Lion Drill

Sub-Surface Sampling Device for Regolith and Sandstone

Team: Columbia Space Initiative

Columbia University (116th St & Broadway, New York, NY 10027)

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Abstract

The Lion Drill was developed to satisfy the requirements of the asteroid subsurface sampling challenge as part of Micro-G NExT project by a team of students from Columbia University. The design requirements were that the tool must be handheld, safe to operate, and able to extract two samples from regolith-like substance and from sandtone. Columbia's solution was the Lion Drill, a design inspired by coring drills and geological sampling devices. The Lion Drill was designed to achieve the challenge criteria using two assemblies, one to sample from sandstone and the other from regolith. The regolith sampling assembly uses a vacuum pumping mechanism to allow for sand extraction, and an inflating closing mechanism to allow for containment of a sample. The sandstone sampling assembly uses a diamond tipped core drill bit to penetrate the surface, a pneumatic drill for powered operation, and handles to help direct the astronaut's motion. The Lion Claw was tested prior to its arrival at Houston on the Columbia University campus, and later at the Neutral Buoyancy Laboratory by professional divers. During testing, the tool was able to obtain 7 inch long and 1 inch diameter regolith sample, as well as 1 inch long and 1 inch diameter sandstone sample. During the underwater test simulating micro-gravity conditions students received user feedback from the divers who commented on design flaws that hindered the comfort of operations, but which were not significant enough to majorly inhibit the test simulation. In addition to the technical part of the mission, the team from Columbia engaged in multiple outreach activities that included hosting four workshops to middle school and high school students about space environment and space engineering in Manhattanville Community Center, running educational booths that taught kids about basics of aerospace engineering at the Intrepid Air and Sea Museum, tabling at the Liberty Science Center with a workshop on basics of kinematics and energy conservation, and engaging with faculty and students at Columbia University in CU in Space.

Nomenclature

Regolith Body: Assembly of parts of the device that directly participate in regolith sampling operation

Sandstone Body: Assembly of parts of the device that directly participate in sandstone sampling operation

Core Drill Bit: Diamond core drill bit that samples sandstone by powered rotation at 400 rpm

Closing Mechanism: Part of regolith body that secures a sample in the device after regolith is already fully inside of the sampling tube; an inflatable balloon was used

Pneumatic Drill: Drill that is connected to sandstone body; powers sandstone operation

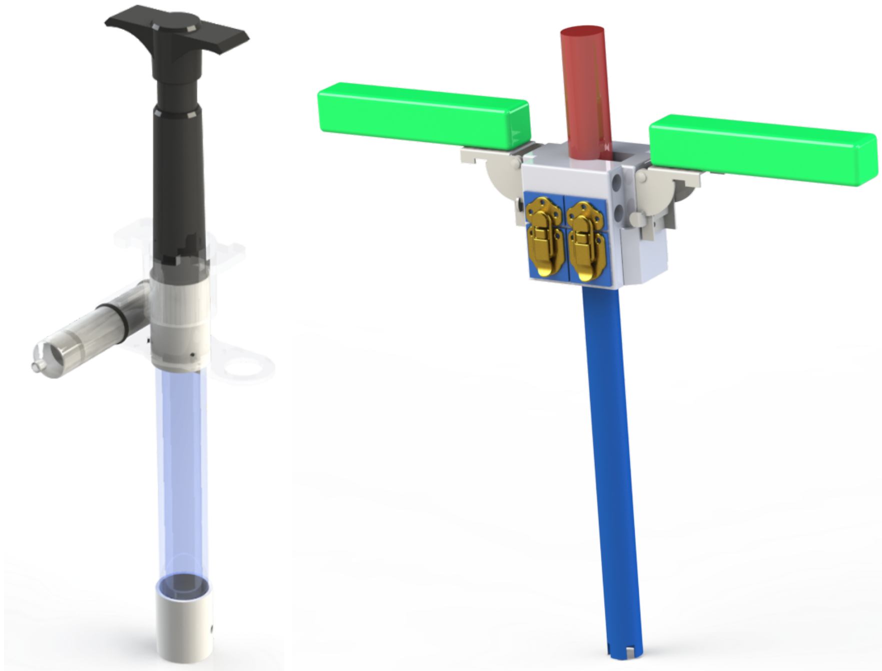


Figure 1. Front CAD view of final designs (IV iteration) of regolith body (left) and sandstone body (right) of Lion Drill

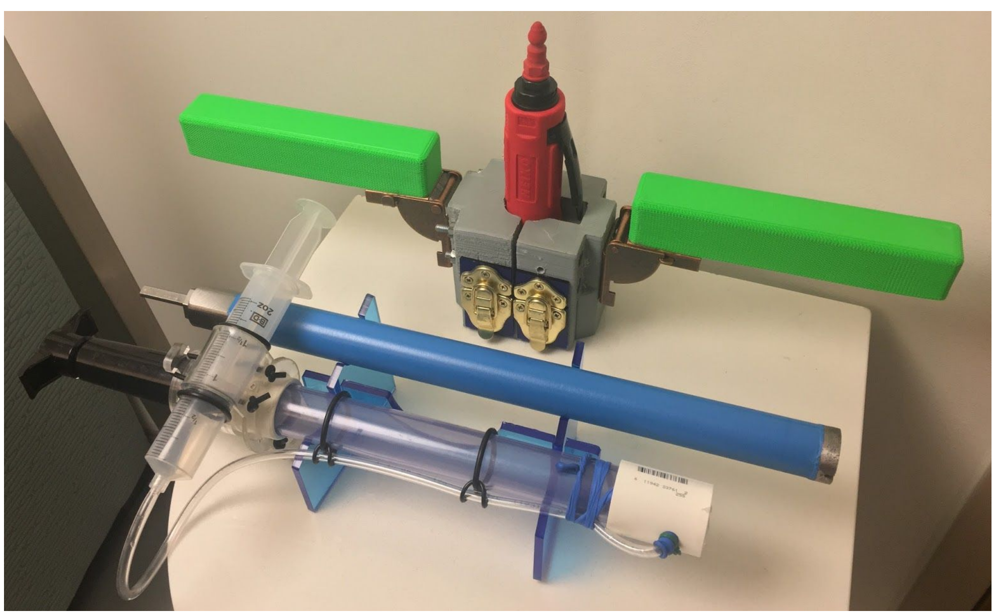


Figure 1.1. Iteration IV (final) of the Lion Drill: sandstone assembly (top) and regolith assembly (bottom)

Introduction

The creation of the Lion Drill was a collaborative effort involving the use of iterative design techniques, mechanical testing, and research. The following report summarizes the development of the drill, including design specifications and changes, results from theoretical and experimental testing, and the methods and considerations taken into account throughout the process. In addition, results from test week at the Neutral Buoyancy Laboratory (NBL) are included to assess how successful the device was in completing the design requirements and give insight to what can be changed to improve our device. Lastly, the outreach events we participated in are described to show how we have inspired and educated our audiences with regard to space exploration and its importance.

Background

The introduction of NASA's Space Launch System (SLS) will greatly expand our ability to explore deep space beyond Low Earth Orbit. NASA plans to collect a boulder from an asteroid moving into cislunar space in the Asteroid Redirect Mission (ARM) planned to launch in the 2020s. Since astronauts will be working in environments with milligravity to microgravity, devices need to be made that will assist them in carrying out tests and sampling while being effective in such an environment. As such, NASA Micro-G NExT challenges college students to design and manufacture a device suited for the astronauts.

The goal of the Lion Drill is to collect a subsurface sample from the asteroid as such samples can give insight to the structure of the celestial body and its history. The tool itself was designed for the simulated environment that it will be tested in, the NBL, a large pool constructed to simulate microgravity and allow for preliminary testing and training here on Earth. Ultimately, the tool should be capable of sampling regolith and a sandstone-like rock from test beds that will be submerged in the pool. Divers will be carrying out the testing procedure as the team instructs them on how to use it from mission control center. For the device to be successful, it needs to adhere to requirements as outlined in the challenge description. The primary ones are as follows:

- The device should be capable of collecting subsurface samples from regolith and sandstone.
- The collected sample should be cylindrical 1" in diameter and 8" deep. In addition, the stratigraphy of the sample should be preserved with minimal cross contamination.
- The device should be ambidextrous and ergonomic enough for astronauts equipped with full EVA gear.
- The device can only be pneumatically or manually powered.
- The device should be free of sharp edges and other potential hazards.

Method

The design process for Subsurface Sampling Device started with considering the asteroid environment that the tool was supposed to operate in. We had to take into account that microgravity conditions exist on asteroid surface, thus gravitational force should not be a factor in our designs. Thus, collected regolith would not stay at the bottom of the device, as it would freely float in microgravity. Also, we had to account for the sampling platform's structure, as regolith has a smooth sand-like structure, and sandstone has a rigid rocky composition. Accordingly, we needed to have differentiated operation for both regolith and sandstone, as regolith operation may require only manual operation, while sandstone operation would need a pneumatically powered mechanism to allow the device to cut through the rigid surface.

Our design process consisted of several iterations of the tool. Our first iteration solution (Figure 2) aimed to combine regolith and sandstone operation in one assembly. Our idea was to implement one coring mechanism with two different sampling tubes - one with aluminum rigid sampling tube for sandstone coring (Figure 3) and the other with transparent plastic sampling tube for regolith sampling. On top of the device we had a home manufactured pneumatic turbine (Figure 3) with 4 plates. The turbine was supposed to have two holes to allow for air inflow and air outtake from its rotor case. On the bottom of the device we intended to put a mechanical iris mechanism we designed (Figure 3) that was supposed to cut the sample from the bottom. It would have rotated along all edges of the coring sample (Figure 4) to close up a sample from the bottom and to secure a sample inside of the device. The iris was supposed to be activated by strings coming from the iris to the top of the device where an astronaut would have a secure hold on the device's side handles (Figure 4). The coring body was supposed to have a bottom piece (Figure 4) with sharp teeth below the iris closing mechanism to allow for penetration of both soft and rigid surfaces.

The first design's major flaw was that the coring body was too thick to allow for sandstone penetration. Designs of both the coring body and the bottom piece did not account for physical properties of sandstone, that dictate that the thicker a core drill bit is, the harder it is to penetrate sandstone surface with it. The second problem was that the string iris closing system was unfeasible to implement, as passing strings through the whole body of the device would have required a structurally fragile manufacturing solution. Finally, the pneumatic turbine's rotor and inside body needed to be revised as this iteration's turbine design was highly inefficient.

The major change implemented in Iteration II of the device was the separation of the device in two parts - sandstone assembly (Figure 5) and regolith assembly (Figure 6). In the sandstone assembly a chuck was attached to a rotor that would stick out of the pneumatic turbine. For this assembly we purchased a diamond core drill bit that would have been connected to a drill chuck. This connection allows for transfer of rotational motion from pneumatic turbine to core drill bit, thus powering the sandstone operation. The regolith assembly acquired a new bottom piece for smoother penetration of an asteroid surface. In addition, a new activation mechanism for iris was developed. Instead of the string system coming to the top of device, we developed a closing mechanism using rotation of the bottom part of mechanical iris (which is rigidly secured on bottom of the main regolith body) relative to the top part of iris. This was connected to the transparent sampling tube. Thus, rotating the sample tube would close the iris. To rotate the sampling tube inside of the device, an operational handle was developed. The operational handle was supposed to follow a groove in the regolith body to rotate the sampling tube. After the sample is already inside of the device, the astronaut turns the operational clockwise to close the iris at the end of a sampling tube, and then pushed down to compress the sample inside of a sampling tube. Iteration II of the device also acquired latches that were intended to connect and disconnect regolith body of the device from a pneumatic turbine.

The major flaws of iteration II was the difficulty in manufacturing some parts of the design and the fragility of many others. Manufacturing the regolith body with fluting in the form of inset grooves was too complicated. Also, development of the first prototype showed the operational handle was too structurally fallible as it bended easily and was susceptible to breaking. The side handles were also structurally weak, and did not have any strong connection to the pneumatic turbine.

The operational handle was made thicker in Iteration III (Figure 7) of the device. Also, the fluting on regolith assembly was switched to be facing outward to allow it to be 3D printed. The shape of the sides pneumatic turbine was changed to be more flat to allow for smooth connection of latches and of side handles to it. The side handles' shape was switched to rectangular to allow for easier grip by astronauts in EVA gloves. In this iteration, latches and hasps were connected directly to the pneumatic turbine (Figure 8). For the third iteration, the pneumatic turbine's rotor (Figure 8) was redesigned to have more plates. The bottom piece acquired a steeper angle in this iteration. The mechanical iris was redesigned to have a more sturdy body in this iteration.

However, several complications made this design ineffective. Upon tests in sand, the mechanical iris was not closing fully and thus was failing to keep all the regolith inside of the sampling tube. The mechanism of putting the sample tube inside of the regolith body proved to be too hard and inconvenient, as extrusions on the bottom of a sampling tube did not readily fit the holes at the bottom piece. (Figure 9) The bottom piece of the operation handle - the part that serves to rotate the sampling tube and to compress the regolith sample (Figure 9) - was breaking apart after any meaningful amount of force was applied onto it. Also, the mechanism used to latch the regolith body onto the turbine was unreliable and did not provide as much stability to the device as needed.

Considering the limitations mentioned above, the fourth (final) iteration (Figure 10) of design was developed. In this design, the sandstone assembly was no longer an in house manufactured pneumatic turbine at its core, but relied on a commercially available pneumatic drill instead. Side handles were connected to two pieces which, when connected, left a hole in the middle. This design allows for the purchased drill to be safely secured in this hole. After several tests of regolith sampling assembly of iteration III, the iteration IV design for sampling regolith was completely redesigned. In this iteration (Figure 10) regolith sampling is powered by vacuum pump, which helps to suck in a sample. To secure a sample inside of a regolith body, an inflatable mechanism in the form of a balloon (Figure 11) is used. The balloon is inflated by pumping a syringe connected to regolith body.

The final test before traveling to Houston was conducted in the 12th floor of Columbia's engineering building. The Lion Drill's regolith sampling assembly was tested in an underwater environment by placing the bucket of sand in a plastic can filled with water and drilling the device into it. The device collected a desired sample, and the test was considered a success. Sandstone assembly of a device was tested in a machine shop in a basement of Columbia's engineering building. Pressurized air line was connected to the Lion Drill, and the sandstone sample was taken from a prepared piece of sandstone. Testing concluded that the device was ready for operation in Neutral Buoyancy Laboratory.

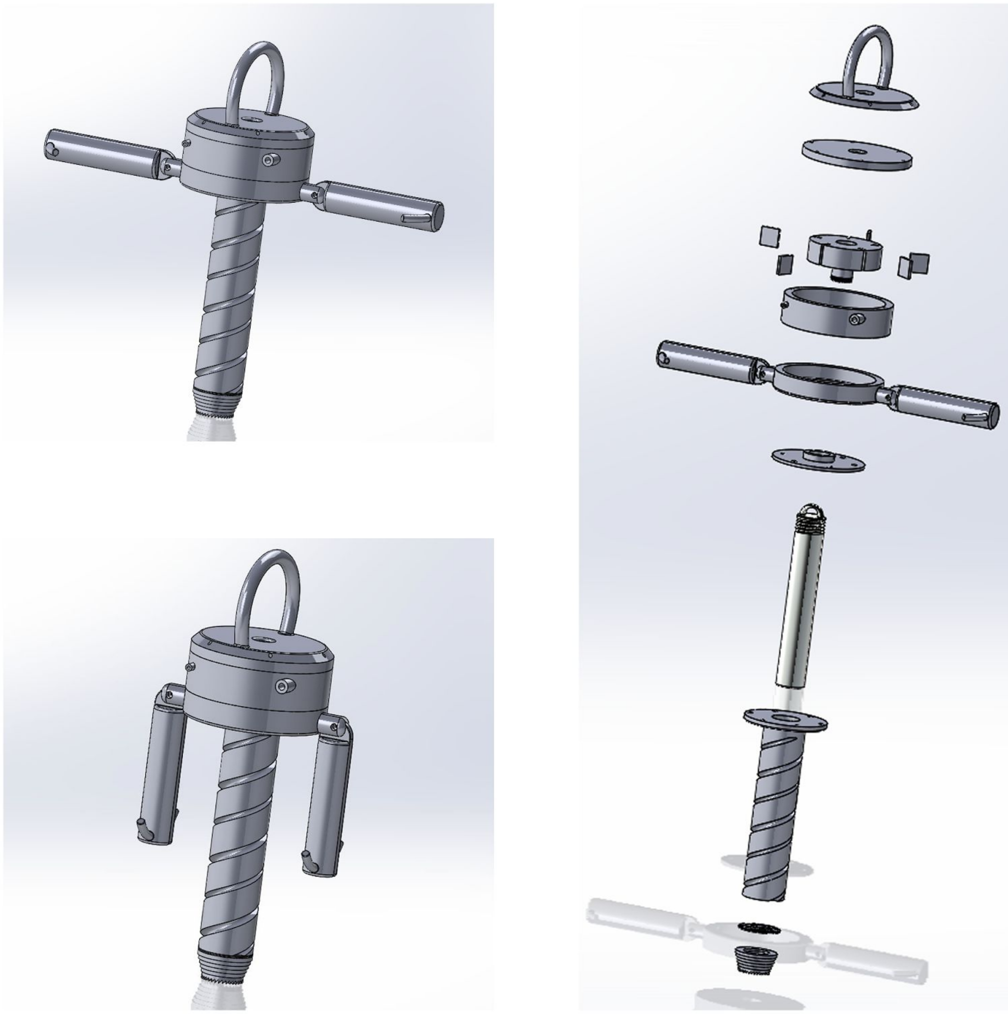


Figure 2. Iteration I of the Lion Drill: assembly for regolith and sandstone sampling

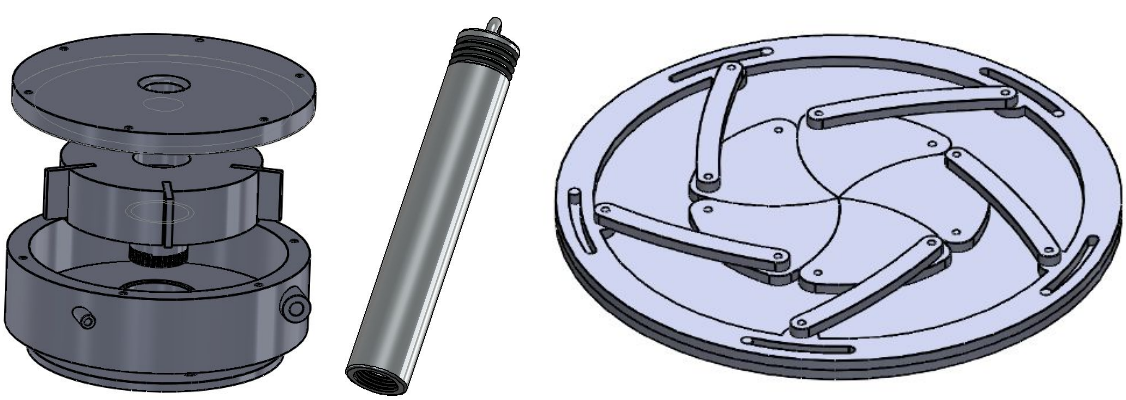


Figure 3. Iteration I of the Lion Drill: pneumatic turbine, sampling tube, and iris closing mechanism

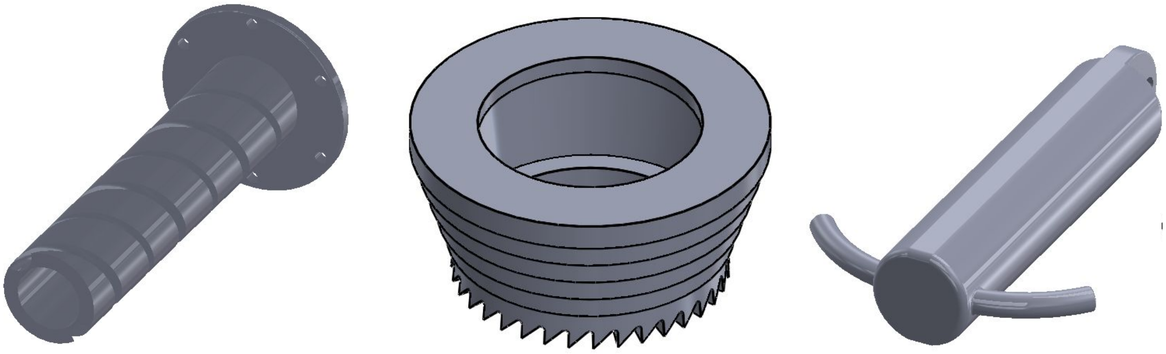


Figure 4. Iteration I of the Lion Drill: coring body, bottom piece, and handle

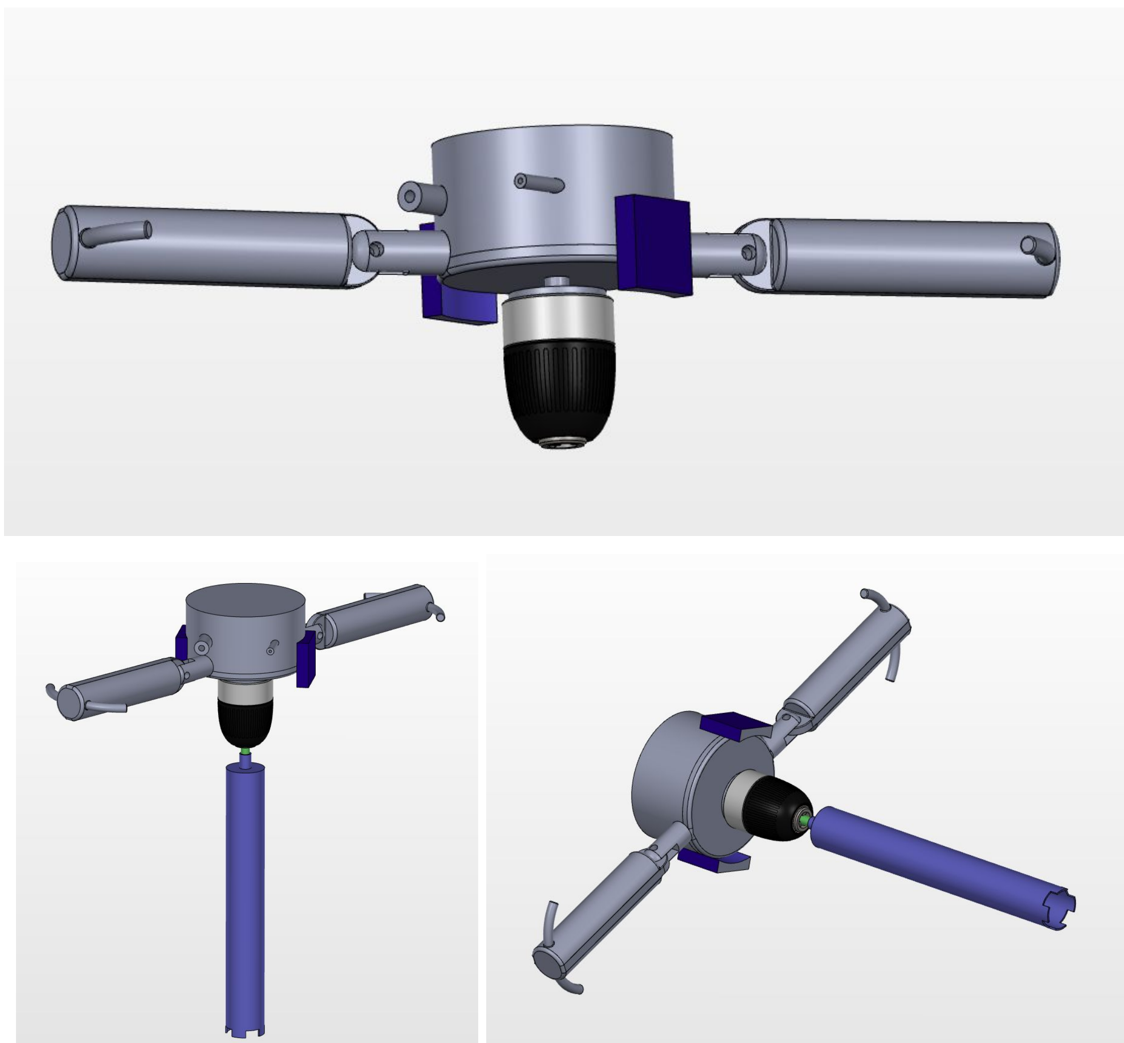


Figure 5. Iteration II of the Lion Drill: sandstone assembly with pneumatic turbine, handles, latches, chuck, and air channels

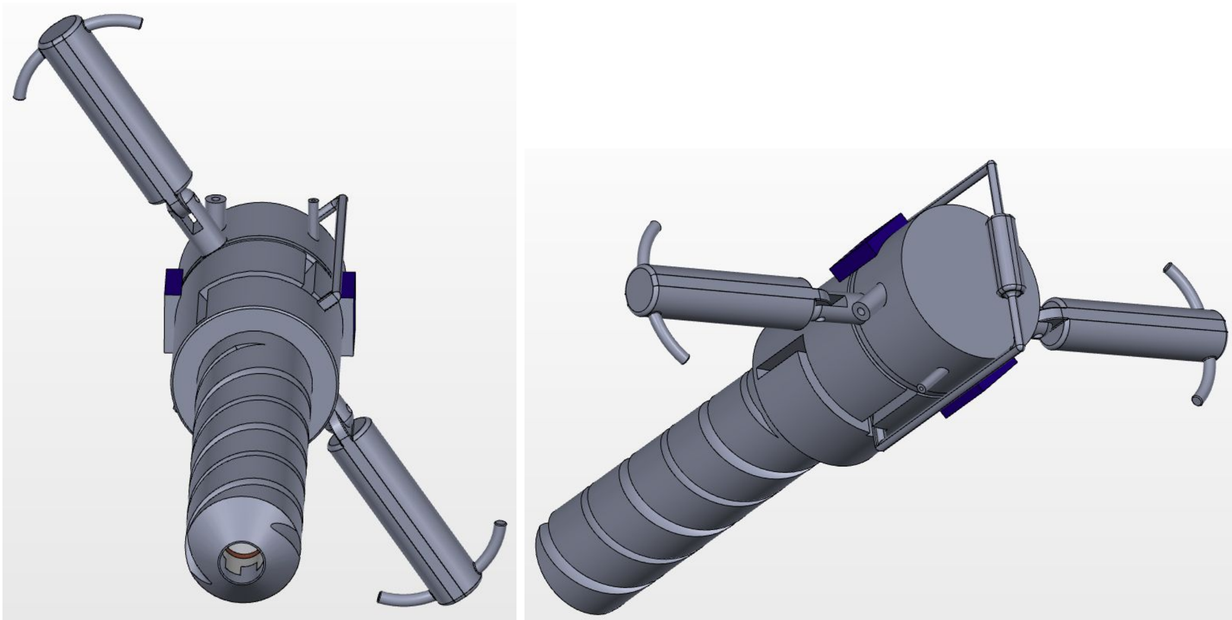


Figure 6. Iteration II of the Lion Drill: regolith assembly with pneumatic turbine, handles, latches, operation handle, regolith body, and air channels

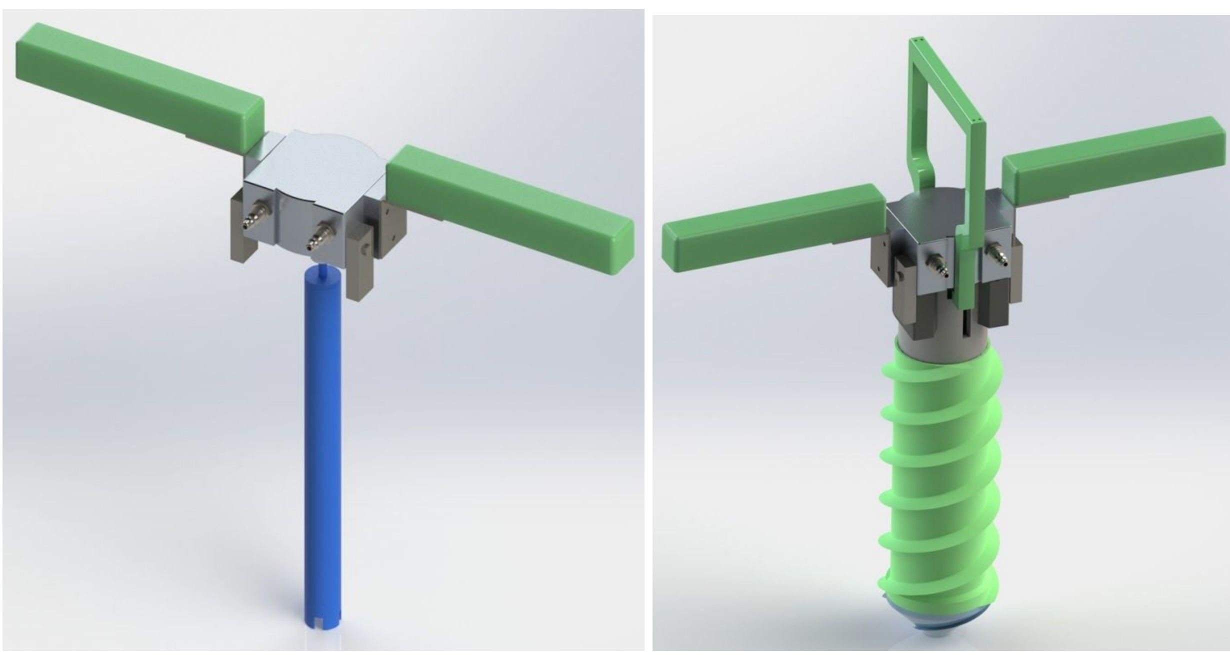


Figure 7. Iteration III of the Lion Drill: sandstone assembly (left), regolith assembly (right)

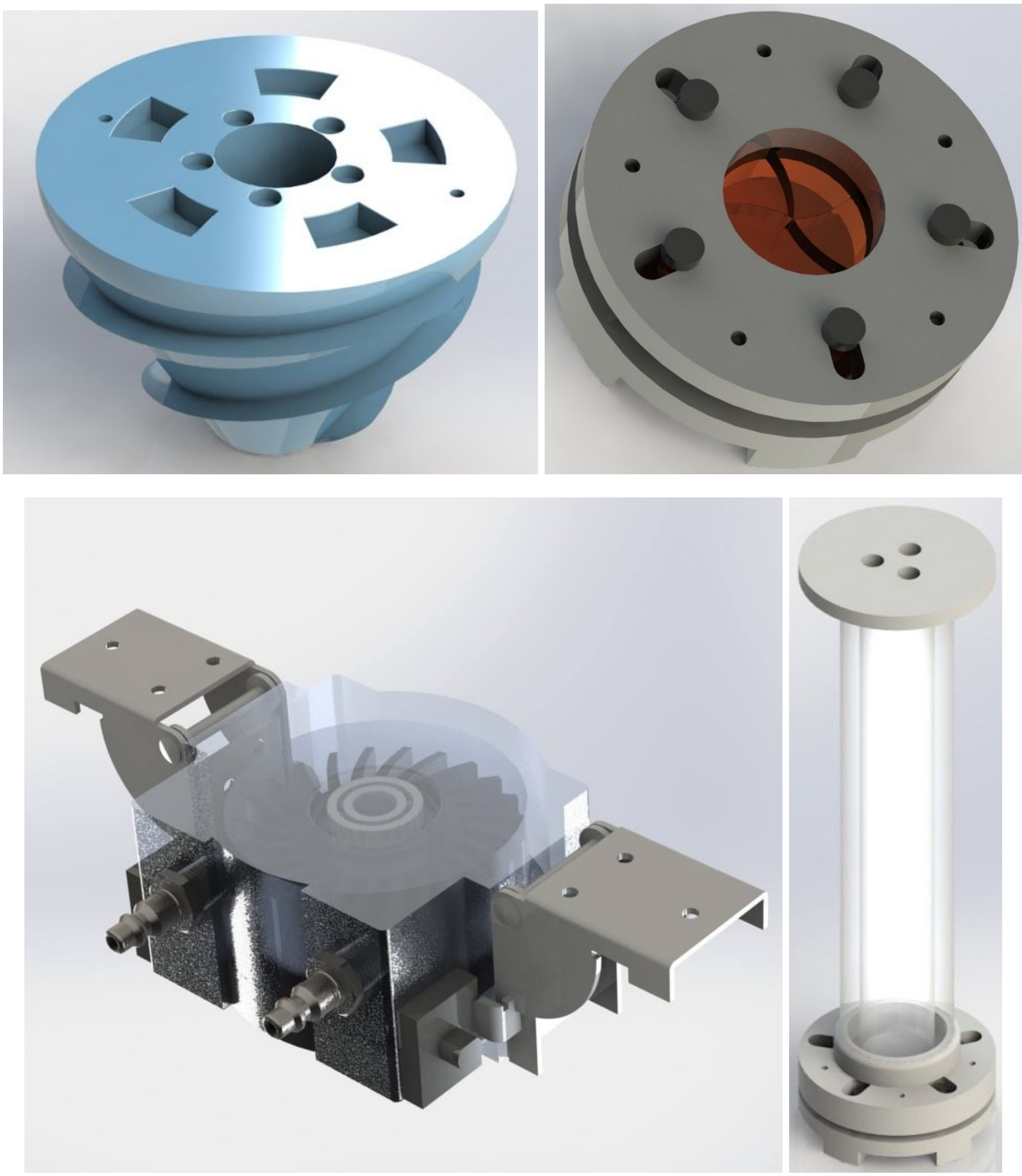


Figure 8. Iteration III of the Lion Drill: bottom piece, mechanical iris, pneumatic turbine, sampling tube

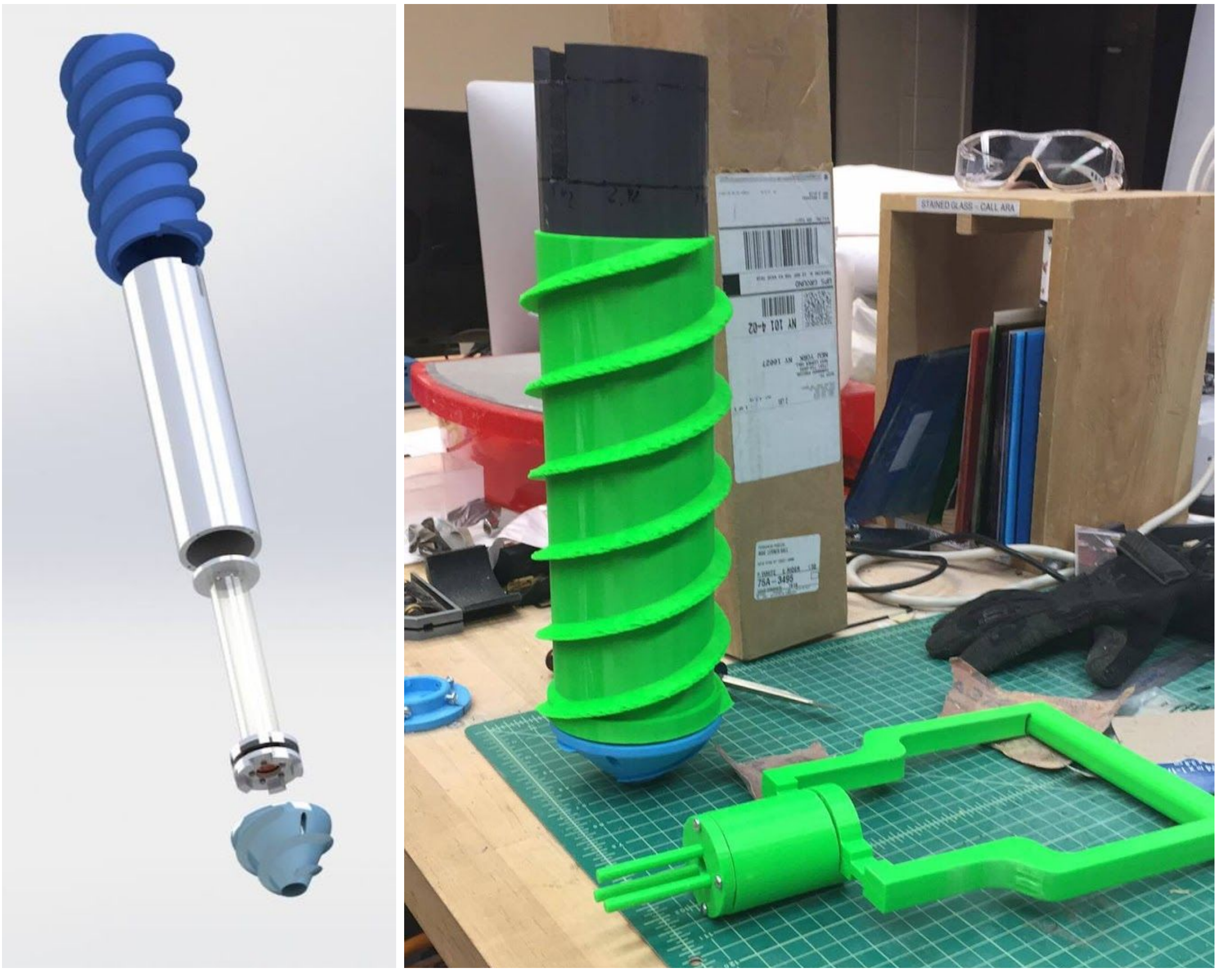
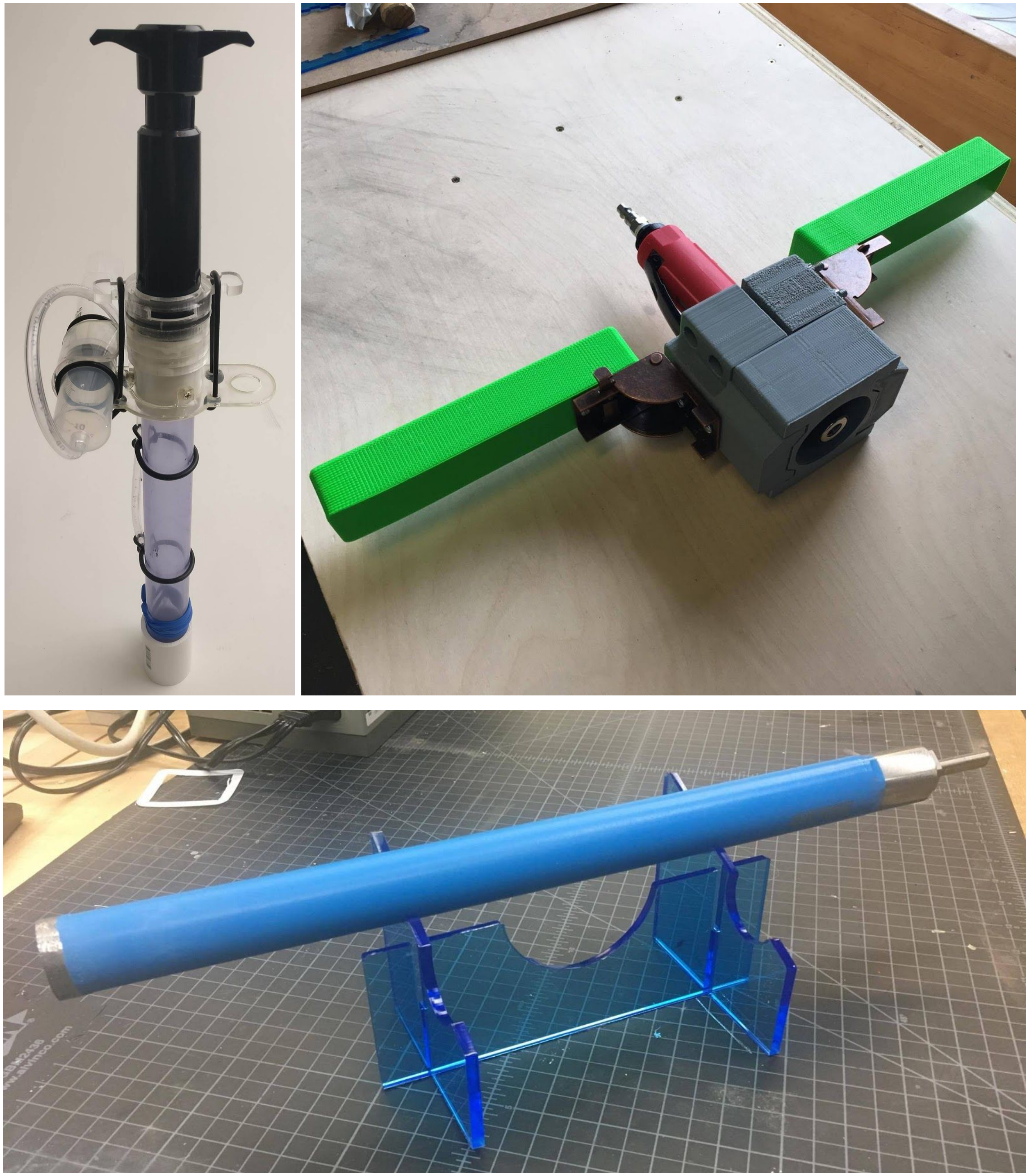


Figure 9. Iteration III of the Lion Drill: exploded view of regolith assembly, manufactured regolith assembly



Figire 10. Final manufactured designs of IV iteration of Lion Drill of regolith body (top left), sandstone body (top right), and core drill bit of on a stand (bottom)

Figure 11. Iteration IV (final) of the Lion Drill: inflatable closing mechanism

Results

Although we conducted many tests and tried to make our device as usable and useful as possible, there were some errors which manifested during NBL testing. During pre-test reviews the primary concern regarding our device was diver safety and usability. We were required to smooth out some sharp edges caused by two uncovered bolts which we rectified by covering them with epoxy. We also were asked to clearly label each part of our device and mark keep out zones. The labels helped during the NBL testing so phrases like “grab handles” made more sense and were less likely to be misconstrued. In addition, we added a line on the drill bit to mark how deep to insert the bit during sandstone extraction. Concerns about the noise level of our drill resulted in an decibel level test which we passed. We ensured the ink and epoxy used were approved for the NBL test environment.

The NBL testing provided valuable feedback and testing information about the Lion Drill. During vacuum aided regolith collection, the water balloon we were using to seal the sample broke as the tool was pulled out. Despite this, we still collected an approximately 7 inch regolith sample. We were unable to determine the success of maintaining stratigraphy as past groups had used the same test bin and stirred the sand inside up. While collecting regolith without the aid of a vacuum pump, the balloon broke as the sample tube was inserted into the regolith. We believe this was due to a manufacturing error rather than purely a design driven one. In this test, we obtained no sample. Another point of feedback we received was that operating the device with EVA gloves was challenging, though not impossible. Despite not collecting a full 8 inch sample, the regolith operation was marginally successful as we managed to obtain a 7 inch sample with the divers using EVA gloves.

For sandstone operation, the first point of feedback we received was that it could not be operated with EVA gloves. Fortunately, it was operational with the much thinner diver gloves. The diver had trouble getting the drilling to start due to the lack of a stable pilot hole. Fortunately, the diver was able to find a slight dip in the rock to get the drilling started. The drilling started off fine, however, about 4 inches in, the core drill bit detached from the pneumatic drill. Continued drilling proved fruitless due to the core drill bit no longer being attached. We had the diver stop drilling and remove the bit. Once the bit was removed, a small rock sample along with a large amount of pulverized rock fell out. We believe the drilling after the drill bit came loose led to some of the sample being pulverized. The divers attempted to reattach the bit but the drill head was hard to access and even when tightened to the best of the divers' abilities the core drill bit did not stay in the tool. We ran out of time so we simply retrieved the 1 inch sample received during the initial drilling.

Discussion

The design of the drill changed drastically during the last two months of the design process. We initially planned to have a singular main body with detachable apparatuses for the sandstone and regolith sampling periods.

One of the main deviations from our initial design was the realization that it was not feasible to create a custom-designed and milled aluminum air motor. Once it became clear that inherent machine errors would compromise the safety of our drill, we decided to purchase a premade pneumatic drill. While this did reduce the overall cost of our device and ensure that our drill would be safer for divers to use, we needed to completely redesign the shape of the main body in order to embed the new pneumatic drill within it.

As for the regolith sampling device, most of the design process was focused on the bottom closure mechanism. We designed an iris, an origami torque cylinder, and a heart valve closure. However, once testing started, we realized that the large surface area of the body tube and the fluting was displacing too much sand outward, resulting in only 2-3 inches of sand inside the sample tube. Eventually, we decided to minimize the base surface area of the device, reducing it to about 1.5 inches in diameter. Rather than drilling into the sand with an auger, we resolved to drive the sample tube directly into the testing bed and close the sample by inflating a water balloon. This new design would involve two separate devices: one for regolith and one for sandstone. For the sake of underwater testing, a one-way valve and a vacuum suction pump in order to pump regolith upward.

With this method, we were able to collect a full 8-inch sample of sand during testing, and a 7-inch sample during NBL testing. This late design change greatly improved the sample collection results.

During the building process, we also ran into difficulties with the ergonomics of the main body of the device. The coring drill bit was difficult to insert and tighten into the drill chuck. Due to time restraints, we were unable to redesign the pneumatic drill holder in order to make the drill chuck more accessible. Due to this issue, divers during NBL testing were unable to re-secure the drill bit once it came loose, which occurred because the pneumatic drill utilized a keyless drill chuck. With a keyed, more accessible chuck, the vibrations from drilling would be less likely to loosen the coring bit.

During underwater testing, we received feedback from the divers which suggested that we add a separate drill bit to create a pilot hole in the sandstone to prevent the drill bit from skipping across the surface of the rock. An improved design would also include vent holes to release water pressure and act as windows for viewing the progress of the sampling process. However, the divers did report that the rectangular handles of the device were helpful for allowing the divers to grip the device.

Outreach

Our primary outreach goal was to engage children in aerospace and engineering in a fun and interactive way. By teaching basic concepts of aerodynamics and aerospace engineering through hands on activities, we hoped to help them find a passion in the field. We also explained our project and conveyed how they too could contribute to NASA and the future of aerospace.

Our first outreach activity took place at the Intrepid Sea, Air, and Space Museum during their Kid's week. We reached children from elementary to middle school with this event. We explained some basic concepts behind parachutes and how and why NASA uses them to safely land astronauts and cargo. We had materials available for kids to design and build their own parachutes and mini rockets. After the kids built their parachutes, we tested them out and let them keep them. The kids really loved being able to engage in engineering and many thought of unique and interesting parachute shapes and designs. Also, dropping parachutes from a chair in a crowded room made them kids super excited and helped draw a larger crowd. We engaged over a hundred children, spreading a strong interest in aerospace and engineering.

Our next event took place in the Liberty Science Center during Engineering Week. Primarily middle school aged students attended this event, though there were some younger ones. We presented prototypes of our device and explained how it contributed to NASA's journey to mars. We also had some pans with flour on the bottom and colored sand on top. Dropping a marble onto the colored sand created a crate much like an asteroid's. We used this to explain how asteroids make craters. We also engaged the kids by challenging them to try different heights and marbles sizes and predict what would happen to crater size. Many were surprised to see a large marble from a medium height made a similar size crater as a smaller one from a higher height. We used this to teach basic physics concepts of energy. The children loved seeing our project and having to think about what might change about the craters if they did something differently. We again reached over a hundred children and taught them about NASA and its mission and engaged them with physics and aerospace.

We participated in an event run by our umbrella club, Columbia Space Initiative called C U in Space. We presented our prototypes to faculty and students at Columbia University and explained how it related to NASA's overall mission and goal. We received a lot of technical questions and interest about designing for a microgravity environment. With about two hundred people attending the event we spread a lot of interest about NASA challenges and aerospace engineering to the Columbia University community.

The rest of our outreach activities took place twice a month at the Manhattanville Community Center, an after school program for underprivileged children whose parents are too busy to take care of them until their workday ends. We did a number of workshops at the center, including the parachute activity from Intrepid, an activity involving the aerodynamics of paper airplanes, an activity involving the aerodynamics of straw rockets, and finally a project in which students worked in groups to build mini roller coasters for marbles to show gravity and basic physics concepts. All the projects involved a short lecture followed by allowing students to do their own design and building followed by testing. We engaged around fifty students total, many of which recurrently came to our workshops. The students loved being able to apply scientific concepts they had just learned in a meaningful way and it was extremely gratifying to see students get more active and engaged over the course of many workshops.

Conclusion

In joining Microg NExT the Columbia team embarked on a several month journey that would challenge us in a variety of ways. We learned and developed not only technical skills such as design creation, prototyping, and machining but also social and life skills. We were presented with challenges such as how to machine a rotor for a turbine, captivate the attention of a group of young children to teach them about aerodynamics, and locate the nearest vending machine in search of Poptarts. Team members shared their thoughts on the experience below:

Asad: "I learned a lot about taking ideas and theoretical designs into the real world. I learned how to think up designs, consider as many scenarios as possible before building and testing it. Most importantly, I gained valuable experience taking test results and finding solutions for problems we encountered then repeating this over and over until we had a working product. In addition, I learned about technical writing and concisely and effectively communicating information."

Mikhail: "Participation in Micro-G NExT defined my first year in college. As a freshman I got invaluable experience in engineering design process, in manufacturing, in interaction with teammates, in financing and fundraising for the project and for team travel, and in educational outreach. Importantly, the challenge opened my eyes on social aspect of engineering, teaching that design process and manufacturing require much more than technical skills."

Francesco: "Knowledge and ideas are not solely possessed by a select few. Throughout the past several months I found the value in speaking with anyone and everyone (so long as they expressed interest) about our challenges and assessing how their advice could forward the mission of the team. I also was led to a better understanding of how individuals work in teams and how to cultivate a harmonious team environment that facilitates success."

Robert: "By participating in the Micro-G NExT challenge I learned a lot about mechanical design and testing. I was happy to be able to use many of the things I've learned in class to create a product i.e. CAD and machining. Having to balance classes during the year and working on the project was challenging but I'm glad it worked out in the end."

Karina: "This year, I learned how to combine and develop multiple ideas which we all brainstormed as a team. I also learned how to apply rapid prototyping techniques to a long-term project."

Ben: "My favorite part of Micro-G was preparing and participating in outreach events. The most challenging aspect of it was balancing time between this project and regular academic studies."

Alex: "As part of Micro-G, I got a better understanding of how engineering team projects evolved in response to obstacles. I was also mainly involved with obtaining funding and learned how to pitch our team's goals and missions so that we could get paid."

Kevin: "Participating in Micro G gave me a better understanding of mechanical design and of teamwork in engineering. I was also involved with outreach a lot and it was really great being able to teach others."

Acknowledgements

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Appendices

Outreach activities

Figure A1. Engineering Week, Liberty Science Center

Figure A2.1. Kid's Week, Intrepid Sea, Air and Space Museum

Figure A2.2. Kid's Week, Intrepid Sea, Air and Space Museum

FIgure A3. Presenting to Dean Boyce at CU in Space in Columbia University

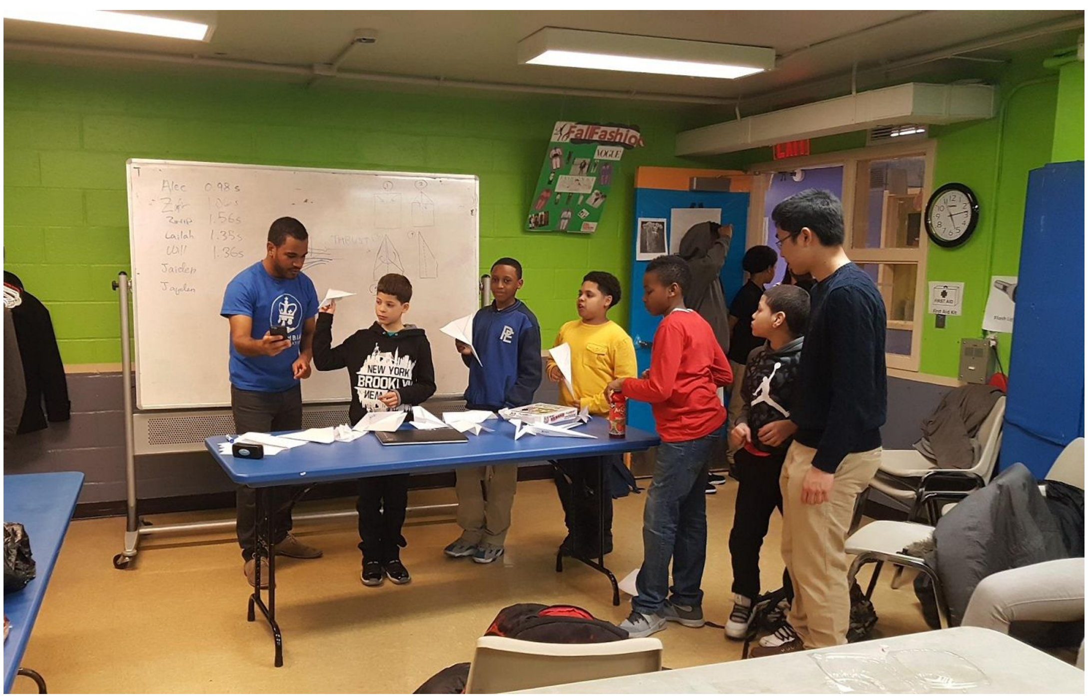

Figure A4. Paper Airplanes Workshop at Manhattanville Community Center

Figure A5. Rollercoaster workshop at Manhattanville Community Center

Figure A6. Straw Rockets workshop at Manhattanville Community Center

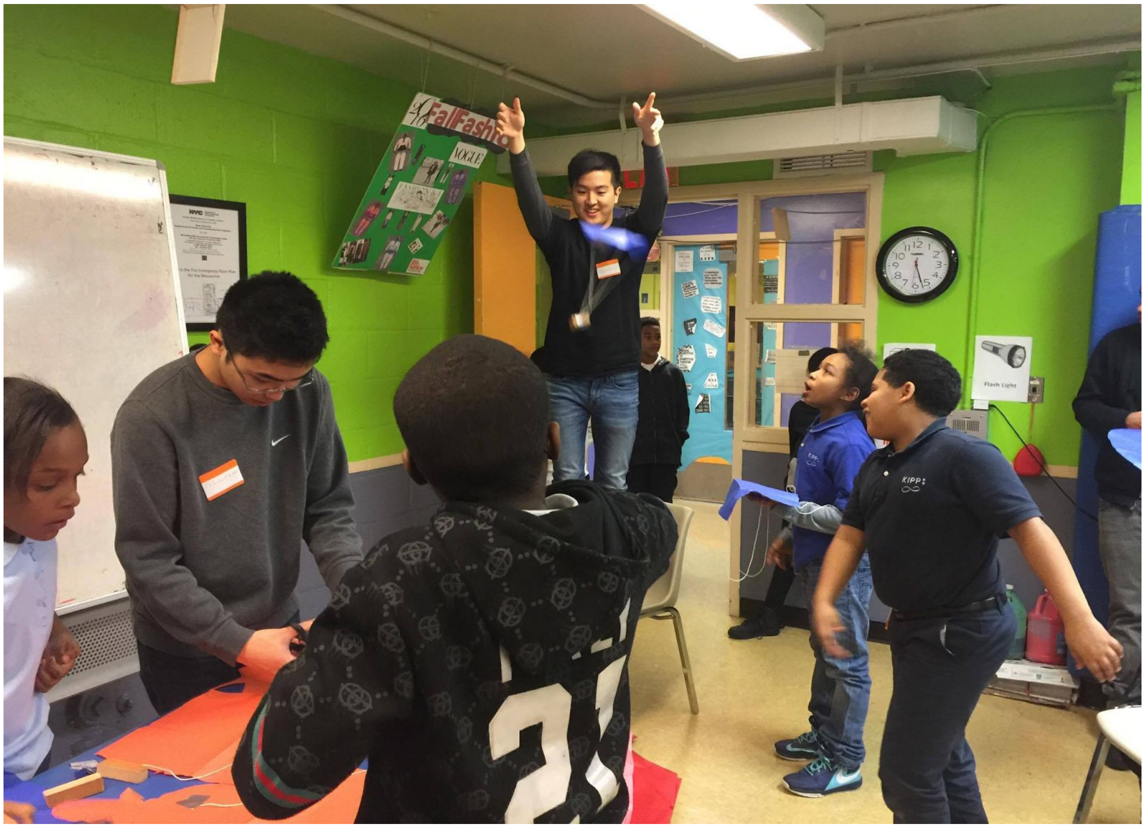

Figure A7. Parachute workshop at Manhattanville Community Center