1 Project Background:

Warhead design engineers and material scientists require mechanical property information under high deformation rates of loading on a wide variety of materials that have military significance. Over the past decade, a new class of materials has begun to receive attention because it affects the performance of most all warhead designs. This new class is called "particulate materials" and includes a diverse collection of materials such as sand, explosive grains and potting materials. One technique used to probe the behavior of such materials is to fill a large "box" with sand and fire a hemispherical-nosed projectile into it. The hemispherical nose provides a spectrum of loading conditions and the rapid projectile deceleration provides a velocity spectrum. During such events, the projectile disturbs and crushes the sand. It has been noted that the disturbed/crushed state of the sand correlates with the conditions that affected it. However, there is no good technique for extracting sand samples making so many measurements not very definitive or useful. The Damage Mechanisms Branch has a requirement to develop a new technique for extracting sand samples from the target.

1.1 Most Important Project Objectives from Customer:

1. A sand sampling technique/apparatus is required that allows sand samples to be obtained from the target.
2. The sand location, density, and local arrangement must be preserved

1.1.1 Design/Results Expected from Customer:

Initial Phase:

i. Evaluate the technique currently used to extract sand samples from the target—the "archaeologist" technique.

ii. Become familiar with the experimental conditions and the project constraints.

iii. Develop an initial design for the sand sampling technique/apparatus.

Final Phase:

iv. Design, fabricate, rehearse, document and implement the sand sampling technique/apparatus.

v. Evaluate the practical application of the team's ideas.

1.1.2 Prototype Expectation from Customer:

The team's technique/apparatus will be implemented as part of an actual experimental series at the AFRL Site C-64 Range B. Optimally the team will have the opportunity to evaluate both the current and the proposed techniques. Note that sand target modifications could be made, being mindful of the size and weight of the heavy steel target.

2 CONCEPT GENERATION

2.1.1 Focus and expectations

The project is open ended and it is just one step of a large scale project. The group and the sponsor have agreed to focus on an ultimate goal to get samples with accuracy of the position of the particles with respect to the path of the projectile. Important issues that they currently have with their method are that they disrupt the sand when digging in search for the crushed sand, their sampling technique is too simple and inaccurate, and ultimately it takes too much time and effort to get the samples. We expect to:

- Locate the projectile and its path before touching the sand
- Clear the sand that is not in interest
- Open space for accurate acquisition of a sample
- Obtain the sample
- Reduce the total time of the experiment

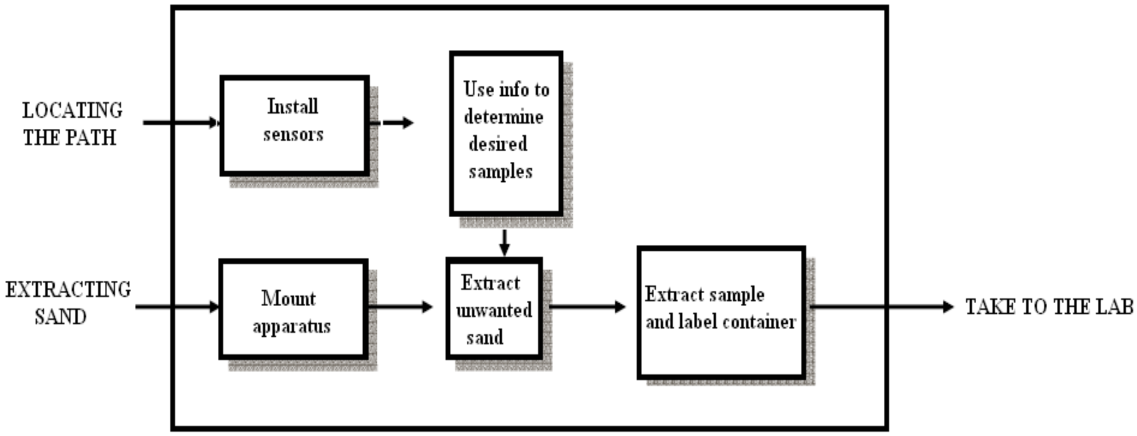


Figure 1: Process of the experiment

2.1.2 Subdivisions and existing solutions

To achieve these goals the design will be divided into three components. The first should locate the path of the projectile, the second should get the sand ready for extraction of a sample, and the third should obtain the sample. The first component could be a method or mechanism to locate the path of the projectile. Currently, they do not know the path of the projectile until they dig and find the crushed sand. Many times they disrupt the sand when digging to find the path. It would be helpful to know it from the place the target made contact until it stopped. The technicians that run this experiment use the path as a reference instead of parts of the target. The problem is that the path is different every time the experiment is performed. Some type of sensors will be installed in the target and the idea is to detect the path of the target without removing any sand. About 20% of the total budget of the project is available for this component. This step is dependent of the second component given that the second component might not need the identification of the path.

There are a few concepts considered for use in the first component of the project. Currently there is no method to locate the path of the projectile without removing sand from the target. Locating the path of the projectile and the projectile have become an important part of the project because it is thought in order to speed up the process of extracting samples one must know the exact location of the projectile path without removing any sand. The three possible concepts considered to locate the path of the projectile are to use ground penetrating radar (GPR), temperature sensors or pressure sensors.

Ground-penetrating radar (GPR) is a geophysical method used in the industrial and research fields that uses radar pulses to image objects underground. This non-destructive method uses electromagnetic radiation in the microwave band (UHF/VHF frequencies) and detects the reflected signals from underground objects. GPR can be used in a variety of materials including rock, soil, ice, fresh water, pavements and structures. GPR can detect objects, changes in material, and voids and cracks. GPR uses transmitting and receiving antennas. The transmitting antenna radiates short pulses of the high-frequency radio waves into the ground. When a radio wave hits an object or a boundary with different dielectric properties the wave get reflected back to the receiving antenna and the receiving antenna records variations in the reflected signal. The figure below shows a technician using a GPR system to locate materials in the concrete wall. The picture to the right shows what the GPR finds in the wall. Using GPR to locate the different densities of sand after the projectile moves through the sand is the idea behind using GPR to locate the path of the projectile.

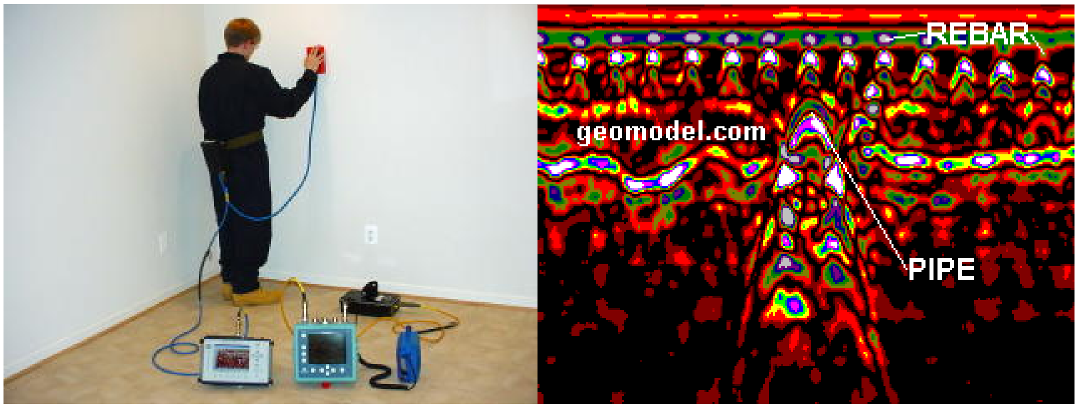


Figure 2: GPR equipment and the result of the scan -Courtesy of Geomodel.com

Infrared Thermography, thermal imaging, or thermal video, is a type of infrared imaging science. Thermographic cameras detect radiation in the infrared range of the electromagnetic spectrum (0.9–14 µm) and produce images of that radiation. The amount of radiation emitted by an object increases with temperature; therefore thermography allows one to see variations in temperature. When viewed by thermographic camera, warm objects stand out well against cooler backgrounds. Humans and other warm-blooded animals become easily visible against the environment. As a result, thermography is use in the military and security services. Thermal imaging photography finds many other uses as well in other areas. For example, firefighters use it to see through smoke, find persons, and localize the base of a fire (Figure 3 below). With thermal imaging, power lines maintenance technicians locate overheating joints and parts, to eliminate potential hazards. Where thermal insulation becomes faulty, building construction technicians can see heat leaks to improve the efficiencies of cooling or heating air-conditioning. After the projectile moves through the sand there is a large temperature increase in the local area of the path of the projectile. Using the thermal camera, it would be possible to locate the path of the projectile.

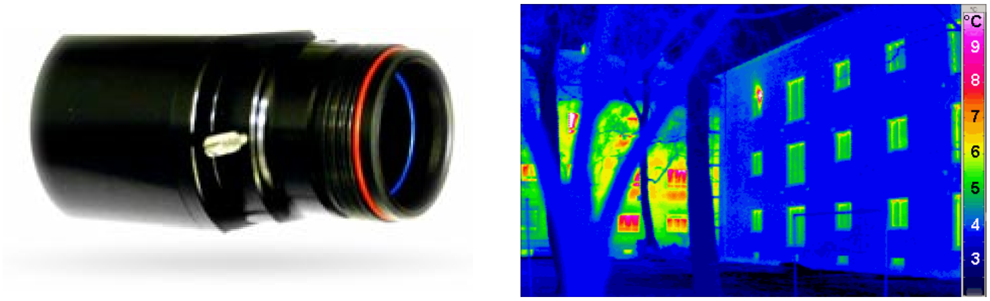


Figure 3: Thermal Camera and what it records

A pressure sensor generates a signal related to the pressure imposed. Normally the signal is electrical, but optic, visual, and auditory signals are not uncommon. Pressure sensors are used for control and monitoring in thousands of everyday applications. Pressure sensors can also be used to indirectly measure other variables such as fluid/gas flow, speed, water level, and altitude. Pressure sensors can alternatively be called pressure transducers, pressure transmitters, pressure senders and pressure indicators. Pressure sensors can vary drastically in technology, design, performance, application suitability and cost. An example application for a sensor would be in the measuring of combustion pressure in an engine cylinder or in a gas turbine. These sensors are commonly manufactured out of piezoelectric materials such as quartz. After the projectile moves through the target there are pressure waves that move through the target. By using multiple pressure sensors throughout the target the position of the projectile pat can be estimated.

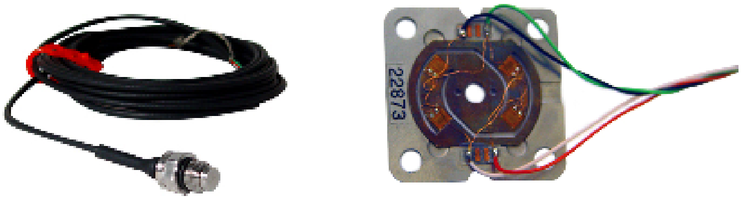


Figure 4: Pressure Sensors

The second component is the mechanism to extract the unwanted sand. Currently they use the “archeologist” method which means they dig down to the estimated depth and brush away the uncrushed sand. This mechanism has to reach into the sand and get to the location where a sample is desired. Regardless of the final design the mechanism should move such that the third component can get samples from any (h,w,L) position in the target. It must be removable and fairly light since it will be placed and removed for every trial of the experiment. Two common methods of extracting sand from the ground in various industries are using vacuum machines and excavators. The concept of vacuuming and shoveling will be base for this part of the design.

Figure 5: Concepts for sand extraction from top left: vacuuming, excavation, and shoveling.

The third component must extract the sample. Currently, they stab the sand horizontally with a pocket knife in random locations and put the sand from the knife into a Ziploc bag. This design must include a method of identifying the exact location (h,w,L) from where the sample was obtained. It must safely put the sample into a container that will be taken into the lab. One concept widely used in biology and geology is core sampling. A tube is inserted into the desired area and sealed at the top creating a vacuum effect and then the tube is raised with the sample of material. The advantage of this concept is that it is easy to preserve the position of the particles. The disadvantage is that this is mostly used when the sample is wet and can maintain its shape. Another concept could be to get the sand to stick on to another material. Often sand samples are glued to special tape and coated with some metals prior to being placed under a microscope. If the concept of core sampling is used the second component might not be necessary.

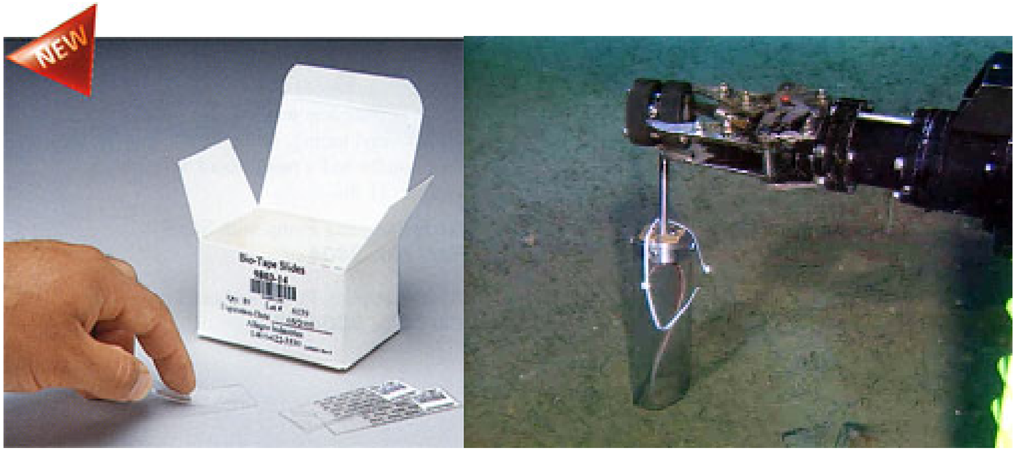


Figure 6: Concepts for sampling the sand from the left: sampling tape, core sampling.

2.2 Constraints

2.2.1 Identifying the exact location of the projectile

The depth range of GPR is limited by the electrical conductivity of the ground and the transmitting frequency. Optimal depth penetration is achieved in dry sandy soils or massive dry materials such as granite, limestone, and concrete where the depth of penetration could be up to 15 m. Since the experiment is done with dry sand most of the time the limits of GPR are not an issue however the cost of a system does remove the possibilities of using a GPR system with a $1500 budget. A manufactured GPR system's price can range from $10,000 to $30,000. The thermal imaging method possibility is also removed because the price of a quality camera is $6000 or above and that a thermal camera can only detect surface temperatures. Pressure sensors are the cheapest of the three possibilities separately at $900 a piece but the amount of pressure sensors needed in the target would make it too expensive to use pressure sensors. After receiving the research on the amount of money needed to successfully complete the first component of the mechanism the first component has been removed from the design.

2.2.2 Current Experiment: UNDER CONSTRUCTION

The mechanism has to be flexible enough to allow for changes of the target. For example, the sponsor recently revealed that a series of devices are being installed on top of the target to pack the sand tighter. This means that the top edges can no longer be used for installing non removable parts of the sand sampling apparatus.

Eleven make screens (Figure 7, below) are inserted rigidly in the sand with the purpose of measuring the changes in velocity of the projectile. These make screens are eventually going to be removed from the experiment and occasionally the experiment is run without them. Currently the sponsor does not have a set size of the screens that the consistently use. The mechanism has to be able to go above the make screens and get samples from both sides of each one of them which can restrict the size of the screens. For testing purposes of the apparatus, the make screens are being removed from the scope of this project. However, the design should take the make screens in account.

2.2.3 Surface Extraction

The extraction of sand samples after the sand has been removed has been achieved by an imprecise method of scoping the sand out of the area and placing it in a zip-loc bag. The method proposed by the team is using a sample tape that is used in the analysis of the samples to collect the sample right from the target. However there must be a smooth surface for the tape to work and care has to be taken to not damage the tape and samples.

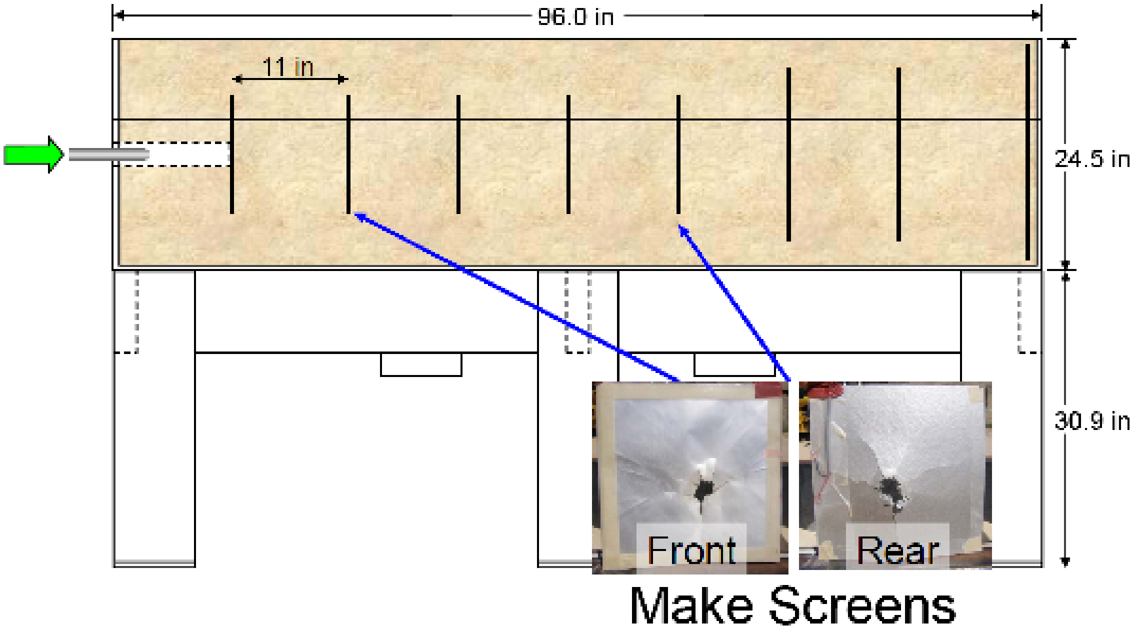


Figure 7: Target schematic courtesy of Eglin AFRL

2.3 Combined concepts and ideas

A simple way to make sure that the mechanism can reach all parts of the box with good accuracy is to make a location system with three degrees of freedom that digitally displays the location of the attachment touching the sand. All the design ideas have been chosen to be able to adapt to this location system. The system shown in Figure 8 consists on the following: A rail will be attached to the target to allow motion in the L direction. That rail is marked to indicate the length and it is connected a platform. The platform is on top of a linear motion actuator (rack and pinion, belt, or chain) that allows precise translation in the W direction. Another linear motion actuator is connected in the vertical extension of the tip of the attachment that makes contact with the sand. This tube has a lever allowing motion in the H direction (not shown on the picture). The vertical part that holds the last attachment must have a range so that the tip of the attachment goes as far as touching the bottom of the target and retracts to avoid the make screens used in the experiment.

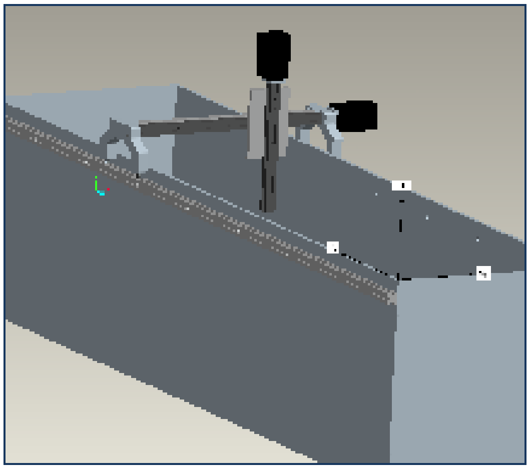


Figure 8: Location system attached to the target.

2.3.1 Concept 1: Vacuuming to get to the sample; Sample will be obtained with sampling tape.

The mechanism:

The extension of the tip of the tube coming from the vacuum machine will be attached to the vertical linear motion actuator. This tube could use a lever as the linear allowing motion in the H direction. The tip of the tube is designed with some type of edge so that layers of sand can be extracted putting minimal vertical force on the sand. The tube reaches from the tip laying on the sand to the vacuum machine on the ground outside of the target.

The method:

After impact the platform is set into the rail. The vacuum machined is turned on and layers of sand are extracted until the desired height. Sampling tape is then laid on the sand. A thin layer of sand sticks to the tape, the tape is removed and placed in a labeled container.

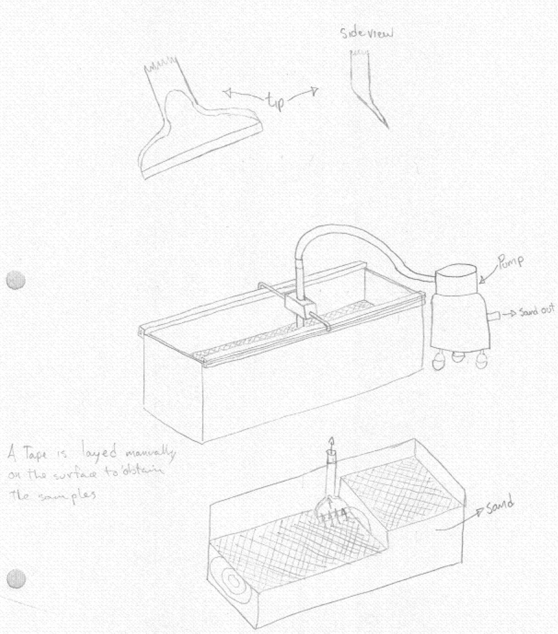


Figure 9: Hand drawings of concept 1.

2.3.2 Concept 2: Gear blade shovel

The structure for this apparatus is based off of the two eight foot pieces of aluminum extrusion that run the length of the box, as seen in idea one. The mechanism desired in this idea is kind of like an old fashioned lawn mower, with three or four blades. It will consistently "mow" a top layer off the top of the sand, and bring the sand to the center between the blades and suctioned outside of the box. The blades will be driven by gears and a motor, and the sand will be suctioned by vacuum.

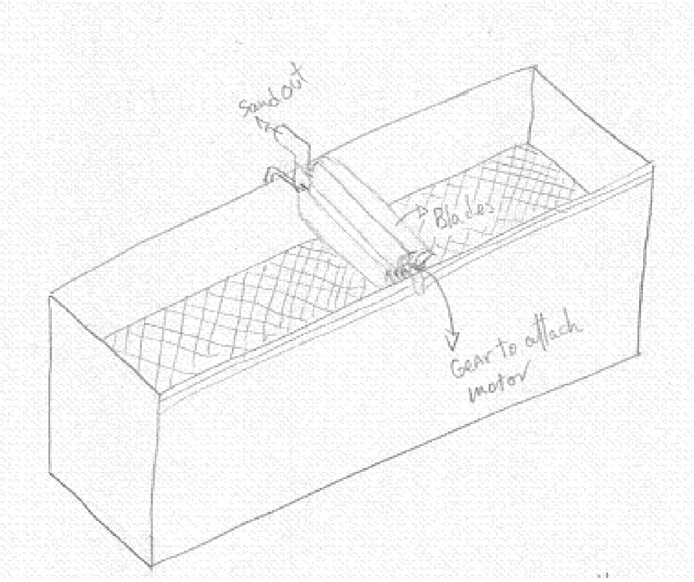


Figure 10: Hand drawing of concept 2

2.3.3 Concept 3: Core Sampling Tube

The core sampling idea is based off of the same structure as the vacuum and tape method. On each side of the box is two eight foot pieces of aluminum extrusion which have rollers to allow for motion in the x direction. The rollers are attached by another piece of extrusion in the y direction, spanning the two foot width of the box as shown in the picture of idea one. A linear motion actuator will be attached to the y direction span of extrusion to create the desired motion. Another actuator will be attached vertically to the y direction actuator, which will provide the desired z motion. A core sampling apparatus made from clear piping will then be attached to the z direction actuator.

After the projectile shot has been fired, the apparatus can be easily secured into place on the box as stated in idea one. Wherever a sample is desired, the apparatus can be moved manually in the x direction and locked in place. Then, the y and z motion can be achieved by a hand crank, such as a mill, or can have a computer controlled motor. The core sampling device will be placed wherever the sample is desired, and will take a core from the top layer of sand all the way to the bottom.

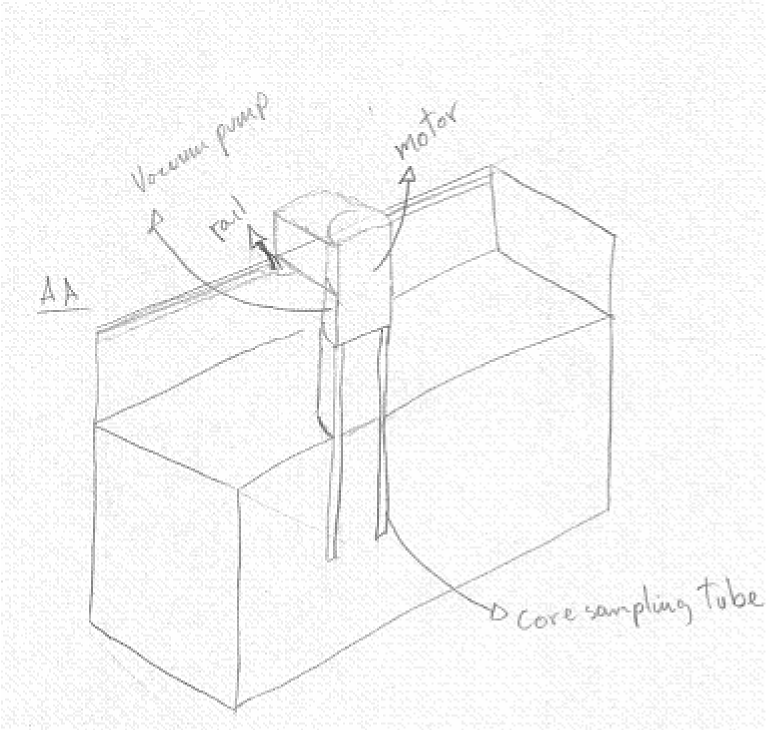


Figure 11: Hand drawing of concept 3

2.3.4 Concept 4: Core sampling with vacuum

This concept is based off of the same idea as concept 3, the core sampling tube. The only difference is that it will use a vacuum to create suction to take out the core of sand. Once the core sample is removed, a piece of tape will be placed under the sample to catch whichever part of the core is desired.

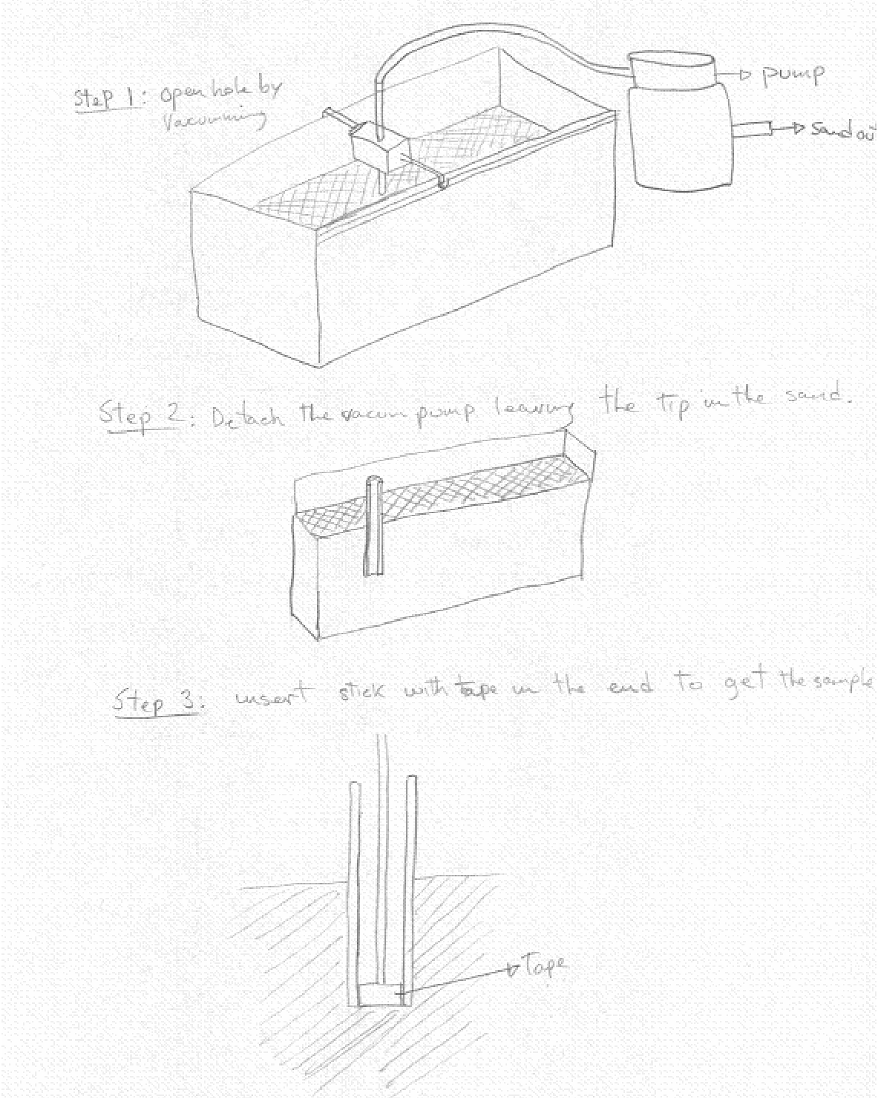


Figure 12: Hand drawing of concept 4

2.3.5 Concept 5:

This concept uses a fine tip on the end of the tube coming from the vacuum machine. Between the vacuum pump and the tip there is a vortex tube that will separate the suctioned materials based on density. In this experiment the fluid is an air and sand mixture. Since the sand is denser than air, centrifugal force will force the sand particles towards the inner diameter of the tube and the air will remain in the center of the tube. The sand can exit and be collected on the outside of the tube while the air will continue moving towards the vacuum pump. A long fine tip will allow getting samples from deep places on the target without removing any sand from the top. A disadvantage from this concept is that without knowledge of the path of the projectile it will be pointless to dig blindly from the top, therefore the path must be known or a few layers have to be extracted before taking any samples.

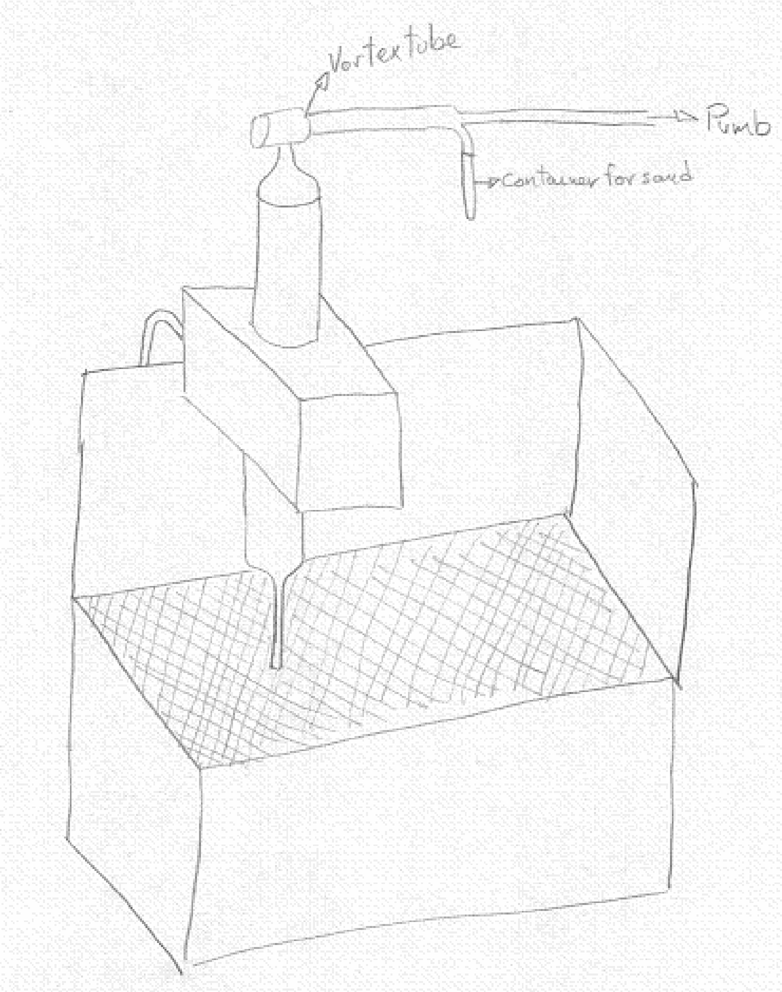


Figure 13: Hand drawing of concept 5

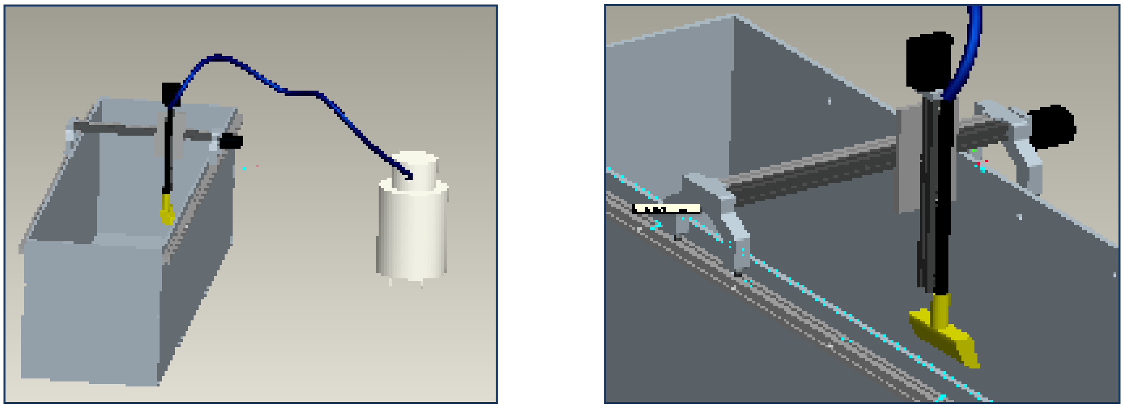
2.4 CONCEPT SELECTION

Table 1: Concept Selection

		Concepts									
		Apparatus with vacuum		Gear blade shovel		Core Sampling		Vortex tube		Vacuum core sampling	
Specifications	*Importance Weight*	*Rating*	*Weighted score*	*Rating*	*Weighted score*	*Rating*	*Weighted score*	*Rating*	*Weighted score*	*Rating*	*Weighted score*
Portability	15%	3	0.45	1	0.15	3	0.45	4	0.6	3	0.45
Lightweight	20%	3	0.6	1	0.2	2	0.4	4	0.8	2	0.4
User Friendly	5%	4	0.2	3	0.15	3	0.15	2	0.1	4	0.2
Accuracy	30%	4	1.2	2	0.6	4	1.2	1	0.3	1	0.3
Ease of construction	10%	2	0.2	1	0.1	2	0.2	1	0.1	2	0.2
Budget	15%	2	0.3	4	0.6	2	0.3	1	0.15	2	0.3
Time	5%	1	0.05	3	0.15	4	0.2	3	0.15	1	0.05
	Score		**3**		**1.95**		**2.9**		**2.2**		**1.9**
	Selection		**Yes**		No		No		No		No

The chart above is the concept generation table to decide which of the ideas is most feasible. The criteria for ranking our concepts is based on seven specifications that we feel are of highest importance to our project: portability, weight of apparatus, user friendliness, accuracy, ease of design and construction, budget, and time to perform experiment. The rankings are based on a one to five scale, with one being the least important, and five being the most important. One each specification is ranked, it is then multiplied by an importance factor, which is out of 100%. The most important specifications to our project are given the higher weight percentage, with accuracy and lightweight ability being the most important. After each rating was given a weighted score, the scores were added up. As shown in the chart, the vacuum and tape apparatus, concept number one, was chosen because it had the highest feasibility rating.

It was decided that this concept meets all the needs of the sponsor and give them room for improvement in case they decide to keep developing the study of these particles. The location of the shot line will be known when it becomes visible after taking a few layers of sand from the top. The sample tape gives them a fine layer of sand which will give them the flexibility to take as many samples as they want and generate a computer modeled 3D version of the target after impact. The tape is also very easy to label and to carry to the lab. The methodology is simple enough to use that it will only take them a couple of runs to get used to it and no intensive training. It is also a concept that will give us experience in the fields of statics, mechanics, dynamics, fluid design/ piping systems, and material selection. It is feasible to build it ourselves in four months and staying very close to the budget of $1500. Figure 14 illustrates the general idea from where this design will be based.



Figures 14: General Idea of selected design concept

3 Mechanism Description

To keep the rigidity of the apparatus, an aluminum drop in frame was designed to fit on the top of the box. It was designed using two pieces of (½'' x 2 ½'' x 96'') and two pieces of (½'' x 2'' x 23'') that were welded in a square shape. Along the two 96'' bars, hole patterns were drilled every 13'' so that steel rod supports could be fastened to them using 8/32 button head screws. The aluminum for this frame will be provided by Eglin Air Force Base, as well as the machining time.

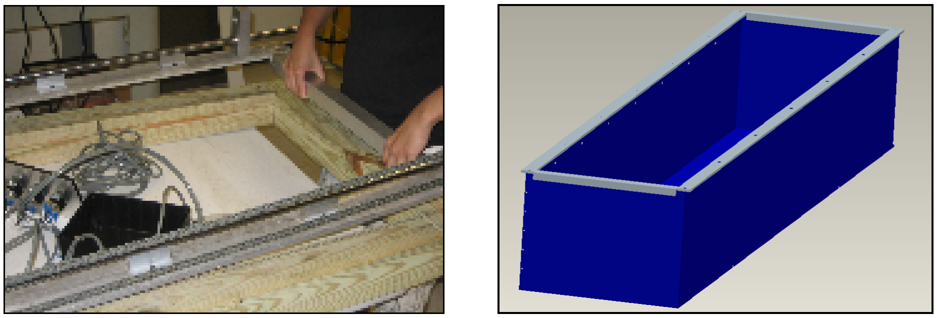


Figure 15: Concept Frame

3.1.1 Motion in the x-direction

To constrain the motion along the x-axis(8ft length), two ¾'' rods made of hardened steel are mounted on top of the drop in frame by their shaft supports. A bearing block, which is mounted on the side of the apparatus, where the chain is, consists of two linear bearings that allow for the motion along this x-axis. Initially, the same type of bearing was mounted on the opposite side of the apparatus; in this case binding was a big factor. If the apparatus was moved slightly in any way, it locked up and was unable to move.

Due to Binding, a new piece was designed, that consists of a bearing block similar to the older version, but instead uses a roller bearing that will roll on top of the shaft and allow for slight movements made by the apparatus. Binding was eliminated with the new piece.

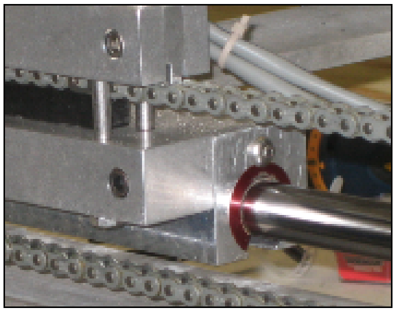


Figure 16a: chain

Figure 16b: Roller Bearing

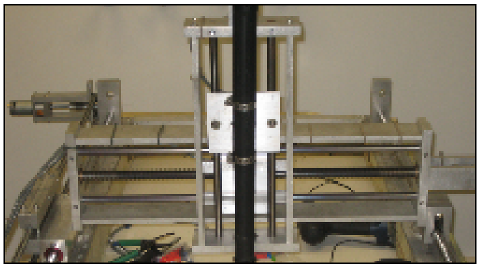


Figure 16c: ProE Design of Actuators

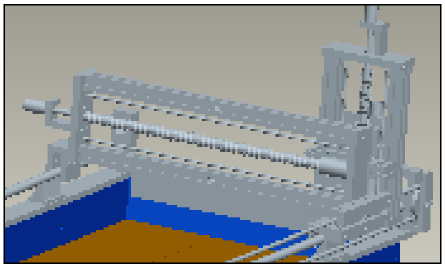


Figure 16d: Actuators

In order to produce the motion along the x-axis a chain and sprocket method was used. Approximately sixteen feet of chain was needed as well as two corresponding sprockets which were mounted to (1" x 2" x 3") aluminum bar. A groove has been machined into the bar to allow for proper fit of the chain and tension in the design. The drive sprocket, as seen below in Figure 17a, is machined with bearings that are mounted rigidly into the sprocket housing, Figure 17b. This was designed in order to make sure that the chain has no chance to pop off or come loose while being driven. The Sprocket housing was also designed with a tensioner to keep the chain in tension. As seen below, the sprocket was machined with a groove to slide back and forth, with a set screw perpendicular to the sprocket to screw or unscrew the sprocket position for full tension. The chain transfers motion to the y-actuator by means of a clamp that is made with the same teeth pitch as the chain. This grabs the chain with the teeth and holds it in place as seen in Figure 18.

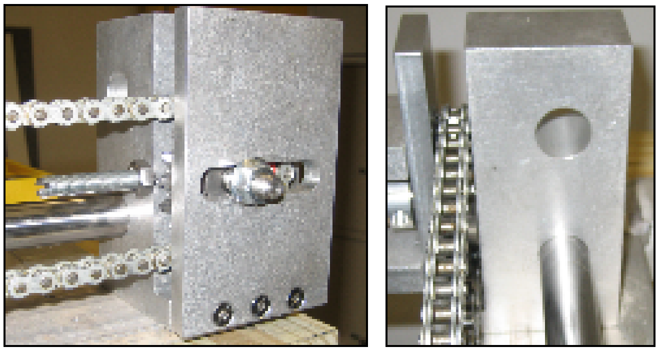


Figure 17a,b,: Drive Sprocket with Tensioner, Sprocket Housing

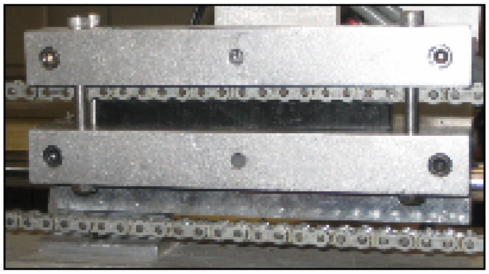


Figure 18: X-Clamp on Chain

3.1.2 Motion in the y-direction

An actuator frame consisting of two pieces of ½’’ by 3’’ aluminum bar stock, cut 24” in length creates a motion in the y-direction. These pieces of aluminum are flanked by two more pieces of 5/8” x 1 ¼” x 2 ½” aluminum bar and secured with ¼ -20 socket head screws. As seen in Figure 19, the aluminum bar ends have holes drilled for added stabilizers and bearing mounts.

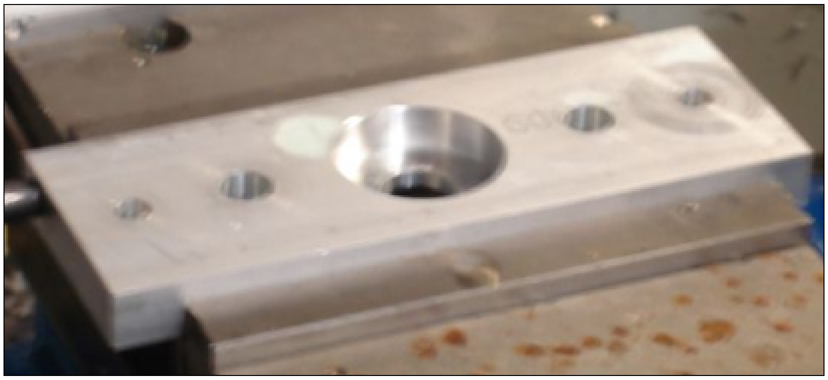


Figure 19: aluminum bar stabilizers

In order to produce the back and forth y-actuator motion, steel ACME threaded rod (a type of precision rod that can be used as a cost effective alternative to a lead screw), purchased from McMaster Carr, will be used the rod selected is a ¾” -10 that is 20” in length. Corresponding bronze lead screw nuts were required. Figure 20 shows a custom housing for the lead screw nuts which will then have a mounting plate attached, made of aluminum bar. The mounting plate securely mounts the nut to the ACME rod as well as has supports that attach to each stabilizer bar. The bearings for the threaded rod have an outer diameter of 1 5/8”, an inner diameter of ½”. The bearings for the stabilizer bars have an outer diameter of ½” and an inner diameter of ¼”.

When the bearings are fitted and all of the pieces are in place, the final actuator produced appears as Figure 21. As a rotational force to the end of the ACME rod is applied, it produces a motion to the mount in either the left or right direction.

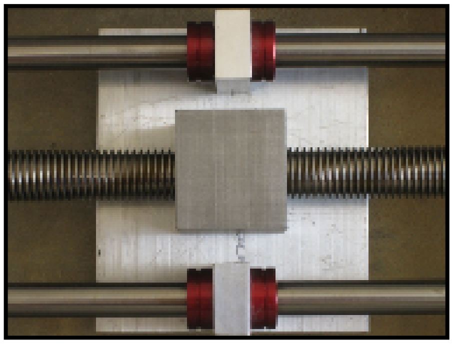


Figure 20: Lead screw housing

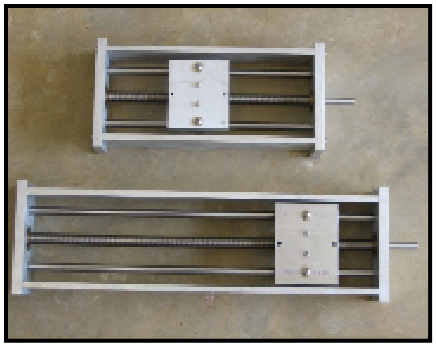


Figure 21: Lead screw actuator

The z-actuator is constructed similarly to the y- actuator, with the exception of the aluminum side pieces being 12” instead of 24”. The reason that this actuator is half the length of the y actuator is because if it was the same size, it would scrub the sand surface. It was assessed that vacuum hose would be mounted so it hangs about two feet below the z-actuator mount, as seen in Figure 22.

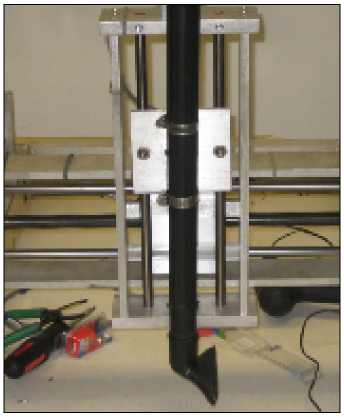


Figure 22: Z actuator mount with vacuum hose

The reason for this is so that when the z-actuator is in the initial top position, the hose tip will be at the sand surface. Thus, the vacuum hose will be able to reach any desired depth in the box. A single piece of aluminum that is 4 ½” in length has been mounted horizontally to the face of the y-actuator mounting plate and two more pieces of aluminum that are 2” in length are mounted to the sides using ¼-20 screws. Shown in Figure 23 is the protrusion from the y-actuator mounting plate to provide the z-actuator with clearance spacing. Figure 24 shows a final assembly of the y and z actuators.

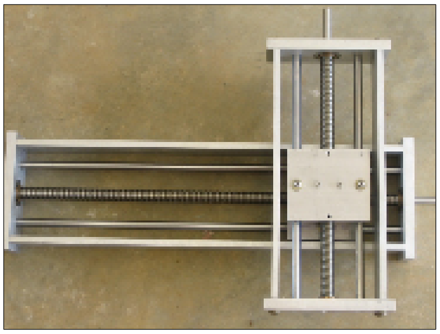


Figure 23: Protrusion from y-actuator

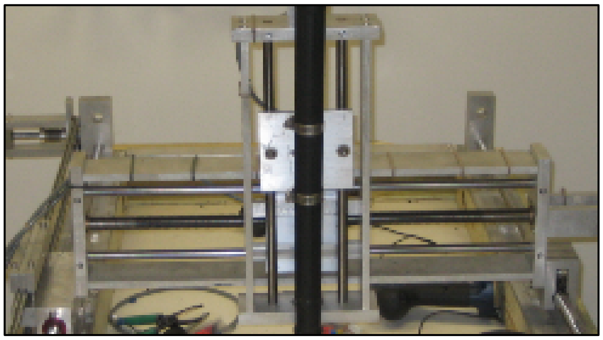


Figure 24: Actuators final assembly

In order to keep sand and other materials out of the wheel tracks and the actuators due to an outdoor environment, two different methods are applied. First, to keep sand from getting into contact with the lead screws of the y and z actuators, plastic accordion style rod boots, may be used. They can be mounted to each side of the lead screw nut assembly and attached to the outer walls of the actuators. As the actuators move in either direction, the rod boots will extend or retract based on the direction of motion. Second, the bearings chosen for the eight foot stabilizer bars can also have shields and brushes that will knock off any debris before it can get caught up in the bearing.

As far as using different materials in our design, such as aluminum structures, steel threaded rod, and bronze nuts for the threaded rod, corrosion should not be major factor. When using the bronze nuts for the steel threaded rod, McMaster Carr's website states that bronze has a very high copper content which makes it more corrosion resistant that brass, and will not have a problem when used with the steel threaded rod. The ACME threaded rod is made of hardened 304 stainless steel which is very highly corrosion and rust resistant. Because of the material of the threaded rod, it will not corrode or produce rust when in contact with the aluminum structures. As far as the aluminum frame rusting or corroding, this is not a problem due to the fact that the apparatus will only be used for a period of four to eight hours in an outdoor environment. The experiment, run by Eglin, is only done about once every month to month and a half, and when it is not in use it is stored in an indoor environment.

3.2 Overview of the Vacuum System

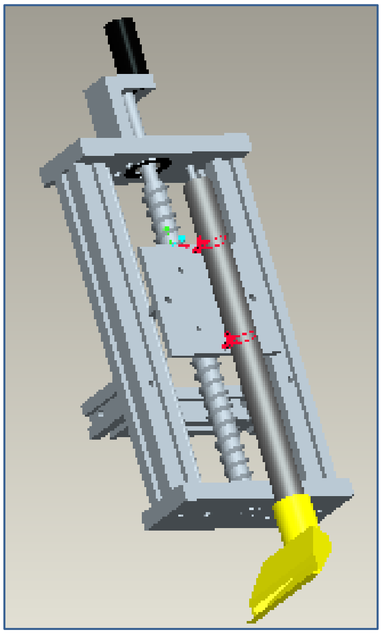


Figure 25: Vacuum tube connection

The mechanism is designed to suck sand out of the target using a vacuum system. Suggestions from the sponsor led original ideas to a commercial Shop Vac, however upon further inspection of the total amount of sand being removed, this was not feasible. The system being used is a dual ended vacuum in which one hose is placed onto the vacuum tip, while the other hose is free to exhaust sand into any open container or outdoor environment. The vacuum cleaner has a flexible tube connected to another straight tube. These plastic tubes are very smooth and the pressure lost due to friction inside of the tubes and turns will be neglected. Calculations attached in APPENDIX A prove that the pressure loss is insignificant to the one created by the vacuum pump. The straight tube then connects to a specific tip depending on the depth of the run. The Z axis of the mechanism will have tube clamps to hold the tube as Shown in Figure 25. Two or more tube clamps will be used as far apart as the connection allows distributing the load and minimizing the moment created by the resistance of the sand. Ideally we will have the clamps as spaced apart as possible for better stability. In the case that there is any bending of the straight tube during test runs. An extension will be made to the plate that holds the clamps so that the vacuum tube is clamped closer to the tip.

3.2.1 Experiment of resistance

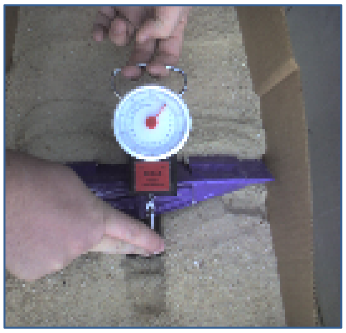


Figure 26a: Resistance Testing

The approximate resistance one inch deep layer of sand was measured to be 5lbs. This was measured performing an experiment on which the tip of the vacuum machine, unattached to the vacuum pump, was inserted about one inch into the sand and then pulled by a luggage scale as shown in Figures 26a and 26b. We added a safety factor of another 50% since the sand in the experiment goes under several packing techniques.

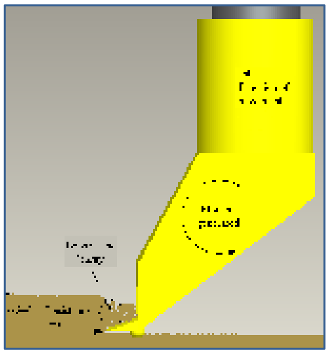


Figure 26b: Resistance Schematic

On the other hand this resistance does not transfer directly to the motor of the Y-axis. The actual resistance of the sand is subtracted by the suction of the machine which is dependent on our tip design. Having a small surface area doing the first contact with the sand will help minimizing the resistance from the sand. An edged surface is ideal since it will break sand clusters making the sand less dense in the other contact points and making it easier to flow towards the hole.

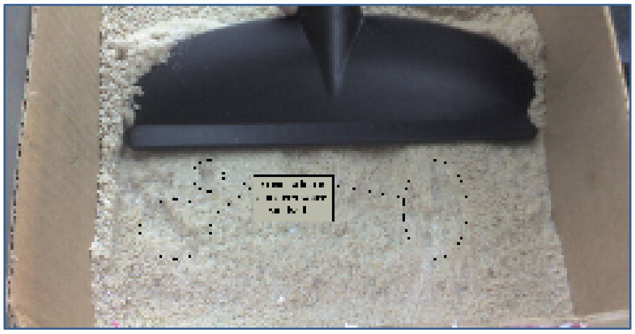


Figure 27a: Vacuum tip down

Figure 27b: Vacuum tip inverted

Another objective of the tip is to consistently take of a layer of sand leaving behind a flat surface. Different tip configurations were tested with a 3HP vacuum cleaner to determine the best way to place the tip. In the first part of the experiment the main focus was to decide whether to place the opening of the tip down or forward, and in the second part whether the tip should have an expansion or contraction at the end. The tip down method was very inconsistent in leaving a flat surface as shown in FIGURE 27a. It looked like the density of the sand was not uniform and clusters of sand were sucked instead of loose sand particles. On the other hand FIGURE 27b shows how placing the opening forward basically allows scooping before sucking and only the desired amount of sand gets through.

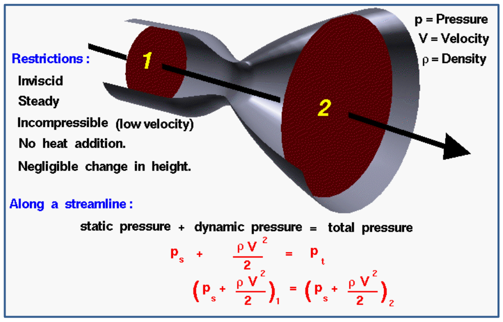


Figure 28a: Bernoulli's Equation along a streamline

For the second part of the experiment it was desired to determine if the tip should have a contraction or an expansion. Based on Bernoulli's equation as the velocity increases the pressure decreases and vice versa. Since the volumetric flow rate is constant a smaller cross section at the end of the tip would raise the velocity, thus lowering the pressure and creating more suction (see Figure 28a). The first trial had the tip as it comes from factory and there was a lot of accumulation of sand as shown in Figure 28b. Overall it was really hard to keep a constant velocity of the tip. Slowing down helped avoiding a lot of accumulation but it seems like an expansion raises the pressure too much and this pump did not have enough power to still work. The second option was to create a nozzle by closing a good part of the opening of the tip. About a half an inch was let open. This run was very smooth as shown in Figure 28c. We were able to vacuum a lot faster without accumulating any sand.

Figure 28b: Sand accumulation on front tip with an expansion

Figure 28c: vacuum nozzle with smaller opening

We will purchase an upholstery nozzle that is four inches in width and has the entrance and exit positioned between 60 and 90 degrees of each other. This will allow for vertical attachment of the hose coming from the vacuum cleaner. To this nozzle we will pin a razor blade to allow breaking of the sand in front of the nozzle. Ideally the razor angle can be modified for optimization. In addition to the razor we will also attach pins to the bottom of the nozzle spaced out in increments of an inch to mark the way the sampling tape needs to be placed (Figure 29). Then we will experimentally test the tip with the actual vacuum pump to see if an extra reduction is needed. As a result we expect the sand clusters will be broken by the razor, slide smoothly towards the nozzle, and exit towards the vacuum pump leaving a flat surface marked with channels an inch apart.

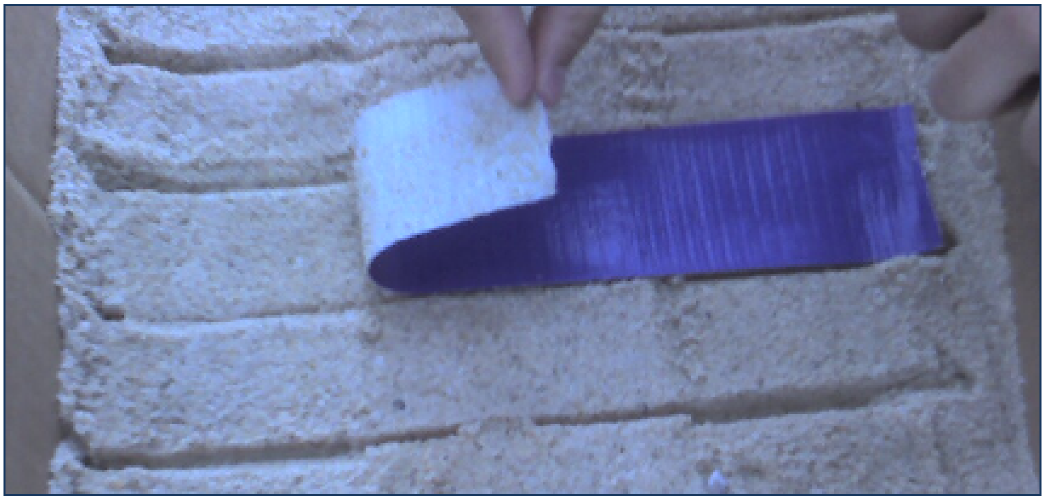


Figure 29: Sampling the sand

3.2.2 Additional fixtures and suggestions

It is a concern to us the safety of the technicians operating the equipment. The area that was previously overlooked in this report is when the technicians mount the apparatus into the target. Since the apparatus is on wheels there is a possibility that the wheels might get off the track if the apparatus is not mounted with care. In the initial stages of our design the X actuator was mounted on a threaded rod and ½” aluminum rod for support. We moved away from this because it was very expensive to purchase an 8” threaded rod and the rod would bend when the mechanism is close to the middle of the target. However we have been exposed lately to a mechanism in the Experimental Fluids lab that used a 1” aluminum rod with open linear ball bearings (Figure 30). This is a good idea for our design since the open bearings allow for supports (red triangular shape on the left picture) to the rod to prevent any displacement from bending. The X mechanism will still be driven by a chain except now it will not have the wheels on the track. Instead it will be securely attached to the bearings which overall is safer since the mechanism can actually be flipped upside down and it will still remain attached.

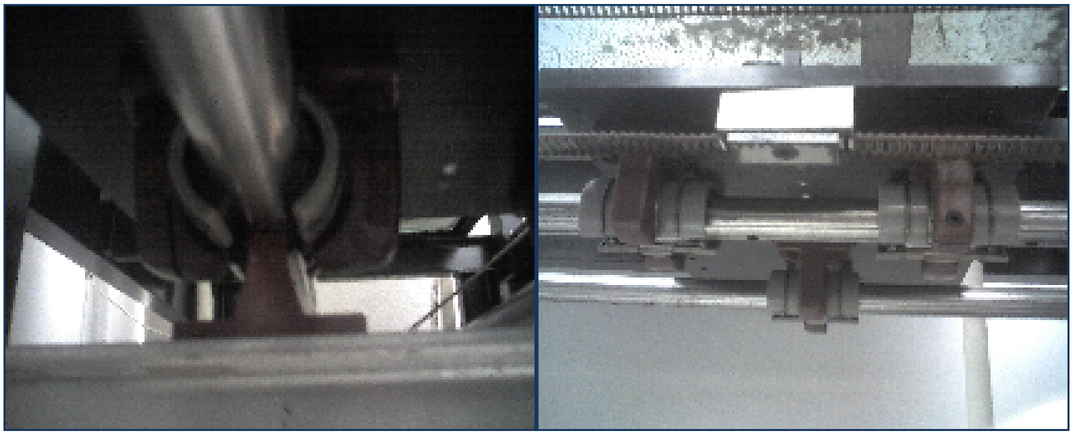


Figure 30: Open linear roller bearings on a supported 1" aluminum rod holding a chain driven mechanism

There are a couple of additions that we think would be beneficial to have in the mechanism. The first one will not be added because it conflicts with our budget requirement and it is to have some kind of sensors that display an image of the path of the projectile. This could be any of the ones discussed in the background section of this report. If the technicians know exactly the location of the path they could instruct the mechanism to dig deeper taking thicker layers for the first few passes and this would decrease significantly the time of operation. For example if they knew the projectile passed 9” under the sand they might like to get rid of the first 6” without taking samples. They could run three layers of 2” instead of six 1” layers until they saw some of the crushed sand.

Another addition that might be a good idea to accurately obtain samples is to actually use the information from the micro processor to label the position of a sample. It discussed with Dr. Cooper that sometimes it is beneficial to take samples with small cylindrical sample tape instead of the long stripes just because they are easier to transport and do not require cutting to put on the microscope. If he requested to have the cylindrical samples we could remove the vacuum tip from the tube, and buy a flanged cylinder used for sampling. This cylinder is closed at one end so it will stick to the tube because of the pressure from the vacuum pump. On the outer side it has circular sampling tape. Inputting the values of the coordinates where a sample is desired, the mechanism will move and obtain the sample.

4 Control System

All design considerations have the movement control of the mechanism controlled by three direct current motors. Each DC motor is located on each movement axis. The locations of the motors are illustrated in Figure 31 by black cylinders. All three motors have a gearbox to have a larger gear ratio to create more torque from the motors. The sizes of the motors are classified in the sections below.

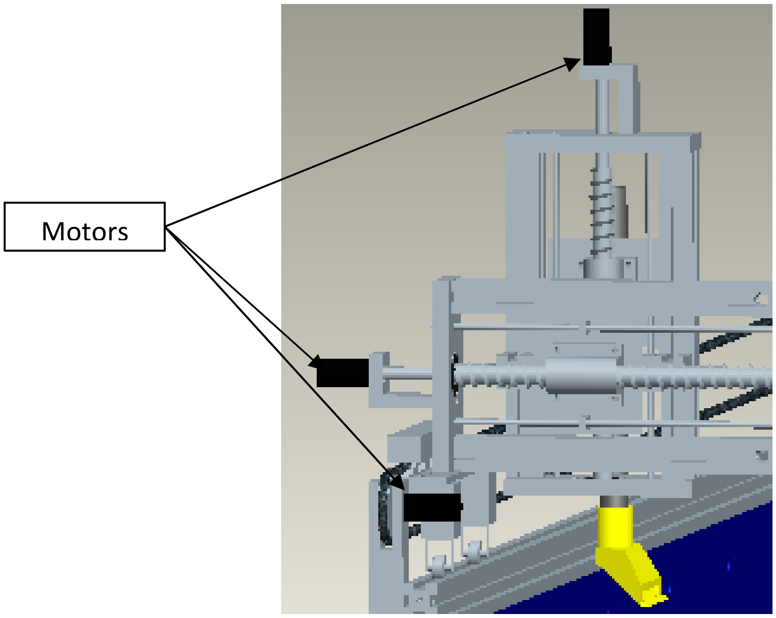


Figure 31: Location of the DC Motors

There were multiple considerations for the control system of the apparatus and below are the descriptions of each.

The first control system, the most ideal system for the project, is composed of multiple components. The system is composed of a power supply that converts alternating current electricity to direct current electricity, a microprocessor with carrier board that controls the motor movements and is used for any outputs desired from the system, three motor controllers to control the power going to the motors, three servo controllers to monitor the encoders, three motor encoders placed on each axis to monitor the location on that axis, two limit switches placed on each axis for safety, and three geared motors to supply the necessary torque to move the apparatus. Figure 32 is a stigmatic of this control system and components.

This method of control is ideal for the project because with the motor encoders and microprocessor the precise location of the tip of the apparatus at all times. However, the cost of such a design is more expensive than the budget allotted for the control system.

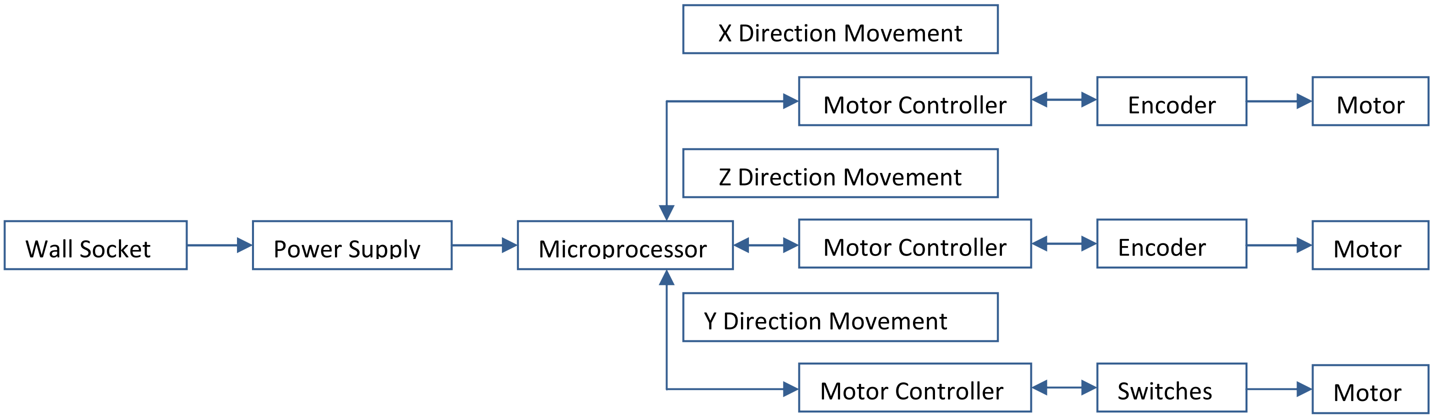


Figure 32: Control System 1 Stigmatic

The second control system, the system for a lower budget project, is composed of multiple of the same components as above with a few modifications. The system is composed of a power supply that converts alternating current electricity to direct current electricity, a microprocessor with carrier board that controls the motor movements and is used for any outputs desired from the system, three motor controllers to control the power going to the motors, two limit switches placed on each axis for motor direction control and safety and three geared motors to supply the necessary torque to move the apparatus. Figure 33 is a stigmatic of this control system and components.

This method of control requires more programming of code and trial and error for motor location for the project because without the motor encoders the precise location of the tip is not known at all times. However, the cost of such a design is much less expensive and within the budget allotted for the control system.

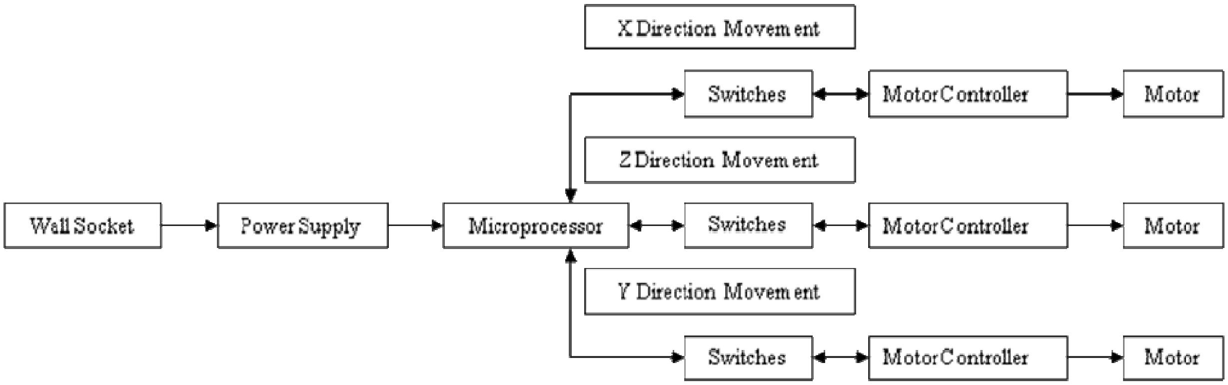
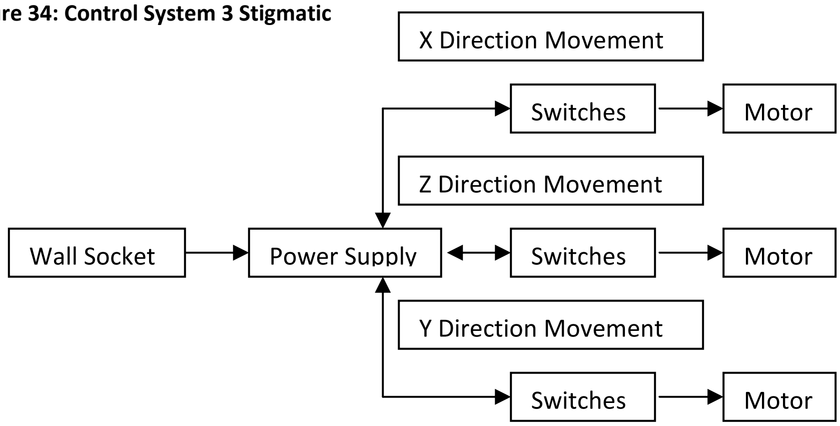


Figure 33: Control System 2 Stigmatic

The third control system is composed of a power supply that converts alternating current electricity to direct current electricity, three forward/reverse switches for direction change and three geared motors to supply the necessary torque to move the apparatus. Figure 34 is a stigmatic of this control system and components.

This method of control requires human input and trial and error for motor location for the project because without all the computer controlled components the precise location of the tip is not known at all times. However, the cost of such a design is much less expensive and within the budget allotted for the control system. This system is a backup system for the result that the computerized control system does not work properly.

Figure 34: Control System 3 Stigmatic



The basis for selecting the control system components started with calculations for the torque needed from the motors. Calculations show that the minimum torque needed from the motors is 20 oz*in and the maximum torque needed is 40 oz*in (Appendix A). The chosen motors need a minimum of ten times the stall torque for continuous movement to prevent damaging the motors over time and to overcome any unforeseen problems. The chart below shows the required torques need from each motor.

Figure 35: Selected motor

Table 1: Torque Requirements

Required Torque Needed (oz*in)	
X movement	20
Y movement	40
Z movement	20

From these calculations, a motor (Figure 35) was selected giving 612 oz*in of stall torque for the Y and Z axis of movement and a motor with 1200 oz*in of stall torque was chosen for the x axis of movement. With each motor, a motor controller is needed to regulate the voltage and current that is supplied to each motor. Switches (Figure 36) and encoders are used to control the distance and direction each motor moves in order to get the desired movements needed. An encoder is a device used to change a signal into code, in this system the encoders change rotational motion from the motors into code to move the desired distances. Encoders are mounted directly to the motors and the two switches are mounted on either side of the axis of movement. The figure below shows the locations of the encoders and the switches used to change the directions of movement.

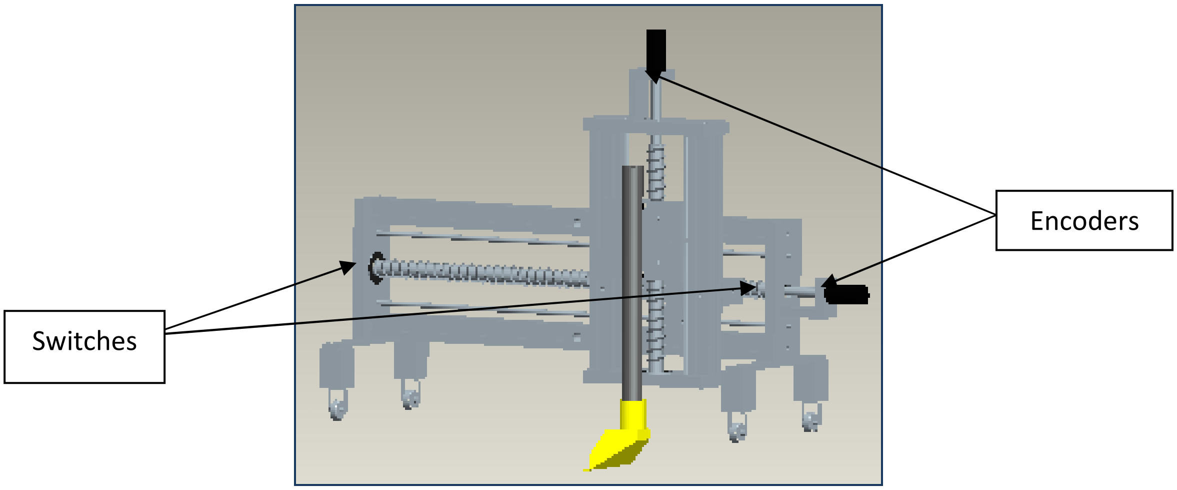


Figure 36: Switch and Encoder Locations (y and z-axes)

Figure37a: Microprocessor

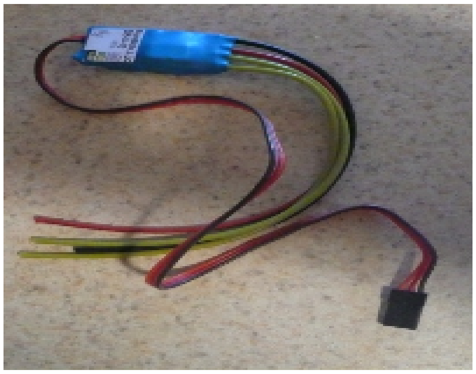


Figure37b: Speed Controller

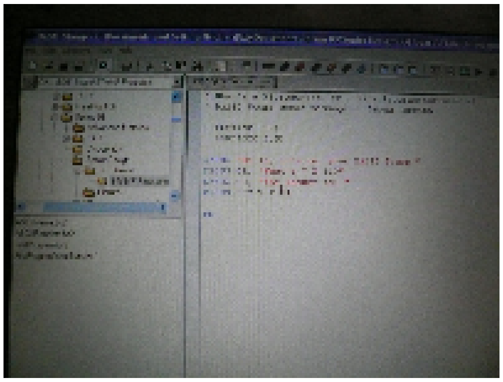


Figure37c: Basic Program

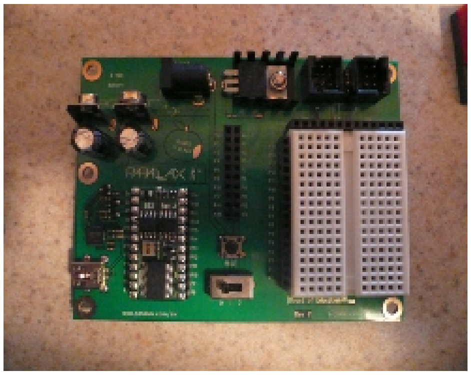


Figure37d: Processor Board

The microprocessor (Figure 37a) has the code saved on to it for the movements needed for the apparatus. The selection criteria for the microprocessor were such that a processor be easily programmable and had the software (Figure 37c) needed for easy coding of the mechanism. This is because no one in the group has experience coding microprocessors and the group was advised to find a processor board that comes with instructions and more than enough data ports for the mechanism. The processor selected is a Board of Education Basic Stamp Kit (Figure 37d)

The chosen control system design is the second concept discussed above. This system was chosen because of the cost budget. It is not the ideal way of doing motor control, however it is upgradable to the ideal system by the addition of the removed components.

4.1 Automation

The decision of what the motion of the mechanism should be was chosen due to the original make screens that the apparatus has to avoid.

In Figure 38 the make screens that are used in the experiment create obstacles that the mechanism must move around. Thus, the movement of the mechanism was chosen to move along the make screens. Thanks to the sponsor, our design does not need to take these screens into account; however it was chosen to keep the general motion of the mechanism (Figure 39) in this direction to prevent any major reconstruction of the mechanism when the make screens are placed back into the experiment.

Figure 38: Make screens

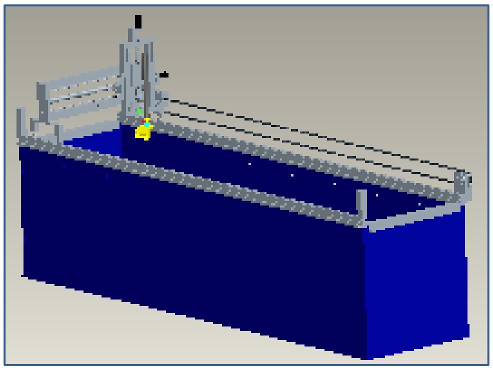


Figure 39: Mechanism

The movement of the mechanism through the sand target is done in twenty-four - one inch increments in the z-direction. The x-direction movement is twenty-four – four inch increments and the y-direction movement is done by moving twenty-four inches through the sand and returning twenty-four inches before moving 4 inches in the x-direction. The x and y-direction movements are illustrated in Figure 40. The mechanism has been estimated to be moving at 2 in/sec in all directions. This speed is thought to be the optimal starting speed for analysis once the mechanism has been assembled and testing has begun. Once testing is begun the speed of the mechanism will be optimized to give the quickest removal time for the sand. However with the given time of 2 in/sec, the mechanism will be able to remove one layer or one inch of sand in ten minutes. Thus, the removal of all twenty-four inches of sand can be done in four hours without any interruptions.

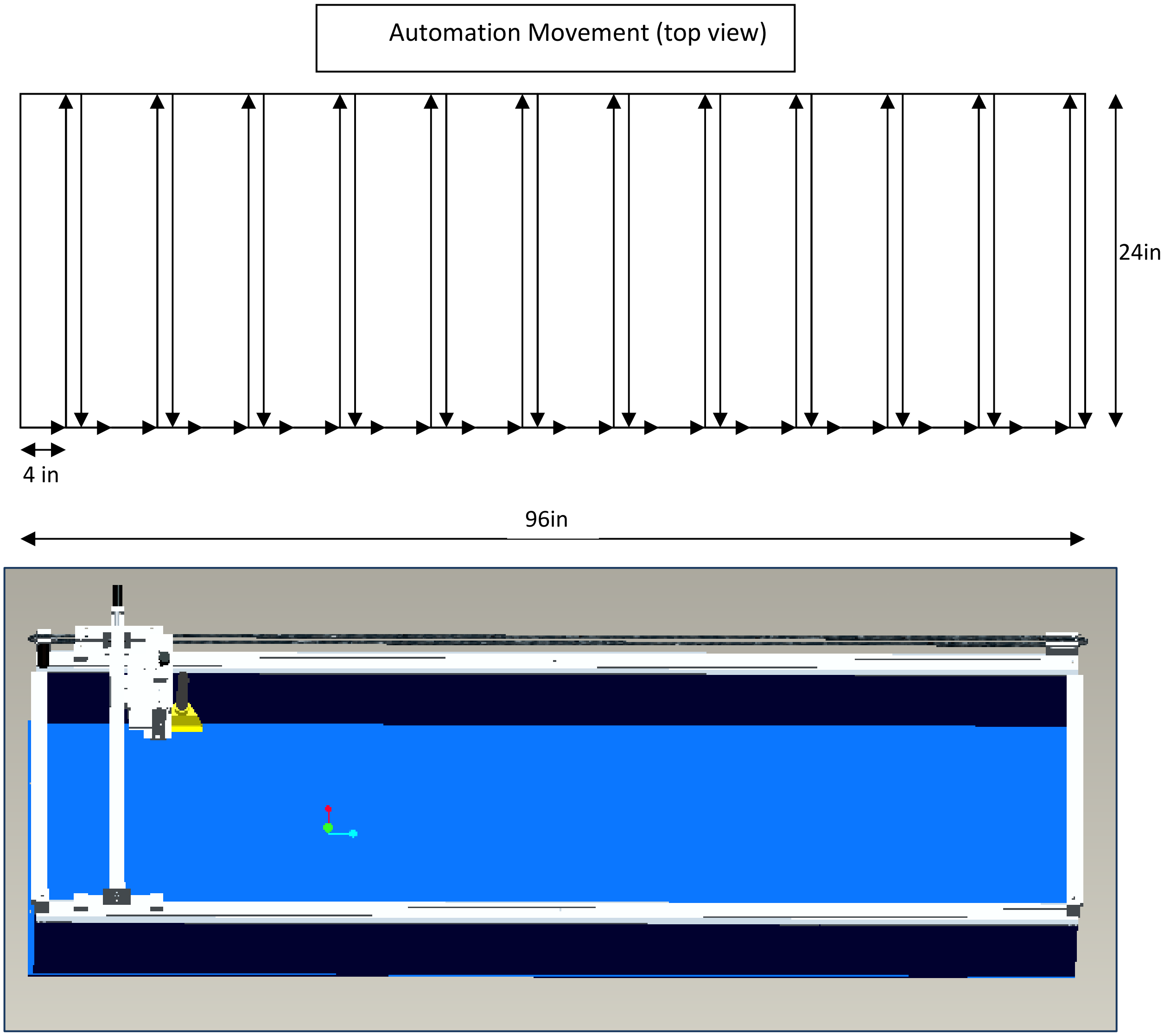
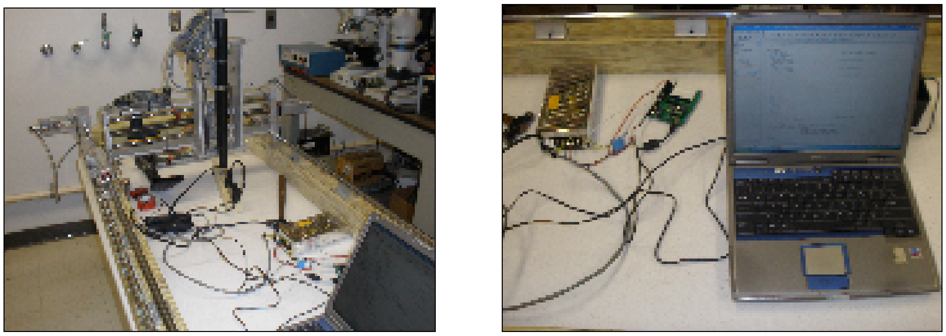


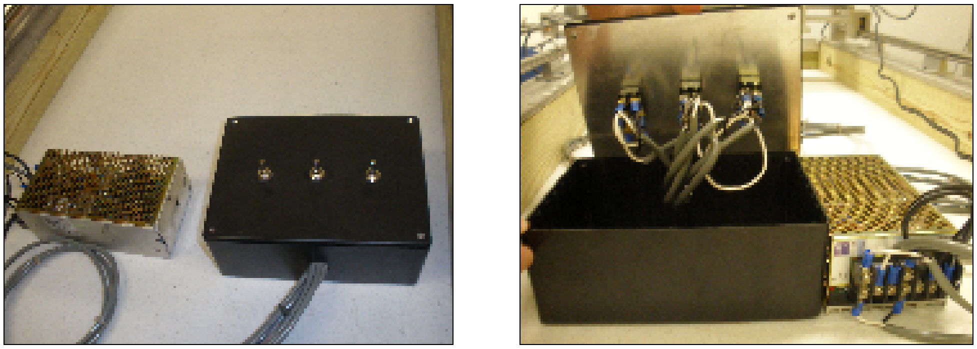
Figure 40: Automation Diagram

4.1.2 Automation Results



Figures 41 a,b: Complete Control System and Program

Through months of work to make the automation of the selected control system to work (Figures 41a,b), a problem arose with communication between the microprocessor and the motor controllers. The problem consists of a communication error with a safety device on the motor controller. The motor controller requires a neutral position signal in order to set itself into ready mode. This signal turned into the automations undoing because after speaking to the manufacturer of the device and several professors and teaching assistants the signal was not figured out and the microprocessor was unable to send the control codes for the motors to the motor controllers in the time we have had for the project. The fix to this problem is to figure out the neutral signal through testing more signals or to buy new motor controllers that do not have this safety feature. The temporary fix for the project was to use the back up control system (Figures 42 a,b) of forward/reverse switches. This is to show the movement of the apparatus and how it works.



Figures 42 a,b: Switches and Switch Box

With the precision of the threaded rods and the use of the tightened chain the movements of the mechanism are precise. The motor controllers and encoders are able to control the mechanism within two degrees of rotation of the motor shaft. This precision equates to +/- 1/32”. This precision is what was desired in the original design concept.

5 Testing and Results

A number of tests were performed in order to find the best method of using the mechanism to meet the sponsor's requirements. The tests can be divided into three subjects. First there was a need to ensure the basic motions of the mechanism were effective, second activate a control system and optimize its speed, and third determine the most accurate way to vacuum the sand.

5.1 Basic motions:

During the manufacturing stage the mechanism's basic motions, forward and backward on the lead screw and the sprocket, was constantly tested just by chucking a power drill to the shafts. Each moving component was tested separately and then in assembly.

5.1.1 Correct assembly of all the parts of each axis

i. Method: Observation
ii. Result: Positive
iii. Observations: The assembly x-axis requires perfect alignment of the two long rods. This is achieved by moving the mechanism back and forth along the x axis while screwing the rod supports into the shaft.

5.1.2 Range of the motion

i. Method: Chucking a drill to each shaft and driving each axis to the extreme positions
ii. Result: x-axis (86'), y-axis (17'), z-axis (10") (see Figure 43)
iii. Observation: This range includes complete area of the usual shot line. Any position of the box can be reached by manually changing the tip and its position if desired.

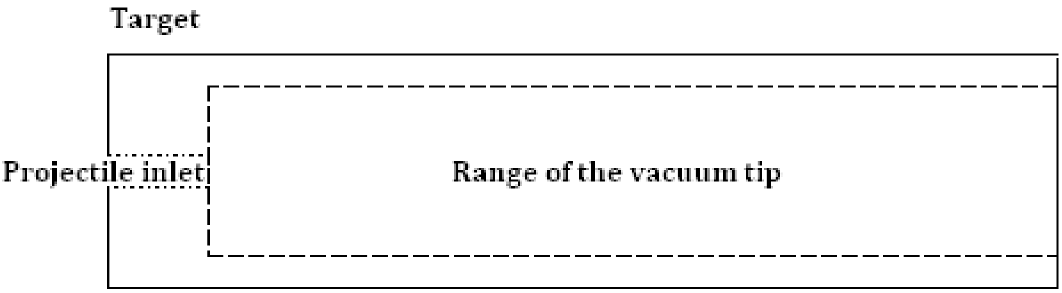


Figure 43: Range of Vacuum Tip

5.1.3 Vibration and binding

i. Method: For vibration the whole mechanism was strapped into a trailer and driven over rough surfaces. For binding chucking a drill to each shaft and driving each axis to the extreme positions.
ii. Result: Positive
iii. Observation: There is a chance of binding in the x-axis after time if the screws that connect the supports to the metal frame become loose due to vibration. This is fixed by aligning the rods and tightening the screws.

5.1.4 Smoothness of the translation

i. Method: Observation. Chucking a drill to each shaft and driving each axis to the extreme positions.
ii. Result: Positive
iii. Observation: The rotation of the sprockets on the x-axis is difficult to control compared to the other two axes that have lead screws.

5.1.5 Basic Motions Discussion

With the motors removed the y and z axis, which have lead screws, presented very little problems. It was noticed however that when the lead screw drives the plate all the way into the extremes of its range it gets stuck disallowing to reverse the motion. This happens because the plate in motion has both the motor and inertia contributing to the torque, while after hitting the wall the plate is stationary and the only source of torque is the motor. Solutions for this are programming the switches to stop the motors before the plate hits the wall, running the plate into the wall at a lower torque than the maximum of the motor and driving it back at the maximum, or simply never driving it all the way into the wall.

5.2 Speed and control

As mentioned before the trickiest part of the project was to control the motion of the three motors. During this test two methods were implemented in order to control the motion on the three directions. The first is fully automated using microcontrollers, and the second is using manual switches.

5.2.1 Fully Automated

i. Method: Computer programming
ii. Result: Failed
iii. Observation: There was no voltage output to the motors from the microcontrollers.

5.2.2 Manually controlled

i. Method: Flipping three switches forward and reverse to allow voltage from a power supply to the three motors. For the velocity placed a ruler next a moving part and used a chronometer to measure the time over a certain distance. (see Figure 44)

ii. Result: At the maximum voltage of the power supply 11.75V and outside of the sand the x-axis translates at (0-26.6 in/s), the y-axis 2.25 in/s, and the z-axis 1.875 (downward)

iii. Observation: For the z-axis only the downward motion was measured since the downward motion is the only one used in the experiment. Also the difference between upward and downward velocities is not very significant.

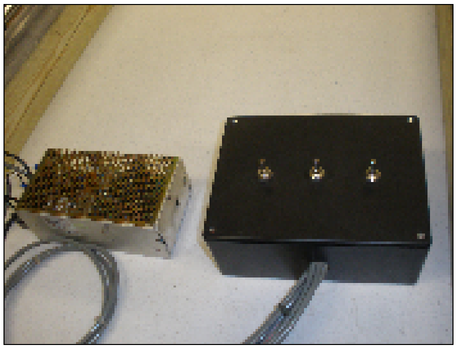


Figure 44: Switches

5.2.3 Discussion

The program was meant to simplify the experiment when in reality it requires a great degree of knowledge in programming to make it work. Even if the program is written correctly, the user should consider that if at any point the program does not work there may not be a technician available with the ability to troubleshoot it. An alternative method to conduct the experiment is needed whether the program works or not. Using switches bring other problems. In the case of the x-axis, it will take some practice to be able to move the tip exactly four inches, since it takes approximately half revolution of the motor shaft. However, it is easy and fast to run the x-axis from wall to wall. This is a good advantage since it would allow taking the layers of sands that will not be sampled a lot faster.

5.2.4 Sand Extraction

One of the crucial parts of the experiment is to not disturb the sand in the process of removing layers above the shot line. The idea of vacuuming avoids high vertical forces into the packed sand, but it was important to make sure that the tip of the vacuum was not sweeping sand which will take it to a horizontal position other than its post impact position. Tests were performed with different tips to check the shoveling and sucking characteristics. Ideally the vacuuming leaves a perfectly flat surface, no accumulation of sand in front of the tip while running the actuator at full speed, and the depth is at least 0.5in each run. Also a test was performed using the best suited tip to discover a simulation of a shot line using flour.

a) Tip 1

i. Method: Placing the smallest tip into the end of the tube. The nozzle is 4.5in by 0.5in for an area of 2.25in^2. (see Figure 45) Drive the z-axis 0.5in into the sand and run the y actuator its full range alternating with the x actuator like explained in the previous section. Then increase the depth until the motors can not overcome the load.
ii. Result: Positive
iii. Observation: Up to 1in of depth leaves a perfectly flat layer with no accumulation in the forward motion.

Figure 45: Nozzle Testing

b) Tip 2

i. Method: Placing the medium size tip into the end of the tube. The nozzle is 4.5in by 1.5in for an area of 6.75in^2. Drive the z-axis 0.5in into the sand and run the y actuator its full range alternating with the x actuator like explained in the previous section. Then increase the depth until the motors cannot overcome the load.
ii. Result: Negative
iii. Observation: Up to 1in of depth leaves flat layer with significant accumulation in the forward motion.

c) Tip 3

i. Method: Placing the standard Shop-Vac size tip into the end of the tube. The nozzle is 10in by 1.5in for an area of 15in^2. (see figure 46) Drive the z-axis 0.5in into the sand and run the y actuator its full range alternating with the x actuator like explained in the previous section. Then increase the depth until the motors can not overcome the load.
ii. Result: Positive
iii. Observation: Up to 1in of depth leaves flat layer with significant accumulation in the forward motion. This tip removes a layer of 10in at a time.

Figure 46: Standard Shop Vac Tip Design

5.2.5 Speed and Control Discussion

When intuitively seems that the smaller the area of the vacuum tip the more sand can be sucked, actually a smaller cross sectional area proved to be the more effective. The nozzle on this tip increases the velocity and decreases the pressure causing the sand particles to smoothly flow through the tip into the tube. Using tips that have a cross sectional area larger than the one of the tube result in less suction power due to the rise of pressure in the joint of the tip to the tube. This is confirms Bernoulli's concept discussed in section 3.2. Even though tip 1 leaves a better surface for sampling, tip 3 can be used to extract the sand that is not going to be sampled since it sweeps 10in at a time instead of 4.5in. It also increases the range of the mechanism by 5.5 in considering that the range test was performed with Tip 1.

The flour experiment proves that the sand particles, even with significantly higher density and smaller size, remain in their same place as long as they are not in front of the vacuum tip. It is feasible to remove sand to a specific depth without disturbing any particles below the layer desired to sample.

6 Problems encountered

This section is intended to set up a project scope for a very possible continuation of this project by another senior design group the following semester. Since project was very much open ended and the customer specifications changed to make the project feasible, the group has decided to provide a list of problems that have been generated during manufacturing and testing thinking that this will be a good advantage to put up to speed the followers of the project. Given to time and budget constraints the following ideas could not be developed:

- Almost one third of our budget was spent in the electrical part of the mechanism. It is suggested that an electrical engineer is included in the group in order to implement the program and optimize the electrical system to get the most out of the power supply.
- The design should be modified to increase the range of motion to reach every position inside of the target.
- Half of the time the vacuum tip is traveling backwards to reposition. This means half of the time is wasted. The mechanism would be more effective if it vacuums at all time.
- This project focused of extracting the layers of sand that were not going to be sampled or that were already sampled. The mechanism would be much more effective if it could take samples as well and display the coordinates of the samples.

7 Cost consideration

Table 1 displays information including the cost of individual parts or materials needed. These materials and parts are definitive. Most of them were chosen specifically to be easily replaceable. The group has access, without charge, to machine parts at the Air Force Research Laboratory's machine shop as well as Dynatech Associates. Dynatech Associates is eligible to receive free shipping from Alro Steel while Eglin can assist in minor modifications.

TABLE 2. ***Prices of parts and materials***

Part	Part Number	Company	Price (USD)	Qty	Total (USD)
*ACME threaded rod	98980A395	McMaster	157.90	1	157.90
*ACME Nut	95365A526	McMaster	48.65	2	97.30
*Bearing (Ball)	60355K48	McMaster	8.12	4	32.48
*Bearing (Open linear)	5986K26	McMaster	23.47	3	70.41
*Bearing (Open linear)	5986K2	McMaster	15.23	4	60.92
*Chain (Corrosion res.)	7210k122	McMaster	95.00	1	95.00
*Sprocket	6663k21	McMaster	19.09	2	38.18
Precision Shafts	1144K34	Alro Steel	34.90	2	69.80
Precision Shafts	1144K33	Alro Steel	33.17	2	66.34
Linear Bearings		Alro Steel	15.05	2	30.10
Support Rods		Alro Steel	100.00	2	200.00
*Power supply		Robot Market Place	33.99	1	33.99
*Motors		Trossen Robotics	41.10	3	123.30
VEX Limit Switch		Trossen Robotics	12.99	4	51.96
*STAMP kit		Trossen Robotics	124.50	1	124.50
*Motor Controllers		Trossen Robotics	46.50	3	139.50
*Motor Bearing blocks		Trossen Robotics	10.00	3	30.00
*Misc. wire		Dynatech Associates	0.00	1	0.00
*Vacuum System		Mid America Vacuum Center	92.00	1	92.00
Travel		FAMU-FSU COE		3	376.96
					1890.56

*These prices do not include shipping and handling cost

8 Conclusion

This project has been a great learning experience so far. We were asked to design an apparatus and method of obtaining sand samples out of a target without losing vital information of this sand. It is interesting that the focus of the apparatus is in extracting the sand that has already been sampled with care and quickness rather than actually core sampling the sand. However, we believe that minimizing the distortion of the sand is the way of getting accurate post impact samples and that is what our mechanism will attempt to do. Overall the robotic mechanism has three degrees of freedom and theoretically is capable of removing a one inch layer of sand from the sample unassisted. It will be able to leave a flat surface behind marked by channels one inch apart to simplify the laying down of the sampling tape. This is a big improvement from the previous method of sampling the sand and it was designed so that additions and adjustments can be easily made to it. In fact, we have developed ideas to use the mechanism to pick up the samples without any major changes and these ideas will be discussed with our sponsor. The mechanism is ready to be built and tested so that a methodology and experimental procedures can be written.

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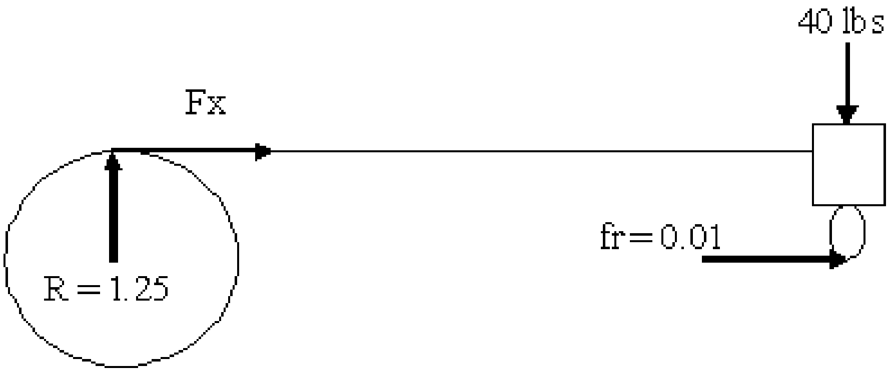
10 APPENDIX A: CALCULATIONS

Motor Calculations:

x - direction movement

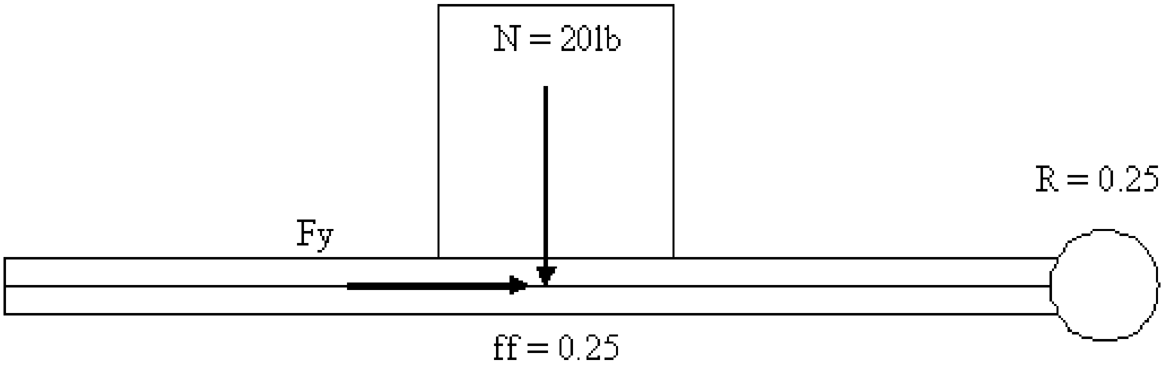


rolling resistance assumed to = 0.01 $fr := 0.01$ $N := 40lb$ $R := 1.25in$

$Fx := fr \cdot N$ $Fx = 0.4 lb$

$Torque := Fx \cdot R$ $Torque = 8 oz \cdot in$

y - direction movement



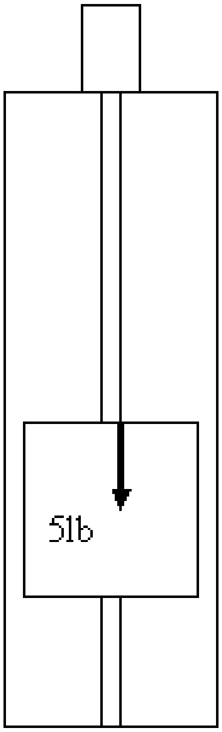
C of friction through the threaded rod is estimated to be 0.25 with no lubrication.

$N := 20\,lb \qquad ff := 0.25 \qquad R := 0.25\,in$

there is a 5 lb force of pushing through the sand

$Fv := ff \cdot N + 5\,lb \quad Fv = 10\,lb \quad Torque := Fv \cdot R \qquad Torque = 40\,oz \cdot in$

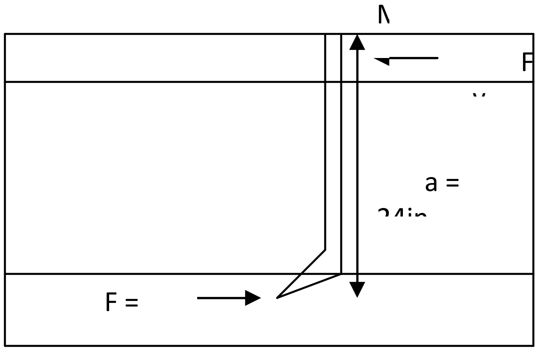
z - direction movement



$R := .25\,in \qquad N := 5\,lb$

$Torque := N \cdot R \qquad Torque = 20\,oz \cdot in$

Moments on the connection points of directions.



Assumptions:

The maximum force extruded on the vacuum tip is when the tip is moving through wet compacted sand at the maximum depth of 1 inch. The force is assumed to be 50lbs. An experiment is going to be conducted to have a closer value for the force. The experiment uses a 4 inch board and a force gauge in 1 inch of wet compacted sand to get a better approximation for the force extruded on the tip.

The maximum moment is extruded when the depth of the vacuum arm is fully extended to 24 inches and moving through 1 inch of wet compacted sand.

CW = clockwise

CCW = counter − clockwise

RtL = Right to Left positive

LtR = Left to Right positive

Guesses $M_{CW} := 1000\,lb\cdot in \quad F := 50\,lb \quad a := 24\,in \quad F_y := 75\,lb$

$$\sum_{CW} M = 0$$

$$\sum_{LtR} F_y = 0$$

Given

$0 = M_{CW} - F\cdot a$

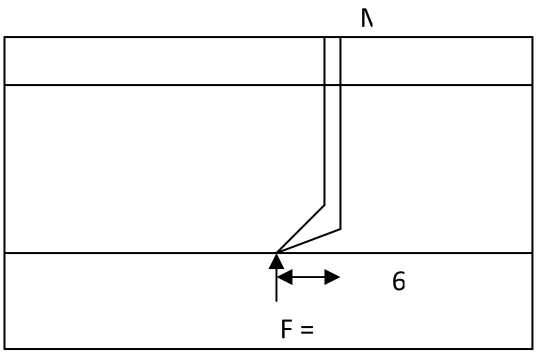
$0 = F - F_y$

$X := \mathrm{Find}\left(M_{CW}, F_y\right)$

$$X = \begin{pmatrix} 13.825\,kg\,m \\ 22.68\,kg \end{pmatrix}$$

$M_{CW} := 13.825\,kg\cdot m \quad \boxed{M_{CW} = 1200\,lb\cdot in}$

$F_y := 22.68\,kg \quad \boxed{F_y = 50\,lb}$



Other Moments:

This moment is caused when the vacuum tip is being pushed into the sand. The worst case for this moment is assumed to be when the tip is being pushed into wet compacted sand with the vacuum.

CW = clockwise

CCW = counter − clockwise

RtL = Right to Left positive

LtR = Left to Right positive

Guesses $M_{CCW} := 1000\,lb\cdot in \quad F := 30\,lb \quad b := 6\,in$

$$\sum_{CW} M = 0$$

Given

$$0 = M_{CCW} - F\cdot b$$

$$X := Find(M_{CCW}) \qquad M_{CCW} := X$$

$$\boxed{M_{CCW} = 180\,lb\cdot in}$$

For dirt devil vacuum pump:

$I := 12A$

$Vol := 120V$

$P_{in} := I \cdot Vo$

$P_{in} = 1.931hp$

Guessed values:

$\rho_{sand} := 1682\frac{kg}{m^3}$

$V := 1\frac{m}{s}$

$\rho_{air} := 1.177\frac{kg}{m^3}$

$\nu_{air} := 15.68 \cdot 10^{-6} \cdot \frac{m^2}{s}$

$\mu_{air} := \rho_{air} \cdot \nu_{ai}$ $\qquad$ $\mu_{air} = 1.846 \times 10^{-5} N \cdot \frac{s}{m^2}$

PVC 1-1/2 schedule 40 with 3*90deg flanged elbows:

$d := 4.090cm$

$D := 4.826cm$

$A_{flow} := 13.13cm^2$

$K_e := 3 \cdot 0.31$

$\varepsilon := 0$

$L_1 := 2ft$

$L_2 := 3ft$

$L_3 := 3ft$

$L_4 := \frac{1}{2}ft$

$L := L_1 + L_2 + L_3 + L_4$

$L = 8.5ft$ $\qquad$ $L = 2.591m$

Reynold's number to find out if the flow is laminar or turbulent:

$Re := \frac{\rho_{air} \cdot V \cdot d}{\mu_{air}}$ $\qquad$ $Re = 2.608 \times 10^3$

Friction factor:

$$f := \left| \begin{array}{ll} \frac{64}{Re} & \text{if } Re < 2100 \\ \left[-2 \cdot \log\left[\frac{\varepsilon}{3.7065d} - \frac{5.0452}{Re} \cdot \log\left[\frac{1}{2.8257} \cdot \left(\frac{\varepsilon}{d}\right)^{1.1098} + \frac{5.8506}{Re^{0.8981}}\right]\right]\right]^{-2} & \text{otherwise} \end{array} \right.$$

$f = 0.045$

Pressure head:

$P_2 := 1 \cdot \text{atm}$

$P_1 := P_2$

$x := (0\text{in}, 1\text{in} .. 24\text{in})$

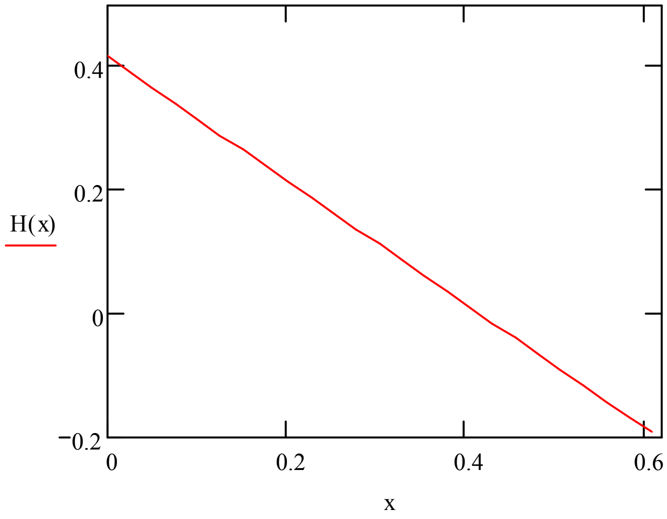
$z_1(x) := 2\text{ft} - x$

$z_2 := 0$

$$H(x) := \left(\frac{P_1 - P_2}{g \cdot \rho_{air}}\right) + \left(z_1(x) - z_2\right) - \left(\frac{f \cdot L}{d} + K_e\right) \cdot \frac{V^2}{2 \cdot g}$$

$H(x) =$

0.416	m
0.391	
0.365	
0.34	
0.315	
0.289	
0.264	
0.238	
0.213	
0.188	
0.162	
0.137	
0.111	
0.086	
0.061	
0.035	
$9.773 \cdot 10^{-3}$	
-0.016	
-0.041	
-0.066	
-0.092	
-0.117	
-0.143	
-0.168	
-0.193	



$$H1(x) := \left(\frac{P_1 - P_2}{g\cdot\rho_{air}}\right) + \left(z_1(x) - z_2\right)$$

$$H2(x) := \left(\frac{f\cdot L}{d} + K_e\right)\cdot\frac{V^2}{2\cdot g}$$

H1(x) = (m)	H2(x) = (m)
0.61	0.193
0.584	0.193
0.559	0.193
0.533	0.193
0.508	0.193
0.483	0.193
0.457	0.193
0.432	0.193
0.406	0.193
0.381	0.193
0.356	0.193
0.33	0.193
0.305	0.193
0.279	0.193
0.254	0.193
0.229	0.193
0.203	0.193
0.178	0.193
0.152	0.193
0.127	0.193
0.102	0.193
0.076	0.193
0.051	0.193
0.025	0.193
0	0.193

$$V_{dot} := 2340\frac{l}{min}$$

$$m_{dot} := \rho_{air}\cdot V_{dot}$$

$$H_{pump} := \frac{P_{in}}{m_{dot}\cdot g}$$

$$H_{pump} = 3.199\times 10^{3}\ m$$

Both the head from the difference in height and from minor and friction losses are insignificant to the power provided by the pump.

Calculation of actual removal time

$R_x := 86\text{in} \qquad V_x := 26.6\frac{\text{in}}{\text{s}}$

$R_y := 17\text{in} \qquad V_y := 2.25\frac{\text{in}}{\text{s}}$

$R_z := 10\text{in} \qquad V_z := 1.87\frac{\text{in}}{\text{s}}$

$$\text{Time\_for\_one\_layer} := \frac{R_x}{V_x} + \frac{2R_y}{V_y}\cdot\left(\frac{R_x}{4\text{in}}\right) + \frac{10\cdot R_z}{V_z}$$

$\text{Time\_for\_one\_layer} = 6.36\,\text{min}$

This time is an aproximation since it ignores reaction time on the switches and all mechanisms in case the program is running, or presition from an operator to not waisrt any time from switching off one switch to switching on the next.This calculation ingnores time for sampling if the mechanism is at stand by during the process.

$\text{Time\_for\_entire\_process} := 24\cdot\text{Time\_for\_one\_layer}$

$\text{Time\_for\_entire\_process} = 2.544\,\text{hr}$

APPENDIX B:
PRO-E DRAWINGS