 14). Therefore, a lower angle of impact is favorable for several different reasons. However, with the current force measurement set up it was difficult to measure the force required at lower angles.

Figure 14: Lower angle scraping results using autohammer in icy soil.

Since the autohammer is more favorable for all different types of soils tested and the mechanism is more compact as well, it is the better percussive scoping system for Axel. Given then current deployment mechanism, only a z-stage mechanism is needed additionally to lower the autohammer and scoop. The rotation of the instrument bay is used for the scooping motion. Several constraints and challenges were considered while designing the sampling system including a robust scooping mechanism, space, and minimized sliding and actuation. The most effective way of building a z-stage is to include an actuator to lower the autohammer, since the z-stage needed to be able to with stand the forces to scoop and the vibration caused by the percussive mechanism. Since the autohammer needs to be lowered to scoop soil and the instrument bay is offset from the wheel, the actual space for the z-stage and autohammer is 2.375” by 3.5” by 4.5”. The most effective actuated z-stage for Axel that is also efficient is a ball screw mechanism. A ball screw mechanism, allows for linear motion of a ball screw nut through the rotation of the ball screw. The ball screw nut uses ball bearing to eliminate sliding friction. The actuated z-stage mechanism design allows for about 3 inches of travel to reach below the wheel and sample soil.

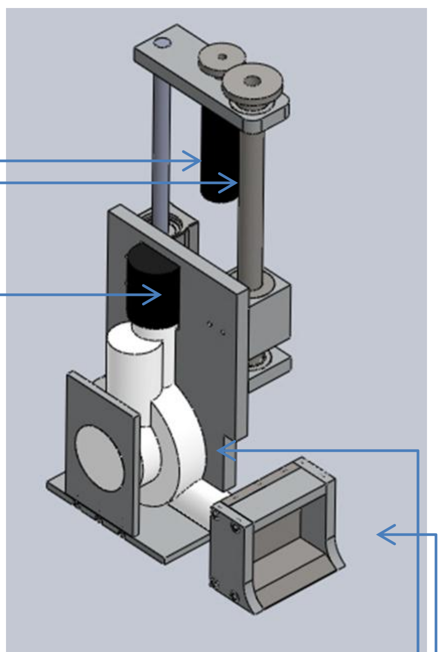

Figure 15: Final design for percussive scooping system for Axel in the extended configuration. In white: percussive mechanism; to the right: scoop, top right: ball screw; in black: motors.

Discussion

The autohammer is the most effective mechanism for a percussive scooping system for Axel. Its impact frequency and energy allows for collection of icy soils and compact soils (represented by wet sand). When percussion is used, the difference in force required is lower at different angles than without percussion. This gives some flexibility in the design of the percussive scoop system for Axel. However, the lower angles between the soil and the scoop seemed to require less force. This was tested for angles greater than or equal to 45 degrees. Although, this sampling system will not be scooping to depth of 12 cm, studying the effects of force with depth allows quantification of the effects of percussion and could be used for future designs of different scooping system. The prototype built needs to continue to be developed before final integration into Axel but a lot of its features have a good potential to work based on tests with the original mechanism.

Implications of the Research

Figure 18: Actual design of percussive sampling system. Right: scoop; front right: ball screw with ball screw nut; white: part of autohammer percussive mechanism.

The implication of this research suggests that if a scoop is used in a robotics system, it is worth considering percussive scooping because it reduces the amount of force required and thus the weight of the rover. This saves power required for rocket propulsion and driving the rover. However, if the rover must be able to exert high enough forces to scoop icy soil for other reasons, the extra actuation to power the percussive mechanism might be a waste of energy. Environments where percussive scooping will be the most beneficial are on low gravity environment and soils with high cohesion factor. Throughout this project, many different ways of achieving percussion were considered, but not all could be tested. At the beginning of the summer, the dog clutch mechanism seemed to be the most promising, but higher impact energy seemed to be required (which is understandable now) and therefore the autohammer was used. If other objective needed to be met other percussive mechanisms should definitely be explored.

Future Research

The first future work is to integrate this percussive system in Axel and add a power system as well as a motor to the autohammer. Based on the results after this integration, more extensive testing to refine the percussive characteristics should be carried out in order to determine the best impact frequency and impact energy. In depth, soil mechanics analysis of known future soil types is also reported to help refine the results of percussive scooping. One particular field that needs to be investigated further is the reasons for the fluid like behavior of the icy sands between the scoop and soil at the boundary (Figure 13). Furthermore, more extensive low angle measurement must be carried out, which will be done most effectively through designing a test bed with better force measurement techniques. For better scientific results for Mars conditions, the use of Mars like soils and Mars pressure and temperature conditions is advisable. Then a complete sampling system should be implemented including a sampling container and sampling retaining system that can hold the sample container in place during sampling. The two design ideas considered have either a rectangular or a circular profile. The rectangular scoop would be very similar to a backhoe with spikes at the front to help loosen soil while the sample system would be looked in place from the back (Figure 17). For the circular scoop, the locking mechanism would allow a sample container to be held inside the scoop (Figure 16). The best way to test the effectiveness of these designs will be to 3D print them and test them in a dusty setting and exposing them to the percussive forces.

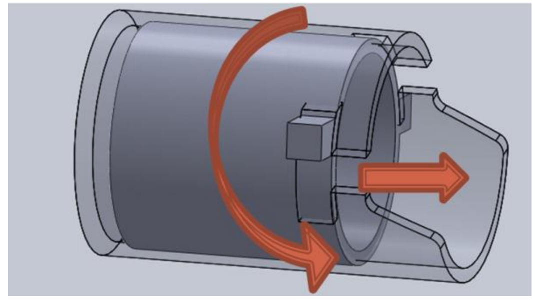

Figure 16: Design idea for sampling container and retaining system using a turning locking mechanism.

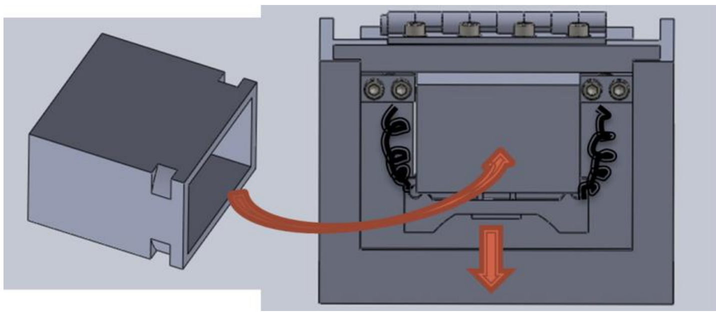

Figure 17: Design idea for sampling container and retaining system using a sliding spring mechanism.

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Appendices.

Testing Charts

Hammer Drill

Icy Soil

Angle (degrees)	Depth (cm)	Force (lb)
90	Less than .5	5

Dry Soil

Angle (degrees)	Depth (cm)	Force (lb) with percussion	Force (lb) without percussion
90	3	1.0	1.0
90	5	2.4	3.5
90	7	3.2	5.0
90	12	6.0	13.0
70	3	0.8	1.2
70	5	2.0	2.2
70	7	3.2	3.6
45	3	0.8	1.4
45	5	1.4	2.4
45	7	3.8	3.4

Only little bit of 7cm with percussion mainly with 12 cm depth that percussion made a different

Wet Soil

Angle (degrees)	Depth (cm)	Force (lb) with percussion	Force (lb) without percussion
90	3	4 .0	6.3
90	5	6.2	11.6
90	7	11.6	21.0
90	12	9.0	31.0
70	3	4.2	5.6
70	5	3.4	7.0
70	7	6.2	15.0
70	12	5.2	33.2
45	3	4.2	4.0
45	5	4.8	7.6
45	7	5.0	11.0
45	12	6.2	26.0

Autohammer

Icy-water sand

Trial	Angle (degrees)	Depth (cm)	Max Force (lb)	obersvation
With percussion (attempting to go as deep as possible)	90	12	N/A	Soil turned into water although scoop is cold afterwards
With percussion (to measure force)	90	0.8	5	Difficulty in activating max force
With percussion (to measure force)	90	11	10-15	Looks like the problem is engaging with compression spring
Without percussion	90	0.1	17	It's amazing how it looks like wet sand with hammer drill and like ice with control only approximation of depth

It looks like only the top 2 cm are frozen :/ I guess I'll leave it in the freezer overnight and do more testing but it can pertrude things much better and it's very loud!!!!

Icy soil

Trial	Angle (degrees)	Depth (cm)	Force (lb)	Observation
Without percussion	90	Indent	30.0	Just shovel plus sensor
With percussion (to measure force)	90	1	15.0	
With percussion	90	1	13.0	Wet mud splashing And fluctuated between 10 and 22 lb
With percussion	90	1.2	24.0	
With percussion (to attempt to go as deep as possible)	90	2.5	N/A	Continues to be cement but battery is out Using both angled setting and straight setting in the auto hammer
With percussion (and with shovel at similar same temp to sample)	90	2.4	10.0	Straight setting of the autohammer
With percussion	90	3	N/A	Last try when force censor broke
No percussion	90	1	30	no indent
With percussion	90	1	15.0	
With percussion	90	1	11.0	Attempted 90 degrees more like 80 degrees
With percussion	90	2	8.0	saw it go up to 10 lb and roughly 90 degrees
With percussion	90	1.7	10.0	but dial went crazy but needle stayed put
With percussion	10	0	8.0	No percussion 10 degree scraping
Without percussion	15	0	3.4	No indentation on ice more ice than icy soil
Without percussion	15	0	3.0	More sliding than collection
With percussion	15	0	0	Trouble engaging hammer at any level

Without percussion	45	0	25.0	Ice melting a bit but no indent
With percussion	45	0.1	9.0	Engaged scraping material not as easy as lower angles depth is an estimation
With percussion	45	0.1	14lb	Engaged but not fully , scraping , depth is an estimation

Dry sand

Trial	Angle(degrees)	Depth (cm)	Force (lb)	Observation
Without percussion	90	12	17.0	Weight allows to dig in about 4cm
Without percussion	90	12	15.0	
With percussion	90	12	5.6	Sank in
With percussion	90	12	5.0	
With percussion	90	12	5.4	Sank in by itself to 4cm
Without percussion	70	12	10.2	Sank in
Without percussion	70	12	15.0	5cm sank
With percussion	70	12	3.4	Sank into 6cm
With percussion	70	12	6.0	Sank into 5cm
With percussion	70	12	6.0	Sank into 5cm
Without percussion	45	12	4.6	
Without percussion	45	12	4.0	
With percussion	45	12	3.6	
With percussion	45	12	3.8	
With percussion	45	12	3.2	

Wet sand

Trial	Angle (degrees)	Depth (cm)	Force (lb)	Observation
Without percussion	70	5	3.4	

Without percussion	70	7.5	5.4	More like 7.5cm
With percussion	70	5	4.7	Sank until 4
With percussion	70	6.5	4.6	More like 6.5cm
With percussion	70	5	2.0	
With percussion	70	5	3.0	
Without percussion	70	12	25.0	Started at 4 inches
Without percussion	70	12	25.0	Started at 2 inches
With percussion	70	12	10.0	Started around 3 inches
With percussion	70	12	9.0	“
With percussion	70	12	7.0	“
Without percussion	70	7	6.4	
Without percussion	70	7	9.2	
With percussion	70	7	6.2	
With percussion	70	7	6.4	
With percussion	70	7	7.8	
With percussion	70	7	5.9	
Without percussion	90	5	8.2	
Without percussion	90	5	7.8	
With percussion	90	5	4	
With percussion	90	5	1.6	
With percussion	90	5	2	
Without percussion	90	7	14.8	
Without percussion	90	7	15.2	
With percussion	90	7	3.6	
With percussion	90	7	3.4	
With percussion	90	7	3.2	
Without percussion	90	12	26.3	
Without percussion	90	12	25.2	recorded but went up to 32
With percussion	90	12	4.2	Might be more force because I used my hand a little to push the autohammer into the soil

With percussion	90	12	7.2	
With percussion	90	12	3.8	
With percussion	90	12	7.4	
With percussion	90	12	4.8	Good reading