Tools and Algorithms for Sampling in Extreme Terrains

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Project Summary

Extreme-terrain robots such as JPL's Axel rover are enabling access to new and exciting science opportunities. The goal of this mini-program was to develop a compact sampling instrument for Axel. Over the summer of 2012, a small group of students designed, built, and tested prototype sampling devices. Nikola Georgiev created a versatile four-degree-of-freedom scoop, which can acquire up to 4 different samples in clean self-sealing containers. Hima Hassenruck-Gudipati studied percussive scooping, and prototyped a percussive scoop that takes advantage Axel's independent body rotation to acquire samples. Kristen Holtz and Yifei Huang collaborated on a pneumatic sampling system, which uses a puff of air to propel loose grains into flexible tubing, and separates the grains into an interchangeable sample container. Each of these sampling systems has been demonstrated, and each proved useful for different conditions. In turn, the students gained valuable design experience and the opportunity to work alongside a number of experts in various fields.

INTRODUCTION

The Mars Science Laboratory rover Curiosity's recent landing on Mars demonstrates the impressive capability of modern engineering. Curiosity can climb slopes of up to 30 degrees, which are difficult for even a human to walk up, unaided [1]. While this state-of-the-art rover can operate on ~60% of the Martian surface, some of the most interesting potential science locations lie in the remaining untraversable extreme terrain. For example, the HiRISE camera on the Mars Reconnaissance Orbiter revealed seasonal dark streaks on the sun-warmed slopes of Newton Crater, as shown in Figure 1. Scientists hypothesize that these recurring slope lineae, or RSL, are cause by subsurface ice melting in the summer sun, and flowing down the slope as briny liquid water. Due to Mars's temperature and pressure being near the triple point of water, water on the surface usually doesn't stay liquid for very long, making detection difficult from space. An extreme terrain rover, however, could access these RSL and analyze them in situ to determine their content. It could study the rock strata revealed in the walls of craters, to learn something about the planet's geologic history. It could even investigate cold traps on the Moon, in search of frozen water sequestered in the shadowed depths.

Figure 1: RSL on the surface of Mars, as imaged by HiRISE. If these RSL are caused by briny water, as hypothesized, in-situ analysis could confirm the presence of water on Mars [2].

To explore similar extreme terrains, the Jet Propulsion Laboratory (JPL) has developed the Axel rover in concert with the California Institute of Technology (Caltech). Axel is a minimally actuated tethered rover that can rappel down cliffs and into craters carrying science instruments. It has four

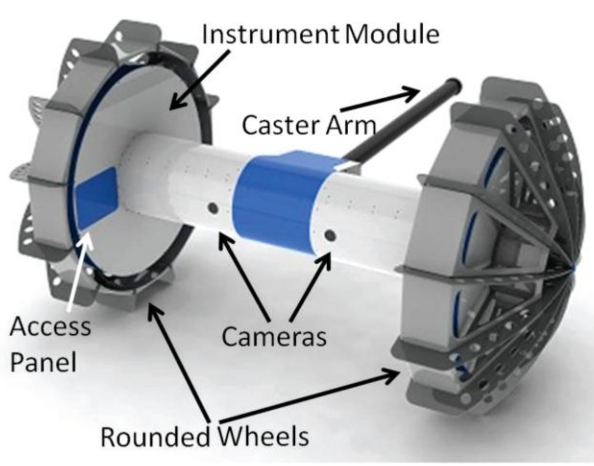

Figure 2: A rendering of the Axel rover.

Figure 3: Axel deploying an instrument from its instrument module on a steep slope in Arizona.

Figure 4: Close-up of Axel deploying an instrument from its instrument module.

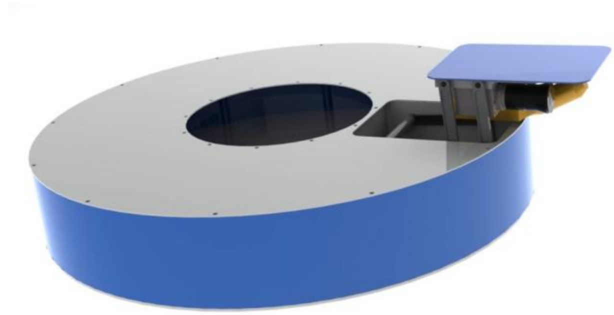

Figure 5: CAD rendering of Axel's instrument module with deployed camera.

motors: one for each of its two wheels, one for the spool, and one for the arm (Figure 2). To propel Axel forward, the arm pushes down on the ground in concert with the wheels. Axel's body was designed to act like a winch to minimize tether abrasion; the tether starts out spooled around Axel's body, and is payed out through the arm as Axel travels. To return to its starting position, Axel reels in the tether, using it as a climbing aid if necessary. This combination of four motors also allows the body to turn independently from the wheels. Thus, Axel can stop at any time on an ascent or descent to take pictures or measurements, as it is doing in Figure 3 and 4. Each wheel bears an instrument module, whose CAD model is shown in Figure 5. Up to four instruments can be mounted on deployable panels inside the bay, such as a laser spectrometer, thermometer, and microscopic imager. Thanks to the independent motion of the body, any of these instruments can be deployed directly onto the planetary surface at any time. [3][4]

Axel's tether acts as both a mechanical support, and a conduit for power and communications. Thus, it can eschew bulky antennas, solar powers, and other power and communications systems; those functions are provided by its anchoring craft. Axel can be carried on another rover, to act as a mobile instrument. Additionally, two Axel rovers can be connected to form the DuAxel system. As shown in Figure 6, DuAxel is a four-wheeled rover comprised of two Axel rovers docked in a central module, which can carry an onboard power supply, antennas, and even additional cameras. DuAxel can travel long distances on relatively flat ground until it reaches a crater, at which point either or both Axels undock. For more details on Axel, DuAxel, and other extreme terrain robots, see [3].

Figure 6: The DuAxel rover climbing rough terrain during field testing in Arizona. DuAxel consists of two Axel-class rovers docked with a central module.

In order to advance Axel's sampling capabilities, the author (Melissa Tanner) led a small team of students in designing and building prototype soil sampling systems over the summer of 2012. The students, pictured in Figure 7 with Axel, were all Caltech undergraduates supported in part by the SURF program. Diego (left) worked a yaw joint for Axel, while Kristen, Nikola, Yifei, and Hima at right participated in this KISS-supported mini-program.

Figure 7: Axel SURF students 2012. From left: Diego Caporole, Kristen Holtz, Nikola Georgiev, Yifei Huang, and Hima Hassenruck-Gudipati.

The students were instructed to develop a device, either singly or in teams, that could collect representative material found in extreme terrain (e.g. soil samples, cores of layered strata, and rock abrasions). This sampler should collect and store at least 10 grams of soil or loose gravel, as well as rasping, scraping, drilling, or otherwise exposing and collecting a small amount of subsurface rocky material. It must fit within the 5"x3.25"x3.5" deployable volume of Axel's science drums, and must run off of the available 24V, 12V, or 5V DC power.

The students each took very different approaches to the problem, developing a variety of scooping, blowing, and percussive devices. Hima and Nikola worked independently, while Yifei and Kristen collaborated on their design. Each group designed, prototyped, built, and tested a sampling system, as described in the following sections.

Percussive Scooping: Hima

The Phoenix mission to Mars discovered water ice under layers of regolith. Since water on Mars exists near the triple point, any sampling device must also be prepared to encounter water ice. In order to scoop samples from hardened or icy soils, Hima Hassenruck-Gudipati (pictured in Figure 8) decided to design a percussive scoop. For the same reasons that adding percussion to a drill allows it to jackhammer through otherwise-unbreakable concrete, adding percussion to a scoop should allow it to break through hard or icy soils.

Figure 8: Hima Hassenruck-Gudipati, a junior at Caltech in Mechanical Engineering.

Research

Hima's literature review revealed that percussive scooping should reduce the force necessary to scoop by a factor of 50% [5]. She started by taking apart a hammer drill and an auto hammer to examine and reengineer the percussive mechanisms in each. A hammer drill, for example, uses a dog clutch mechanism as shown in Figure 9 to transfer the motor's rotary motion into percussion. The insides of an autohammer are shown in Figure 10. In order to test the effectiveness of percussive scooping, Hima attached a trowel head to each of the two percussive mechanisms, as shown with the auto hammer at left in Figure 11. She measured the amount of force necessary to scoop sand, both with percussion and without. The results for the hammer drill in wet sand are given

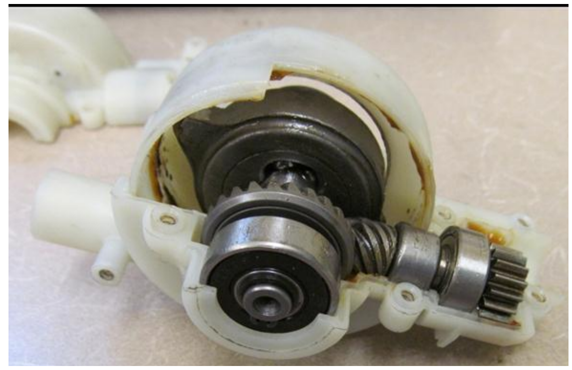

Figure 9: Dog clutch mechanism from a Drill Master Hammer Drill.

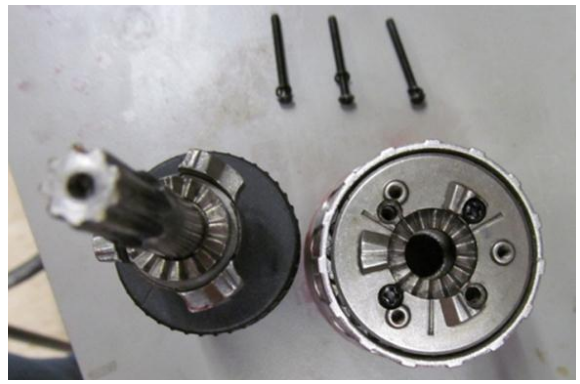

Figure 10: Impact mechanism from a 12 V Craftsman Autohammer.

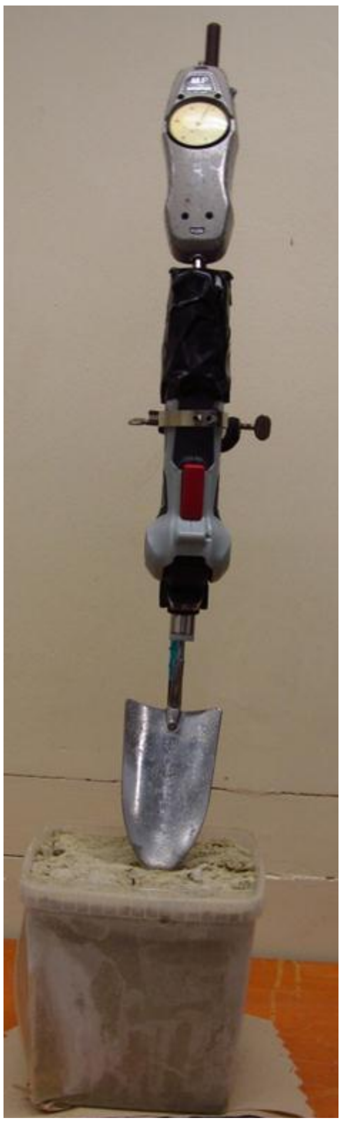

Figure 11: Force sensor, Craftsman Auto Hammer, and trowel head test setup, scooping in icy sand.

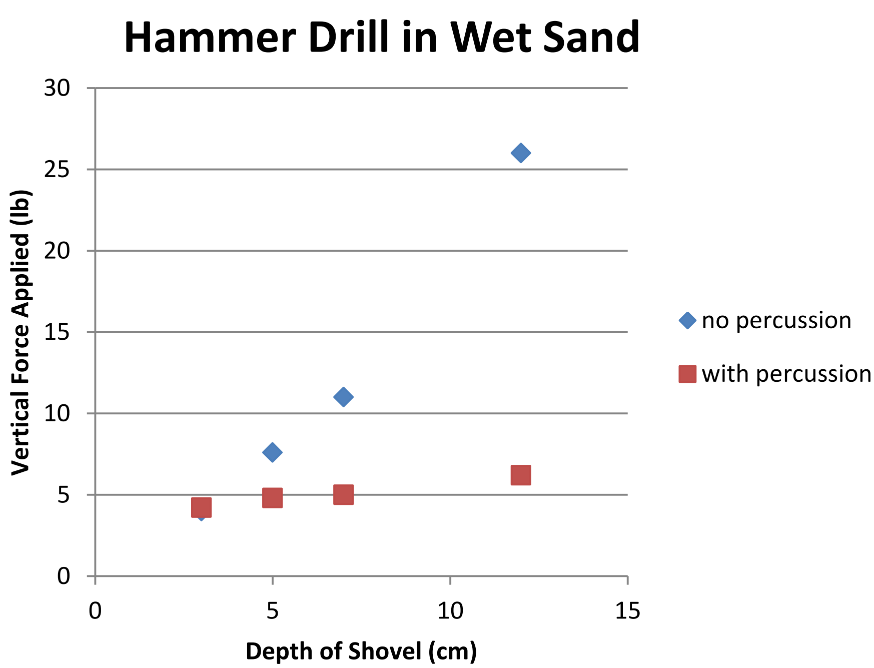

Figure 12: Results of experiments with hammer drill percussive scoop prototype in wet sand. In general, less force is required to reach a certain depth with percussion than without.

above in Figure 12.

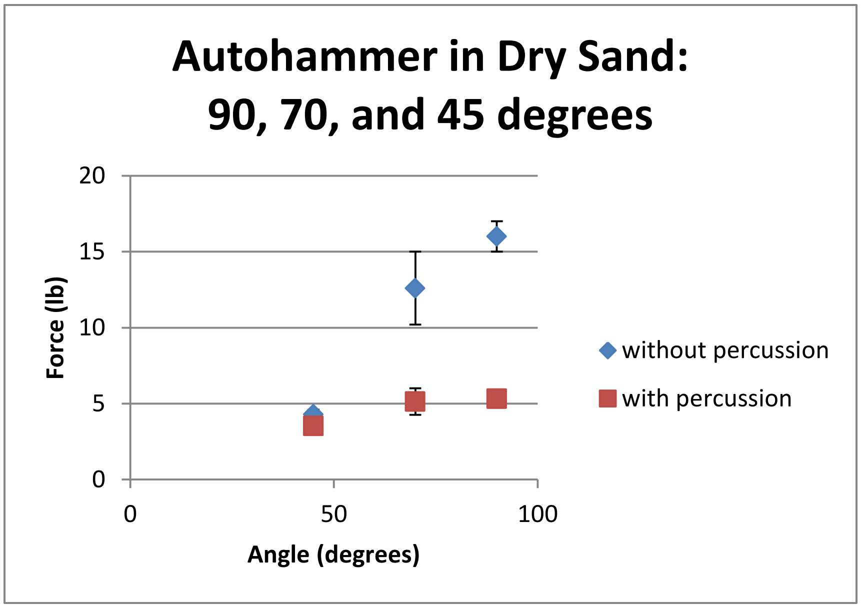

Figure 13: Results of experiment with autohammer percussive scoop prototype in dry sand, at various scraping angles. Without percussion, a low scraping angle was most effective, requiring less force.

Hima tested each percussive mechanism in dry sand, wet sand, and "icy sand" – wet sand that had been frozen solid. In addition to testing different percussive mechanisms, Hima also studied "scraping angle", or the angle at which the scoop enters the surface. One resulting chart is shown at right in Figure 13. In this example, increasing the scraping angle seemed to have little effect on the force required for percussive scooping, although scooping without percussion actually required less force at a low scraping angle. For further results on scraping angle, and observations on the effects of percussion on icy sand, please see Hima's final report.

PROTOTYPE

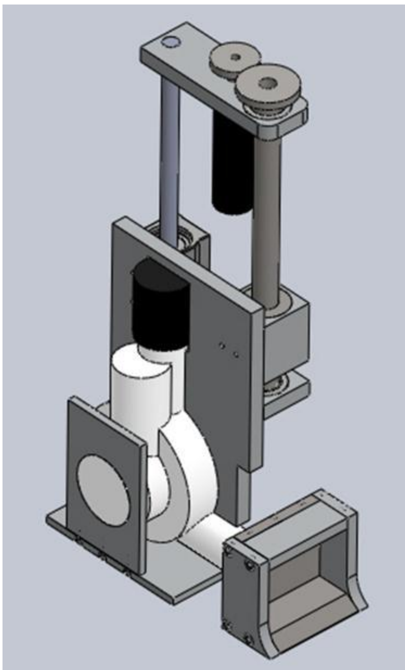

Figure 14: CAD rendering of Hima's percussive scoop.

Figure 15: Hima's final percussive scoop prototype.

This simple experiment suggested that percussive scooping is, indeed, more effective and more efficient (requiring less force to reach a certain depth) than regular scooping. So Hima designed a percussive scoop mechanism that would fit in Axel's instrument bay. Figure 14 is a screen capture of the resultant CAD file. It includes a ball screw, a percussive mechanism, and a scoop, all packaged for the size constraints of Axel's instrument bay. Axel's body rotation would provide the tangential motion to drive the scoop into the ground. Due to time constraints, she was able to build that design but not test it. Hima's final percussive scooping mechanism is pictured in Figure 15. Hima's final report can be found online at [6] and her final presentation for the SURF program is at [7].

PNEUMATIC SAMPLE ACQUISITION: YIFEI AND KRISTEN

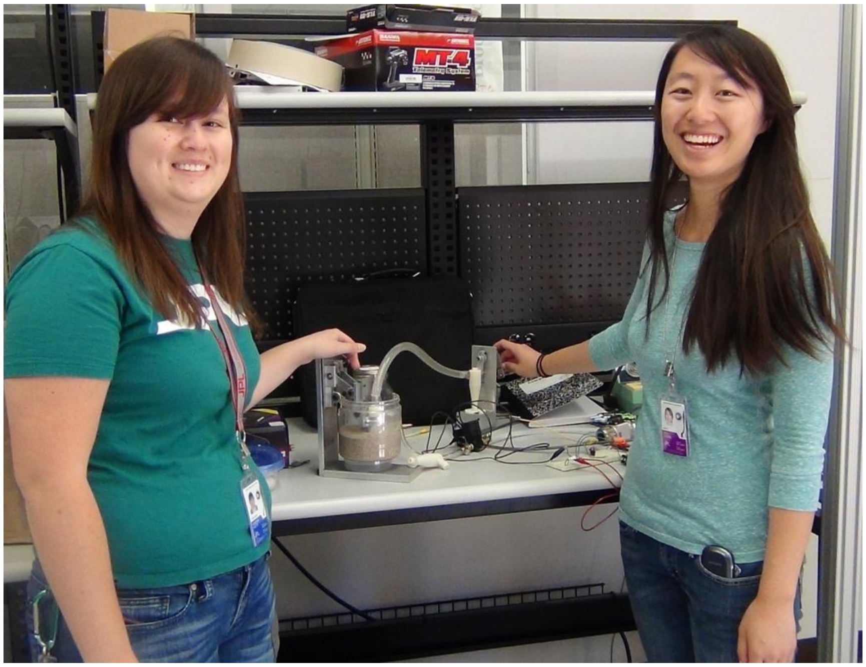

Figure 16: Kristen Holtz (left) and Yifei Huang (right) with their benchtop pneumatic sampling system. Both are studying mechanical engineering at Caltech.

Yifei Huang and Kristen Holtz worked together on a pneumatic sample-capture system (Figure 16). A pneumatic system uses gas to blow or entrain sample particles; it works best on sand or loose regolith. Research has shown that, in low-pressure environments like the Moon or Mars, positive pressure works better than suction. A nozzle is pushed into the sand, and gas is blown down around the sides of the nozzle. Assuming the nozzle is deep enough that the air cannot escape out the sides, the air entrains sample particles travels back up the nozzle, and flows into tubing that can deposit the sample where desired. Pneumatic sampling is attractive because it requires fewer actuators or moving components, and because a flexible tube allows us to store the sample far from the acquisition site. Yifei and Kristen worked with all aspects of the system, designing a nozzle, cyclone separator, and sample container, as well as experimenting with the ideal pressure and time period for gas.

Nozzle Design

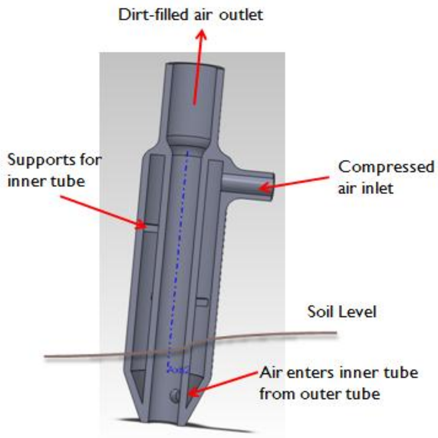

Figure 17: Nozzle 1.

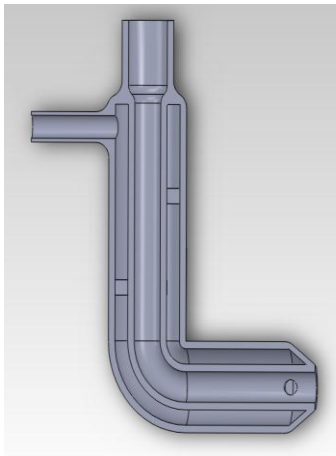

Figure 18: Nozzle 2.

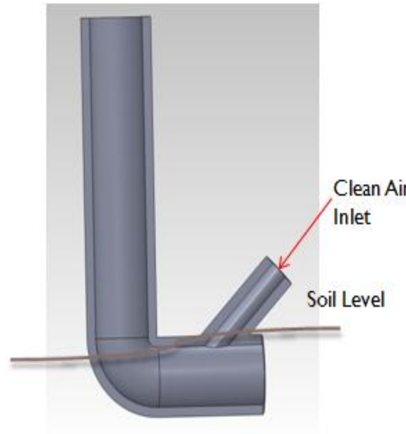

Figure 19: Nozzle 3.

Although research showed that a positive-pressure gas system worked best (as opposed to vacuuming up dirt), several design variables remained unknown. To find the best design experimentally, Yifei and Kristen designed three nozzles to test, and prototyped them in a 3D printer. Nozzle 1, in Figure 17, was similar to a nozzle in the literature. Nozzle 2, in Figure 18, was designed to penetrate the soil at a 90-degree angle, instead of vertically. Nozzle 3, in Figure 19, used a slanted air inlet to direct airflow back up the tube.

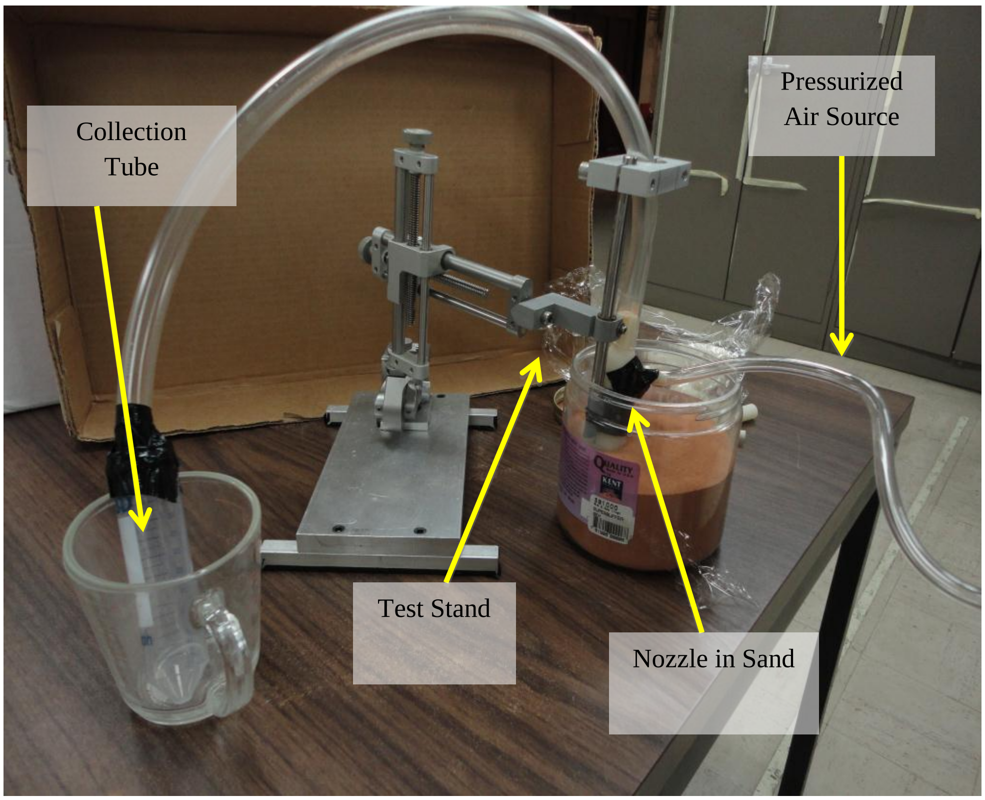

Figure 20: Nozzle testing experimental setup.

Yifei and Kristen printed these nozzles on a 3D printer, and used the experimental setup shown in Figure 20 to test the nozzles for the most lifting power. As shown in Figure 21, Nozzle 3 far outperformed the other two. It is believed that the angled air inlet was the cause of this improvement. Furthermore, the straight nozzle seemed to work better than the curved nozzle. The team consequently tested two more designs, both with straight nozzles and angled air inlets. Nozzle 4, in Figure 22, had more air inlet holes than Nozzle 5, in Figure 23. As Figure 24 shows, Nozzle 5 outperformed Nozzle 4. We hypothesize that the multiple holes in Nozzle 4 diluted the force of the air from the lowest inlet hole, and the higher holes did not add performance if the nozzle was not embedded deep enough in the sand.

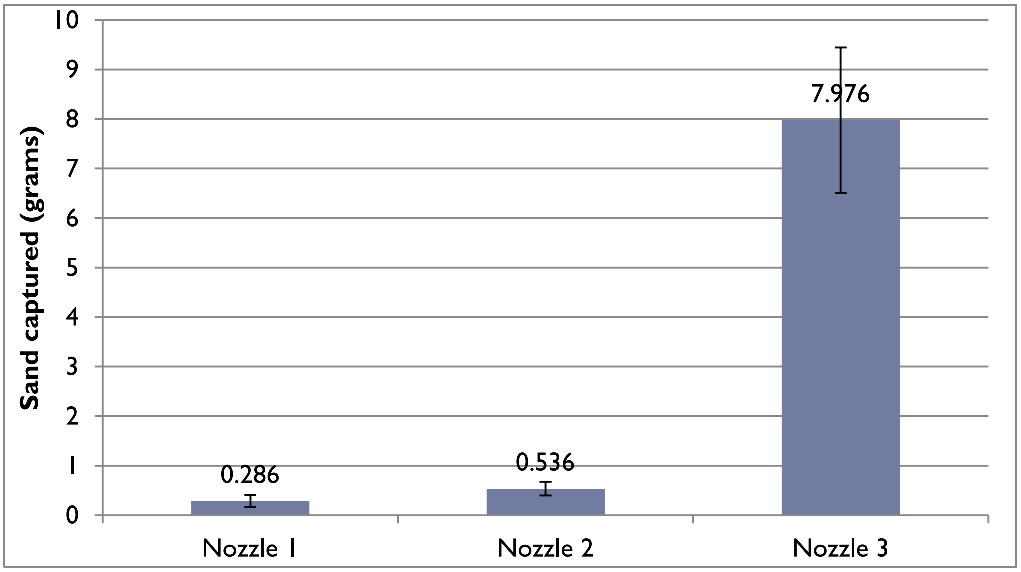

Figure 21: Results for amount of sand captured for each of the 3 nozzles.

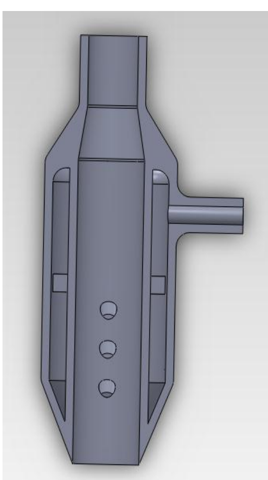

Figure 22: Nozzle 4

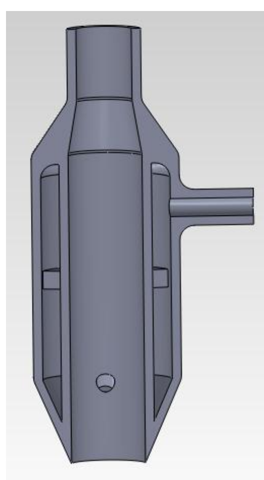

Figure 23: Nozzle 5.

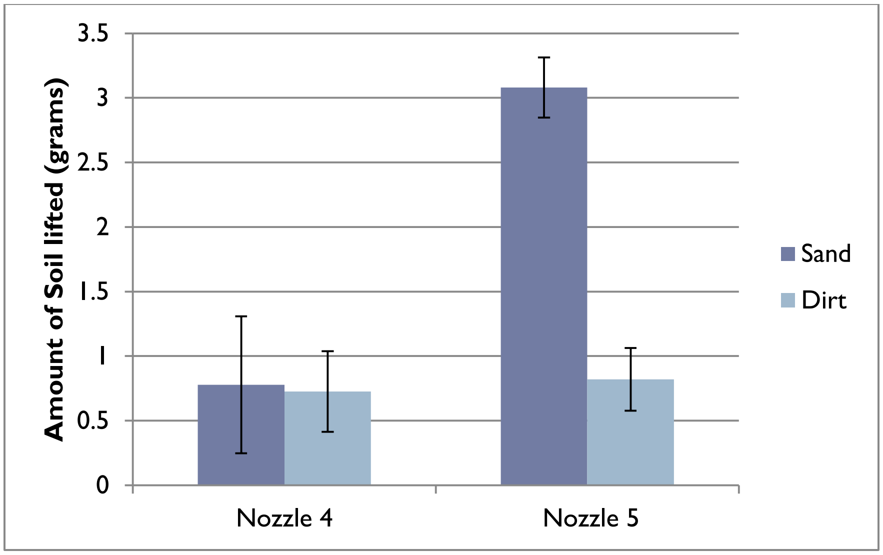

Figure 24: Results for amount of sand captured for Nozzles 4 and 5.

Figure 25: Plastic cyclone separator based on Honeybee Robotics' design.

Sample Container Design

After the air and particulate mix is blown into the flexible tubing, we must remove the air in order to store the sample. A cyclone separator achieves this with gravity; the dirt-air mix enters at the top, and swirls around the conically-shaped separator until the particles fall out the bottom, and the air escapes through a vent near the top. Yifei and Kristen obtained a cyclone separator design from Honeybee Robotics, and 3-D printed it for use in the benchtop system (Figure 25).

After the dirt falls out the bottom of the cyclone separator, it must be stored in a sample container. Yifei and Kristen designed an automatically-closing container that could easily be swapped out for another one on an assembly line. Figure 26 shows a sketch of the sample container design. The 3-D printed sample container prototype is shown in Figure 27, with a duct-taped cap so as to be reusable. In an actual Mars mission, sample containers would be one-time use only.

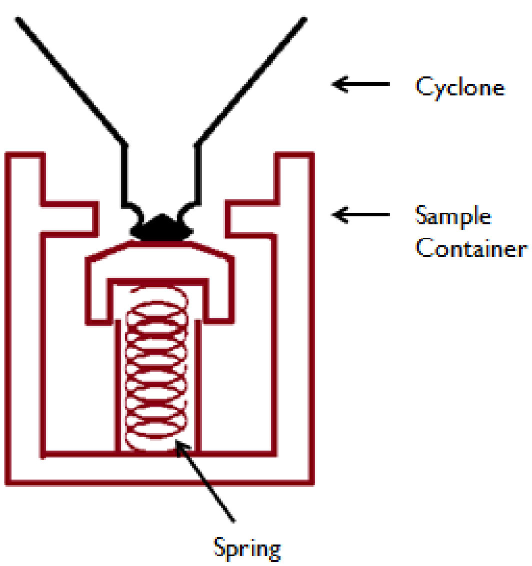

Figure 26: Sketch of sample container concept.

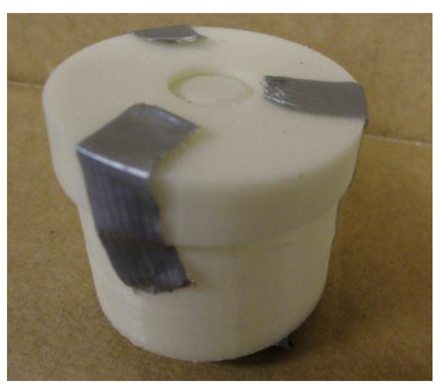

Figure 27: Plastic sample container prototype.

Instrument Deploy Mechanism

Yifei and Kristen decided to link the nozzle to Axel's instrument deploy mechanism, using gear such that the instrument's deploy would drive the nozzle down into the ground as well. This coupled 4-bar linkage design is shown in Figure 28.

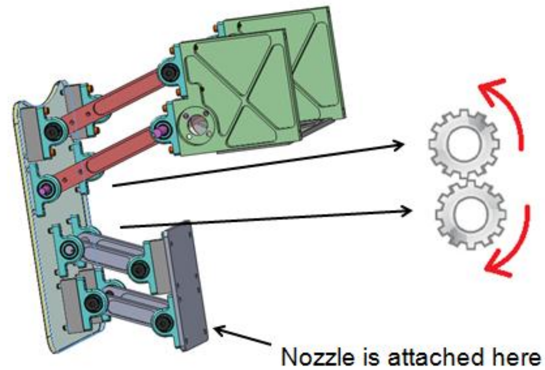

Figure 28: Coupled 4 bar linkage drives the nozzle into the soil, preventing contamination of the cover as well.

Pressure Release and Benchtop System

In initial tests, Yifei and Kristen primarily used pressurized lab air to drive the pneumatic system. They used a regulator to set the desired pressure, and experimented with the amount of mass that could be collected for a given pressure. The results of this test are given in Figure 29. ~25 psi gave the maximum amount of sand, so it was used in all nozzle tests. In an attempt to make the system portable, and small enough to fit in Axel's instrument module, the two later switched from lab air to a pressurized container of 20g of CO2, used for inflating bicycle tires. This pressure container presents a limit on the number of samples that can be taken, but in our experience 2 second puffs of air can collect 8-10 samples under Earth conditions.

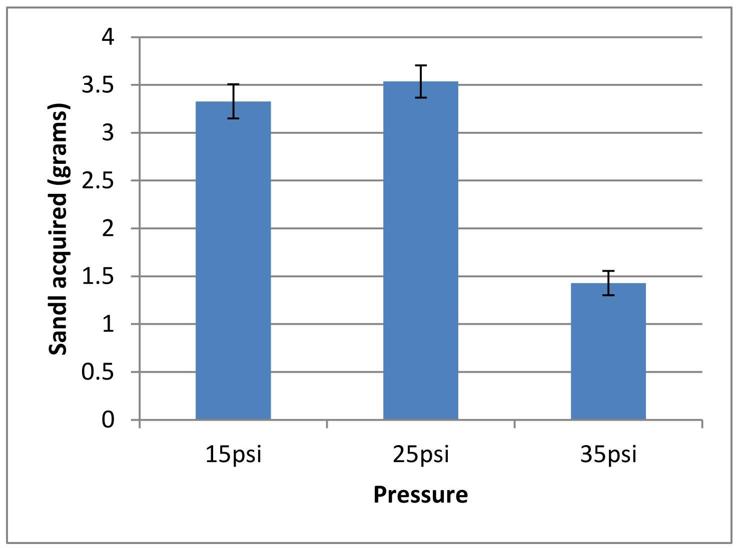

Figure 29: Testing mass of sample acquired for a given pressure. Around 25 psi was the optimal pressure for maximum sample acquisition.

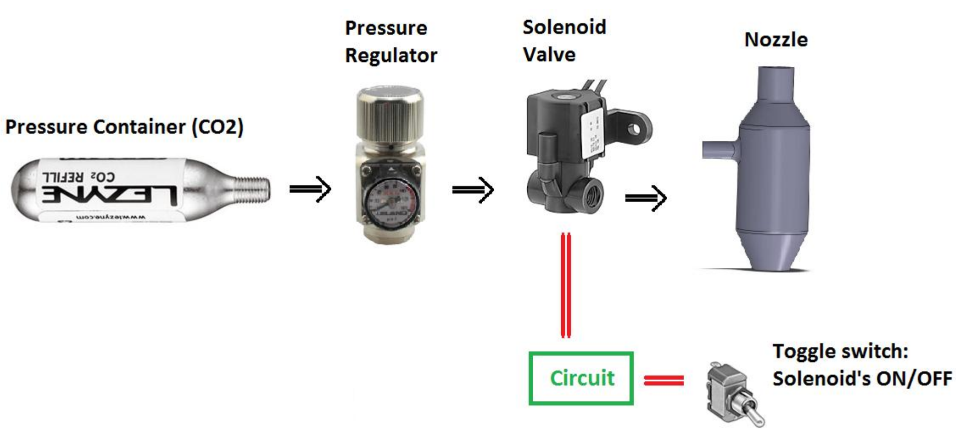

Figure 30: A diagram of the portable benchtop system, with pressure container, regulator, and on/off switch.

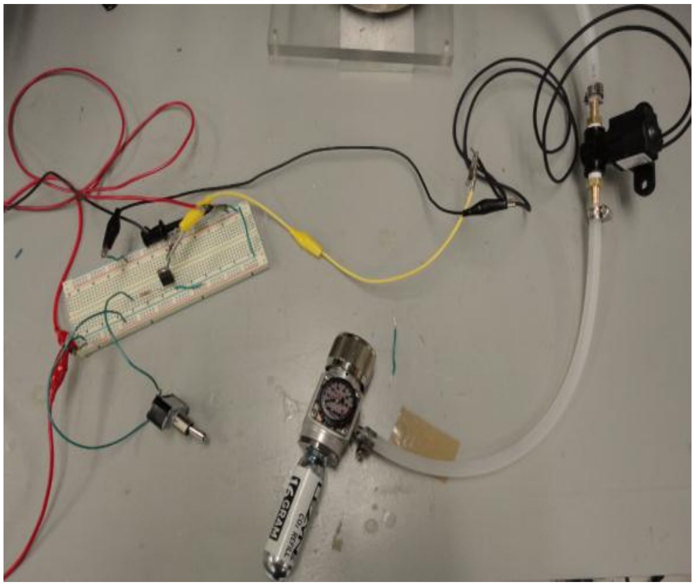

Figure 31: The electronics and pressure regulation for the benchtop pneumatic system. At left, toggle switch and on/off circuit. At bottom, air canister and pressure regulator. At top right, solenoid driven by on/off switch.

A diagram of the resulting benchtop system is given in Figure 30. Figure 31 shows the pressurized air canister, regulator, toggle switch, and circuit driving the solenoid. The nozzle, mounted to a benchtop mockup of Axel's instrument deploy system, is shown in Figure 32. It can be raised or lowered by turning a hand crank on the side. Clear plastic tubing would connect the pressure container to the nozzle, and would carry the sample-laden air from the nozzle to the cyclone separator. The cyclone separator, in Figure 33, can also be raised or lowered by hand. When lowered, it deposits the sample in the sample container; when raised, the sample container could be swapped out for a new one.

Figure 32: Nozzle and benchtop instrument deploy mechanism.

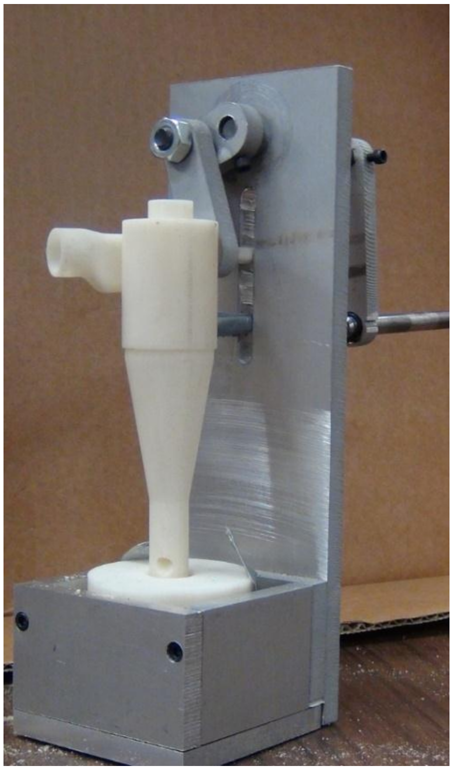

Figure 33: Cyclone separator and sample container.

For more details, please see the online reports. Yifei's final report can be found online at [8] (with an abbreviated version at [9]) and her SURF presentation is at [10]. Kristen's final report is at [11] and her SURF presentation is at [12].

4 Degree-of-Freedom Scoop: Nikola

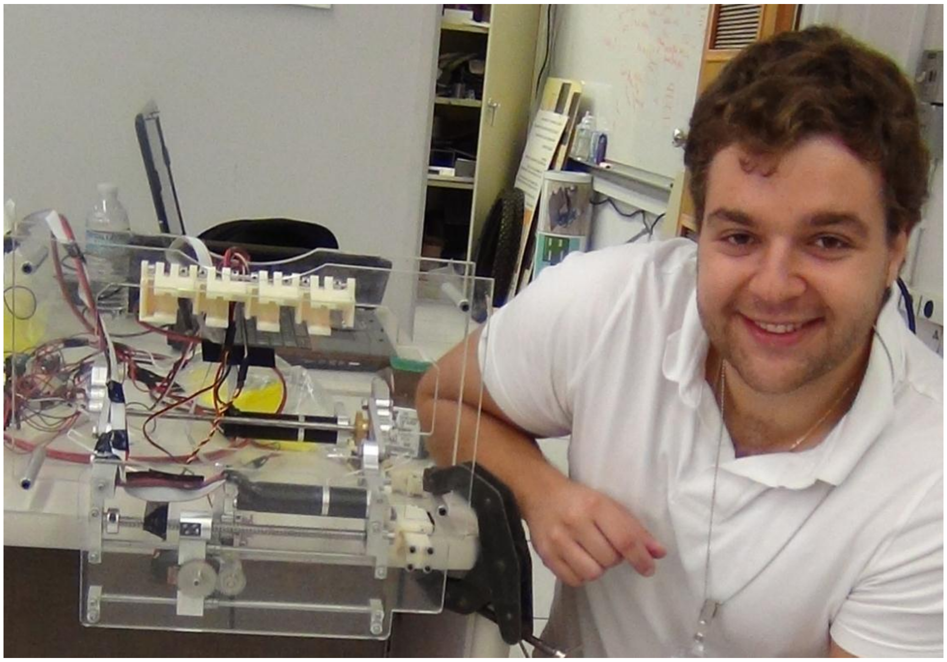

Figure 34: Nikola Georgiev is a visiting student in mechanical engineering at Caltech, from University of Edinburgh.

Nikola's goal was to design and build a multi-functional scoop. In doing so, he also designed sample containers to act as the scoop, and redesigned the panels on Axel's instrument bay to create a larger instrument deploy section. Nikola is shown in Figure 34 with his versatile 4 degree-of-freedom scoop.

Sample Container

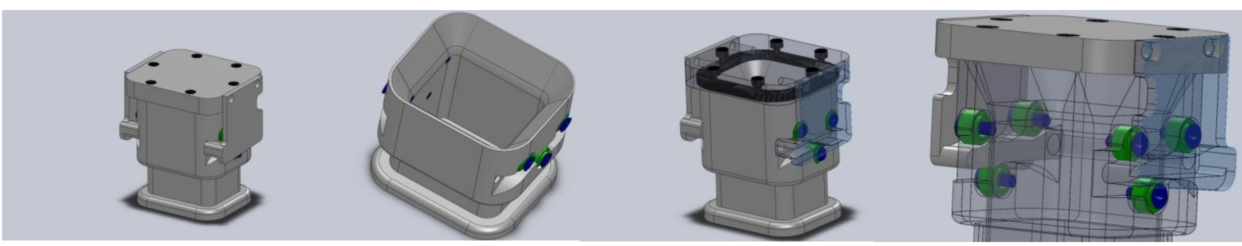

Figure 35: Four different views of the sample container CAD model.

In order to minimize contamination, Nikola's sample container acts as both a scoop and sample storage. The placed a design constraint that it be sturdy, with a sharp edge to scrape away at hardened surfaces. It also must form a tight seal, to prevent the sample from escaping. Most sealing containers depend on a rotary screw-in motion to seal, but in order to avoid the additional complexity of adding an additional actuator Nikola designed a slide-on top. The container is lined by a rubber gasket that is compressed by the top, which is held in place by the cam sliding surface. Spring plungers in the side hold the lid on as well. The

Figure 36: The sample container and lid prototype.

cam surface and ball bearings that hold the lid in place are designed to be self-cleaning, pushing dirt away from the cutting edge to form a tight seal. Figure 35 shows the container CAD model, and Figure 36 shows the 3-D printed prototype.

DESIGN

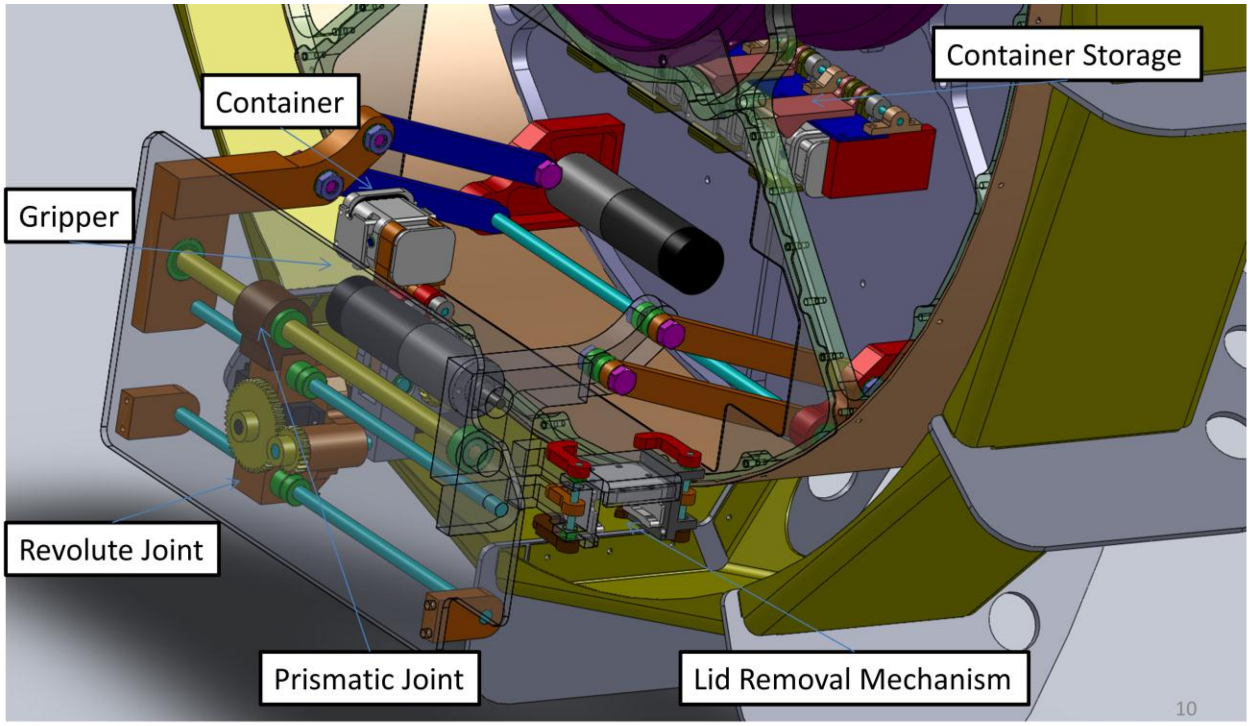

Figure 37: CAD model of Nikola's scoop sampling device, showing the various subsystems.

Nikola's design multiplexes the existing instrument deployment motion, using it to store and remove sample containers. To fit his sampling mechanism in the instrument bay, he had to redesign the instrument deployment panel, making it longer. In addition to the instrument deploy motor, Nikola's mechanism uses 3 motors to drive a prismatic joint, a revolute joint, and a gripper's open-and-close motion (Figure 37Figure).

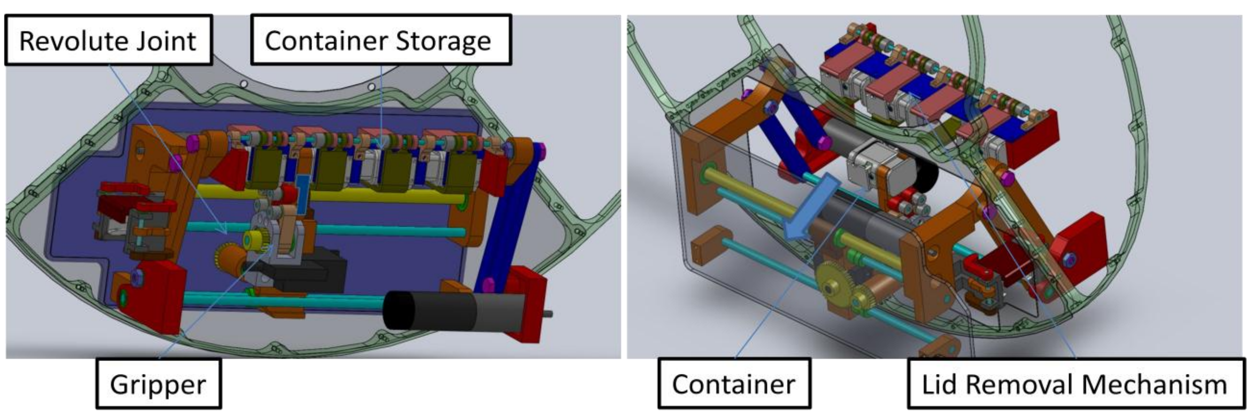

Figure 38: To remove a sample container, the gripper slides sideways along the ball screw and closes on the desired container. Axel deploys its instrument, which pulls the container out of container storage.

Most of the scooping system is mounted on the inside of the instrument deploy panel, but the sample container storage is mounted opposite it in the instrument bay, and is fixed. The gripper can slide sideways along a rail to select a sample container, and then close its fingers around the desired container. The container storage rack is spring-loaded so that a slight force will remove the sample container; this force is provided by deploying the instrument panel with the existing Axel motor. This sample container selection is shown in Figure 38.

Having removed the sample container, the gripper carries it over to the lid removal mechanism on the side. The gripper rotates the container and lid through this spring-loaded mechanism that removes the lid, and holds it there. Meanwhile, the gripper and container move on to sample acquisition. The process is depicted in Figure 39.

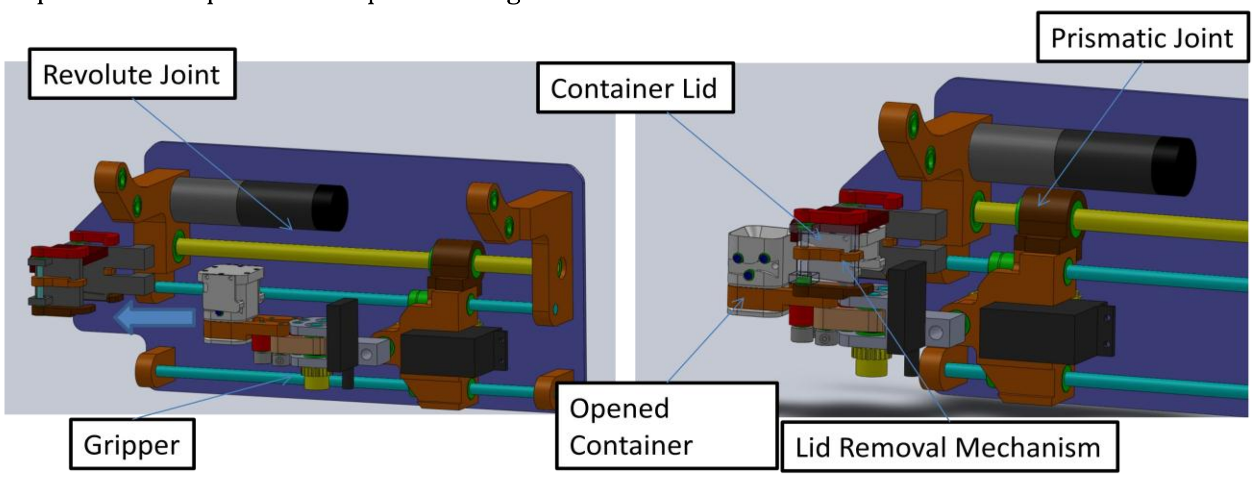

Figure 39: To remove the lid, the gripper slides horizontally through the lid removal mechanism.

Thanks to the large number of actuators, Nikola's sampler can produce a wide array of scooping motions. It can rotate the gripper and sample container to any angle, then drive them linearly across. It can move the gripper linearly to the desired location, and then use the gripper rotation to make a small-radius rotational scooping motion. In addition, it can combine these motions with Axel's body motion, a larger-radius rotation. These potential scooping motions are shown in Figure 40. Once a sample has been obtained, the system repeats the steps shown in Figure 39 and Figure

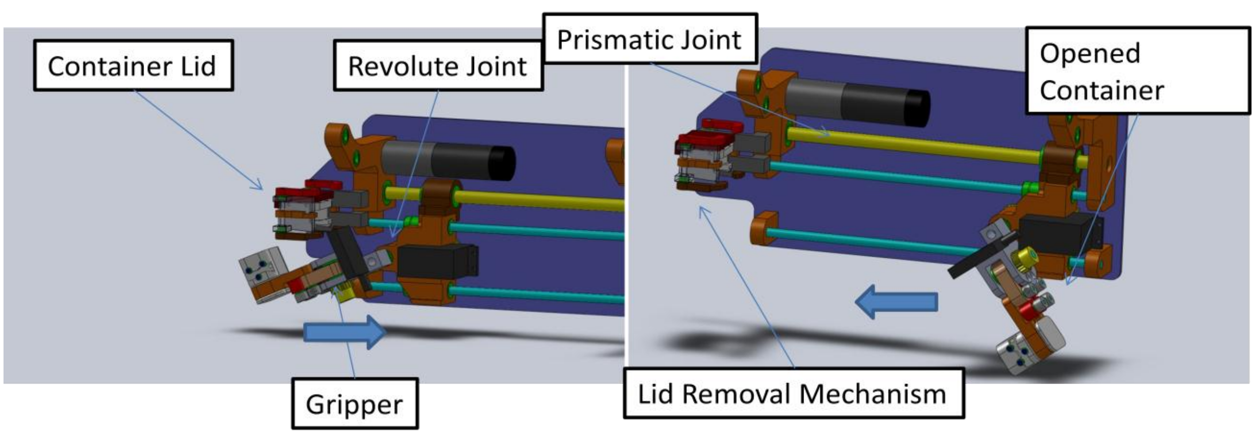

Figure 40: To scoop a sample, the system can rotate the joint holding the gripper, slide the gripper along the horizontal axis, or use Axel's body rotation.

40 in reverse order: the gripper travels through the lid removal mechanism in the opposite order, to replace the lid, and the instrument deploy panel tucks back into the instrument module, returning the sample container to the container storage unit in the process.

Prototype

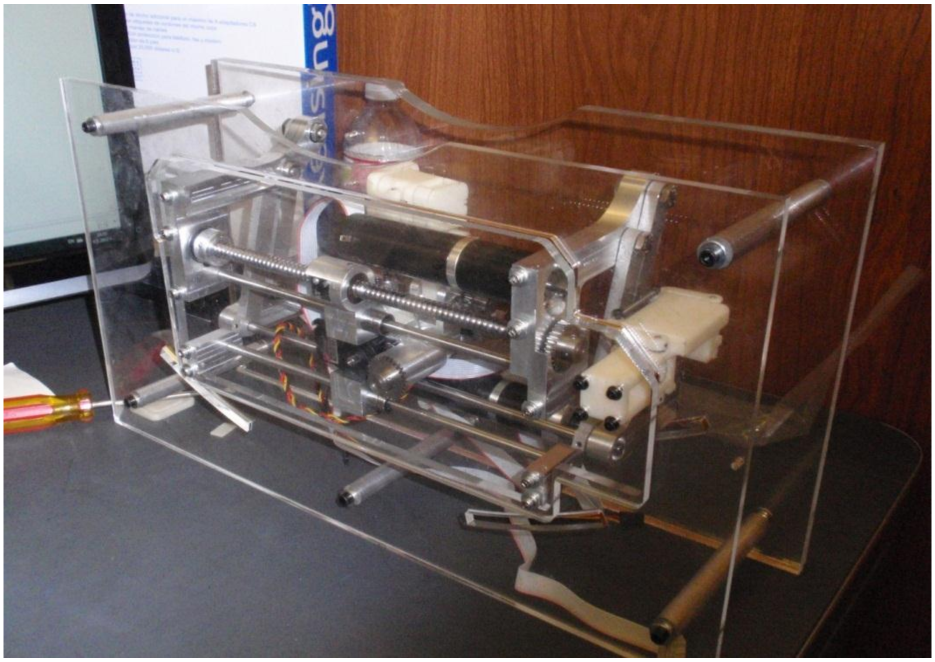

Figure 41: Complete 4-dof scoop sampling prototype.

Nikola prototyped his scoop sampling system with a combination of off-the-shelf motors and bearings, 3-D printed gears and sample containers, laser-cut acrylic sheets, and aluminum and steel pieces milled or turned in the Caltech MCE machine shop. Figures 42 -48 show the prototyped subsystems; Figure and Figure 49 show the completed prototype scooping system. For more details, see Nikola's final report at [13] and his final presentation at [14]. Video can be found online at [15].

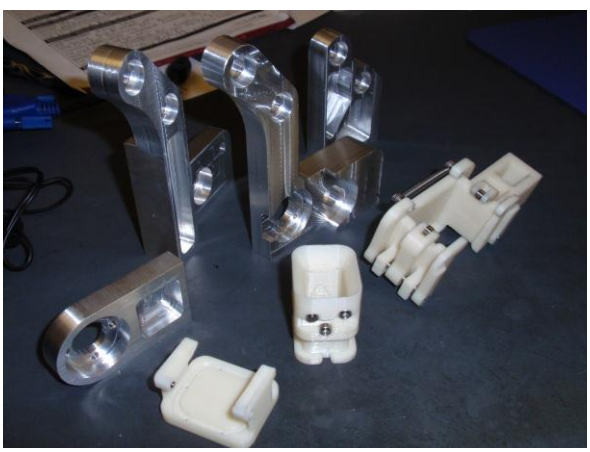

Figure 42: 4-bar linkage and actuation parts in aluminum. Container, lid, and lid-removal assembly in plastic.

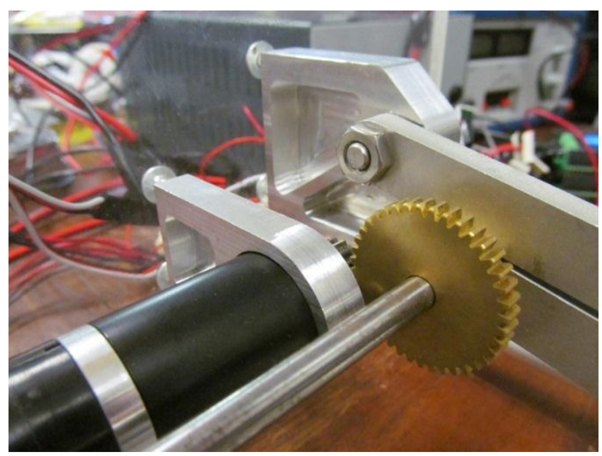

Figure 43: Instrument deploy panel actuation.

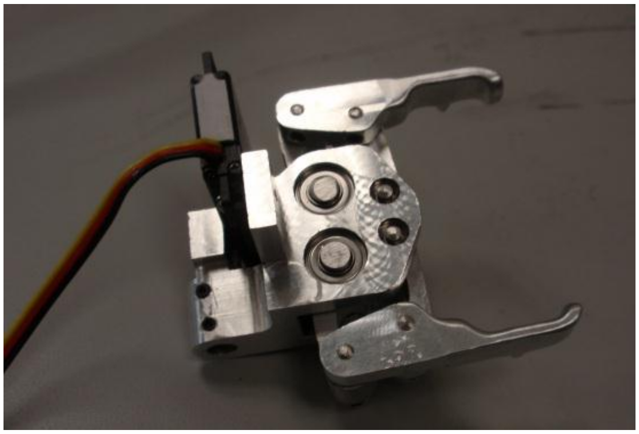

Figure 44: Aluminum gripper mechanism with high-powered flat servo.

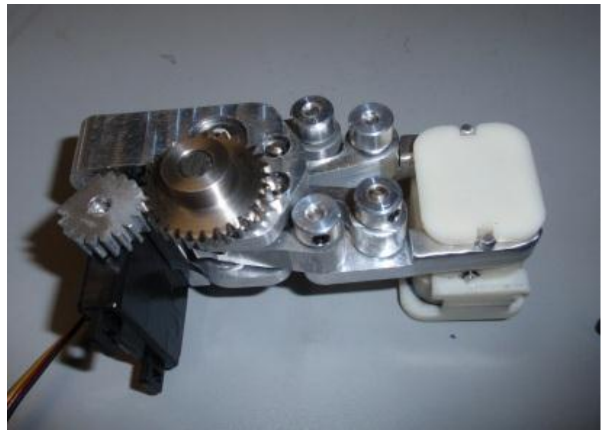

Figure 45: The gripper with a sample container.

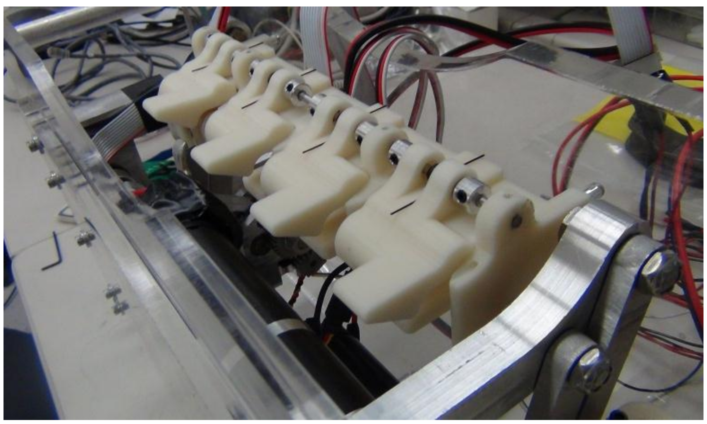

Figure 46: The sample container storage unit.

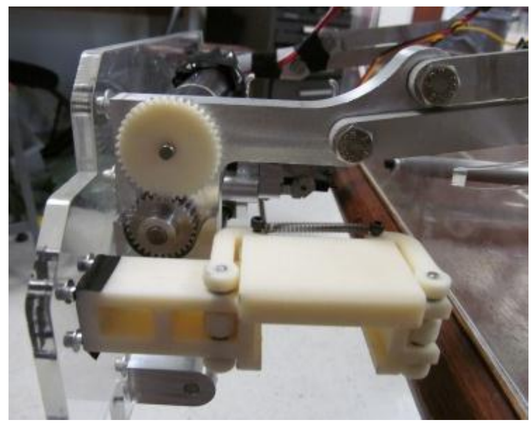

Figure 47: Lid-removal mechanism

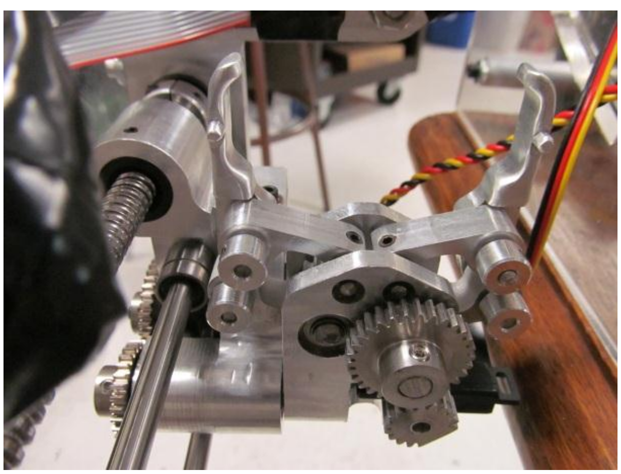

Figure 48: Opened gripper, inside the scooping mechanism.

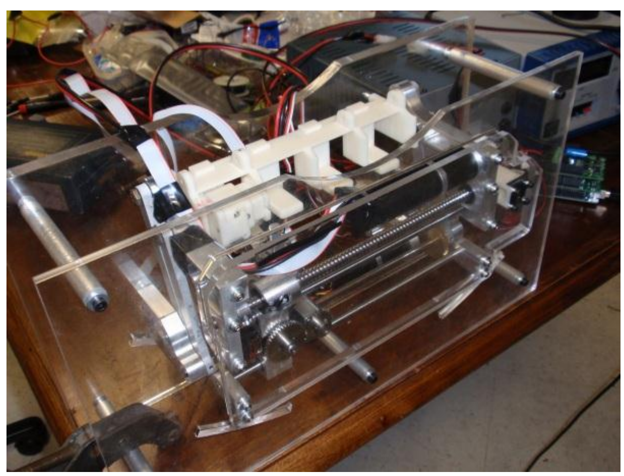

Figure 49: Another view of the completed prototype.

CONCLUSION:

We have concluded that there is no single solution to developing a sampling device; the effectiveness of a design depends on the hardness, type, and composition of the soil involved. For loose, light material a pneumatic device is most effective; its flexible tubing allows us to place the bulky vacuuming machinery and sample holders away from the surface that touches the ground. Percussive scooping reduces the force necessary to break through hard or icy ground, so this may be the best method for a limited-power sampler, or one expected to encounter ice. Nikola's 4 degree-of-freedom scoop, in contrast, is the jack of all trades. Multiple motors allow it to fill multiple sample containers, and even select from several different scooping motions as needed. Thanks to this KISS project, the Axel team now has multiple sampling system prototypes that can be installed in the instrument bay as needed. The Axel team also gained some understanding of the design challenges involved, thanks to the KISS students' presentations.

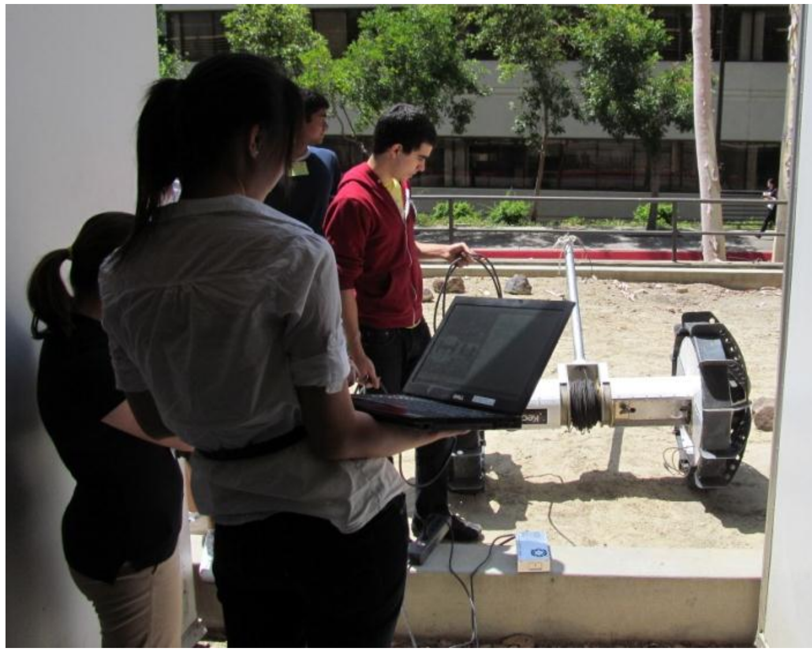

Figure 50: Yifei Huang driving Axel in JPL's Mini-Mars Yard.

To gain some intuitive understanding for the physics involved, our team traveled to JPL and practiced driving Axel in the Mini-Mars Yard (Figure 50). We also toured the Mars Yard (Figure 51), and examined Scarecrow, the MSL engineering model of Curiosity housed nearby (Figure). Several experts in the fields of drilling and sampling also generously volunteered their time; we were able to arrange tours, lunch meetings, and consultations.

Figure 51: KISS student team touring JPL's Mars Yard.

Figure 53 shows Honeybee Robotics Vice President Kris

Zacny describing their ice-drill, during our tour of their Pasadena office. At JPL, Paulo Younse spoke about his work on sample sealing for Mars Sample Return caching. The Robotics Group Supervisor, Paul Backes demonstrated his work on placing sampling systems on a rover, as shown in Figure 54.

Figure 52: KISS team looking at Scarecrow, MSL's engineering model.

Figure 53: Dr. Zacny demonstrates Honeybee Robotics' ice drill.

Figure 54: Dr. Backes describing a soil sampling system.

It takes a village to raise a child or, in this case, support a project. In addition to touring JPL, we consulted with several Caltech professors and members of the Axel team at JPL. Assistant Professor Bethany Ehlmann kindly spoke to us over lunch about the motivation behind science on Mars, and what scientists are looking for. Professor Melanie Hunt gave Yifei and Kristen sands collected during her field trips to test their pneumatic system. In the MCE teaching machine shop, the Jim Hall Design and Prototyping Lab, the students gained valuable machining advice from machinist John Van Deusen and several shop TAs (as in Figure 55 and Figure 56). The Axel team, and especially mentors Issa Nesnas and Joel Burdick, provided invaluable support and advice (Figure 57). This KISS team also worked alongside fellow Axel SURF student Diego Caporale, and mentored Sheila Murthy, a high school student working on Axel at Caltech.

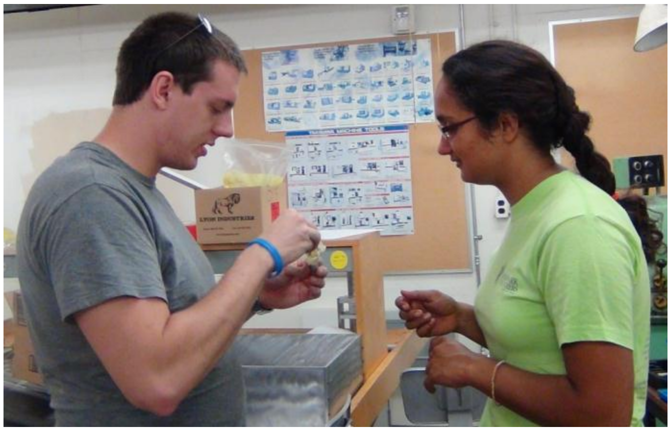

Figure 55: Machine Shop Assistant Russell Newman and Hima discussing her percussive mechanism.

Figure 56: Machine Shop Assistant Mike Rauls helping Hima with her percussive mechanism.

In addition to the opportunity to network with experts in the field, the team of students gained experience in designing, building, and presenting their work. They spent the first several weeks researching the problem of extraterrestrial robotic soil sampling, by reading papers and talking to experts. The next month was spent in the iterative design process, brainstorming, sketching ideas, and prototyping. By August, each student/pair of students had settled on a design, and spent that month making it. For some, this involved using drill presses, mills, lathes, the CNC mill, laser cutter, and water jet in the machine shop (Figure 58); for others, construction consisted of specifying, ordering, and putting together off-the-shelf parts to form a working system. Finally, each student had to communicate his/her work multiple times throughout the summer, through team meetings, SURF reports, final presentations, and demonstrations (Figure 59). This provided excellent practice in communication skills.

This KISS student-led mini-program on sampling in extreme terrain succeeded in developing prototype sampling devices and

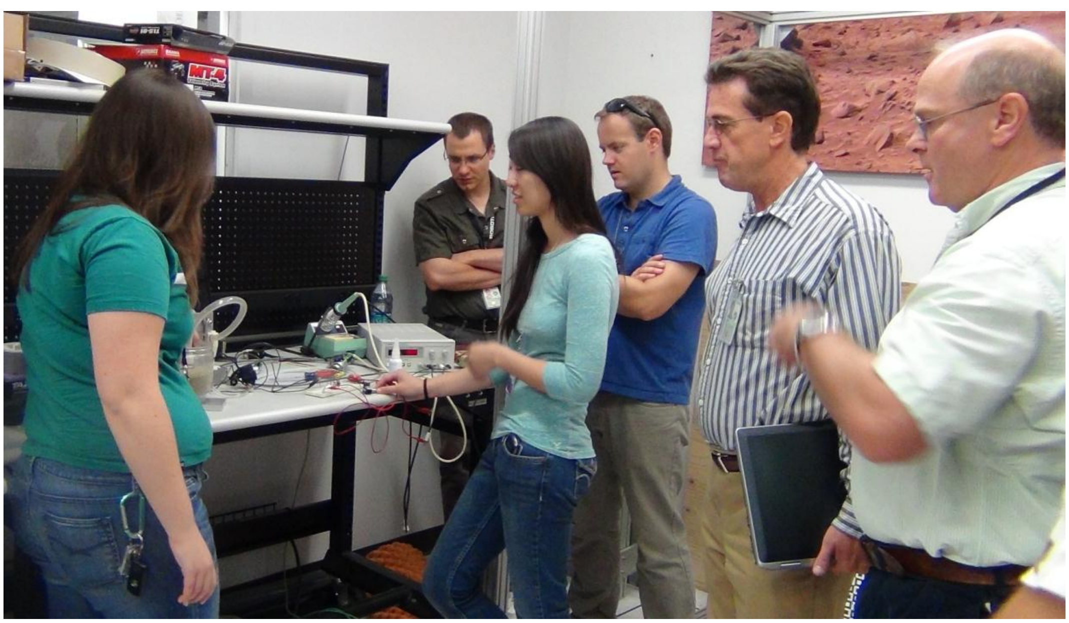

Figure 57: Kristen and Yifei presenting their pneumatic sampling system to members of the Axel team and other JPL engineers.

Figure 58: Hima working on the press in the MCE machine shop.

sampling strategies. It proved an excellent opportunity for students as well, who gained hands-on experience and the chance to work with a number of talented engineers and scientists in related fields. The student team (Nikola Georgiev, Hima Hassenruck-Gudipati, Kristen Holtz, and Yifei Huang, led by Melissa Tanner) would like to thank all of the aforementioned JPL employees, Caltech professors, Caltech staff, and others who helped us. We especially would like to thank our mentors, Professor Joel Burdick and Dr. Issa Nesnas. Finally, this work would not have been possible without the generous support and funding from the Keck Institute for Space Studies, as well as co-funding from the Caltech Summer Undergraduate Research Fellowship program.

Figure 59: Nikola demonstrating his 5-DOF sampling system to the Axel team and other JPL engineers.

REFERENCES

[1] (August 2012) First Color Mars-Rover Pictures + Space Shots of Crashed Gear, National Geographic Daily News. [Online]. Available: http://news.nationalgeographic.com/news/2012/08/pictures/120807-first-color-pictures-nasa-space-mars-science-laboratory/#/first-pictures-new-mars-rover-mountain_58038_600x450.jpg

[2] P. Abad-Manterola, I. Nesnas, and J. Burdick, "Motion planning on steep terrain for the tethered axel rover," in *Proc. IEEE Int. Conf. Robotics and Automation*, Shanghai, China, May 2010, pp. 4188–4195.

[3] (2011) Mars Reconnaisance Orbiter: Multimedia. [Online]. Available: http://mars.jpl.nasa.gov/mro/multimedia/images/?ImageID=3580.

[4] I. Nesnas, J. Matthews, P. Abad-Manterola, J. Burdick, J. Edlund, J. Morrison, R. Peters, M. Tanner, R. Miyake, B. S. Solish, and R. Anderson, "Axel and DuAxel rovers for sustainable exploration of extreme terrains," *J. Field Robotics*, pp. 663–685, Jul-Aug 2012.

[5] Craft, J; Wilson, J; Chu, P, Zacny, K; and Davis, K. Percussive Digging Systems for Robotic Exploration and Excavation of Planetary and Lunar Regolith. "IEEE Aerospace Conference Proceedings" pp. 17-23, 2009.

[6]H. Hassenruck-Gudipati, "Percussive Scoop Sampling in Extreme Terrain (Final Report)." Available: http://www.robotics.caltech.edu/~melissa/Axel_sampling_SURFs_2012/Hima/Hassenruck-Gudipati_Final_Report.pdf.

[7] H. Hassenruck-Gudipati, "Percussive Scoop Sampling in Extreme Terrain (Final Presentation)." Available: http://robotics.caltech.edu/~melissa/Axel_sampling_SURFs_2012/Hima/final_presentation.pptx.

[8] Y. Huang, "Pneumatic Sampling in Extreme Terrain with the Axel Rover (Long Final Report)." Available: http://robotics.caltech.edu/~melissa/Axel_sampling_SURFs_2012/Kristen_and_Yifei/Huang_Final_Report_Long.pdf.

[9] Y. Huang, "Pneumatic Sampling in Extreme Terrain with the Axel Rover (Short Final Report)." Available: http://robotics.caltech.edu/~melissa/Axel_sampling_SURFs_2012/Kristen_and_Yifei/Huang_Final_Report_Short.pdf.

[10] Y. Huang, "Pneumatic Sampling in Extreme Terrain with the Axel Rover (Final Presentation)." Available: http://robotics.caltech.edu/~melissa/Axel_sampling_SURFs_2012/Kristen_and_Yifei/Huang_Final_Presentation/Presentation_082312.pptx.

[11] K. Holtz, "Soil Sampling on an Extreme Terrain Rover: A Pneumatic Device (Final Report)." Available: http://robotics.caltech.edu/~melissa/Axel_sampling_SURFs_2012/Kristen_and_Yifei/Holtz_Final_Report.pdf

[12] K. Holtz, "Soil Sampling on an Extreme Terrain Rover: A Pneumatic Device (Final Presentation)." Available: http://robotics.caltech.edu/~melissa/Axel_sampling_SURFs_2012/Kristen_and_Yifei/surf_2012_presentation_kholtz.pptx.

[13] N. Georgiev, "Axel Scoop Sampling Device (Final Report)."Available: http://www.robotics.caltech.edu/~melissa/Axel_sampling_SURFs_2012/Nikola/Georgiev_Final_Report.pdf.

[14] N. Georgiev, "Axel Scoop Sampling Device (Final Presentation)." Available: http://www.robotics.caltech.edu/~melissa/Axel_sampling_SURFs_2012/Nikola/Georgiev_Final_Presentation/Final_Presentation_video.pptx.

[15] N. Georgiev, "SURF Project (YouTube Video)." Available: http://www.youtube.com/watch?feature=player_embedded&v=gB3_IiNS4wI.